

4 JSAP-Optica Joint Symposia 2025 | 一般セッション(口頭講演) : 4.1 Plasmonics and Nanophotonics

[7p-N203-1~14] 4.1 Plasmonics and Nanophotonics

[7p-N203-1]

[JSAP-Optica Joint Symposia Invited Talk] Metal-Based vs. Metal-Free SERS Substrates

○Yasutaka Kitahama^{1,2}, Keisuke Goda^{1,2,3,4,5} (1.Univ. of Tokyo, 2.LucasLand, 3.Wuhan Univ., 4.Univ. of California, 5.Tohoku Univ.)

[7p-N203-2]

[JSAP-Optica Joint Symposia Invited Talk] Multiscale Manipulation of Gold Nanocubes: Bridging Colloid Science and Nanophotonics for Tailored Optical Properties

○Jeong-Eun Park¹ (1.Gwangju Institute of Science and Technology)

[7p-N203-3]

Optical Chirality Enhancement Induced by Lattice Resonances of All-Dielectric Metasurfaces

○(M2)Yongan Hu¹, Hiroshi Sugimoto¹, Minoru Fujii¹ (1.Kobe Univ.)

[7p-N203-4]

Plasmonic Dimer Enhanced Polarized Single Photons Coupled into Optical Nanofiber

○(D)SUBRAT SAHU¹, KALI P. NAYAK², RAJAN JHA¹ (1.Nanophotonics and Plasmonics Laboratory, IIT Bhubaneswar, Odisha, India -752050, 2.Department of Engineering Science, University of Electro-Communications, Chofu, Tokyo, Japan-182-8585)

[7p-N203-5]

Broadband plasmon nanofocusing for Raman spectroscopy

○Yuto Okamura¹, Prabhat Verma¹, Umakoshi Takayuki¹ (1.Osaka Univ.)

[7p-N203-6]

Chirality transfer in Mie-resonant silicon nanoparticle-chiral molecule composites

○HIROKI KASAI¹, Kento Shintani¹, Hiroaki Hasebe¹, Shahin Ghamari², Frank Vollmer², Hiroshi Sugimoto¹, Minoru Fujii¹ (1.Kobe Univ., 2.Univ. of Exeter)

[7p-N203-7]

Landau Polaritons in Nanoslots in the Ultrastrong Coupling Regime: Breakdown of the Electric-Dipole Approximation

○(B)Sae Endo¹, Dasom Kim¹, Sunghwan Kim², Dukhyung Lee³, Shuang Liang⁴, Geon Lee^{5,6}, Michael J. Manfra⁴, Minah Seo^{5,7}, Dai-Sik Kim^{2,6}, Junichiro Kono¹ (1.Rice Univ., 2.Ulsan National Inst. of Sci. and Tech., 3.Mohammed VI Polytechnic Univ., 4.Purdue Univ., 5.Korea Inst. of Sci. and Tech., 6.Seoul National Univ., 7.Korea Univ.)

[7p-N203-8]

[JSAP-Optica Joint Symposia Invited Talk] Engineering Emission Properties of Transition-Metal Dichalcogenide Monolayers by Mie-Resonant Silicon Nanospheres

○Hiroshi Sugimoto¹ (1.Kobe Univ.)

[7p-N203-9]

Optical Modulation via Atomically Thin Dielectrics in Membrane Metasurface

○(P)CHIHZONG DENG¹, Kuniaki Konishi², Vincent Tung³, Chun-Wei Chen⁴, Ya-Lun Ho¹ (1.NIMS, 2.School of Sci., The Univ. of Tokyo, 3.School of Eng., The Univ. of Tokyo, 4.National Taiwan Univ.)

[7p-N203-10]

Broadband Solar Absorber Design Using Optimization-Driven Nanostructures for Efficient Solar-Thermal Conversion

○(DC)Chih-Chung Wang^{1,3}, Jia-Han Li^{1,3,4}, Tadaaki Nagao^{1,2} (1.NIMS, 2.Hokkaido Univ., 3.Dept. of ESOE, National Taiwan Univ., 4.RTRC, National Taiwan Univ.)

[7p-N203-11]

Flexible and reconfigurable silicon carbide metasurface stickers

○Shunsuke Murai¹, Hiroya Maruyama², Joshua Tse², Hongjie Gao², Katsuhisa Tanaka² (1.OMU, 2.Kyoto U.)

[7p-N203-12]

Floquet Matrix Formulation for Dispersive and Dissipative Time-Varying Media

○(D)Yuchen Sun¹, Guangwei Hu¹ (1.NTU)

[7p-N203-13]

Helicity-Resolved Raman Spectroscopy on MoS₂ coupled with Mie-Resonant Silicon Nanospheres

○(P)Mojtaba Karimi¹, Daisuke Shima¹, Hiroto Shinomiya¹, Hiroshi Sugimoto¹, Minoru Fujii¹ (1.Kobe Univ.)

[7p-N203-14]

Design of Unidirectional Non-Hermitian Multilayer Structures in the Near-Infrared Region

○Ayaha Yamamoto¹, Wakana Kubo¹ (1.Tokyo Univ. of Agri. and Tech.)

Metal-Based vs. Metal-Free SERS Substrates

Yasutaka Kitahama^{1,2}, Keisuke Goda^{1,2,3,4,5}

¹The University of Tokyo, ²LucasLand, ³Wuhan University, ⁴University of California, Los Angeles, ⁵Tohoku University

E-mail: kitahama@g.ecc.u-tokyo.ac.jp

1. Introduction

Surface-enhanced Raman spectroscopy (SERS) represents a powerful extension of conventional Raman spectroscopy, a label-free analytical technique renowned for its ability to resolve sharp vibrational signatures of analyte molecules. Two predominant mechanisms are widely acknowledged to underpin SERS: the electromagnetic (EM) and chemical mechanisms.

In the EM mechanism, the local EM field is enhanced at the interstitial gaps between noble metal nanostructures via localized surface plasmon resonance, which arises from the resonant oscillation of conduction-band electrons under incident light. While metal-based SERS substrates leveraging this mechanism offer exceptional sensitivity, they often suffer from poor uniformity (high coefficient of variation (CV)) and limited durability, owing to the nanoscale confinement of the EM field and plasmon-enhanced photo-thermal effects.

Conversely, extensive research has recently been directed toward the development of efficient metal-free SERS substrates based on the chemical mechanism. These systems rely on the resonance Raman enhancement facilitated by charge transfer complexes formed between the analyte and the substrate. Although metal-free substrates typically demonstrate superior uniformity and durability, their sensitivity remains suboptimal.

In this study, we present a comparative evaluation of metal-based and metal-free SERS substrates. We have developed a novel metal nanomesh substrate, which operates on the EM mechanism [1–3], as well as metal-free SERS substrates that harness the chemical mechanism [4–7]. These substrates are assessed in terms of sensitivity, uniformity, and additional performance metrics.

2. Methods

To fabricate the metal nanomesh [1–3], a nanomesh composed of polyvinyl alcohol (PVA) was fabricated via electrospinning. Subsequently, a gold or silver layer was deposited onto the PVA nanomesh through thermal evaporation under high vacuum. The final step involved dissolving the PVA nanofiber templates with a water spray, yielding a pristine gold or silver nanomesh.

To fabricate the metal-free substrates, three types of carbon-based precursors were synthesized. First, polyacrylonitrile nanomesh was produced via electrospinning [4]. Second, conducting polymer nanowires, such as those composed of poly(3,4-ethylenedioxythiophene), were synthesized on carbon paper through conventional electropoly-

merization [5]. Third, porous nanowire arrays of polypyrrole were fabricated via template-assisted electropolymerization using anodized aluminum oxide templates [6]. These precursors were subsequently carbonized in a vacuum furnace [4–6]. Additionally, Prussian blue analogue (PBA) nanoparticles, representing another class of metal-free SERS substrate, were synthesized chemically [7]. Crystal defects enhancing SERS activity were introduced by incorporating various metal ions during the synthesis.

3. Results and Discussion

The gold or silver/PVA nanomesh is characterized as an ultrathin, flexible, stretchable, scalable, adhesive, and biocompatible SERS substrate, achieving enhancement factors on the order of 10^{8-6} [1,3]. The 3D network of nanofibers facilitates a high density of plasmonic hotspots, enabling consistent measurements with uniformity levels reflected by a CV of 16–20% [3]. Remarkably, the silver nanomesh demonstrates excellent preservation properties and functions across a broad range of excitation wavelengths [3].

The carbon-based SERS substrates exhibit robust enhancement factors on the order of 10^{6-5} [5,6], along with excellent uniformity (CV = 3–13%) [5,6], high durability [4], and effective fluorescence quenching [5]. Furthermore, PBA nanoparticles deliver high enhancement factors (10^{8-5} -fold), superior uniformity (CV = 7–13%), as well as long-term stability, fluorescence suppression, preservation capability, and biocompatibility [7].

4. Conclusions

The metal nanomesh is highly suited for integration into wearable SERS sensors due to its superior sensitivity. In contrast, the metal-free SERS substrates primarily excel in uniformity, offering promising alternatives for applications requiring reproducibility and long-term operation.

Acknowledgements

This research was supported by the MEXT Quantum Leap Flagship Program and Advanced Research Infrastructure for Materials and Nanotechnology in Japan (ARIM).

References

- [1] Limei Liu, et al., *Adv. Optical Mater.*, **10** (2022) 2200054.
- [2] Yasutaka Kitahama, et al., *Anal. Methods*, **15** (2023) 1028.
- [3] V. Kesava Rao, et al., *Adv. Photonics Res.*, **5** (2024) 2300291.
- [4] Machiko Marumi, et al., *Mater. Adv.*, **5** (2024) 4764.
- [5] Huanhuan Zhang, et al., *Adv. Optical Mater.*, **13** (2025) 2402673.
- [6] Nan Chen, et al., *Nat. Commun.*, **11** (2020) 4772.
- [7] Xingxing Yu, et al., *ACS Nano*, **18** (2024) 30987.

[7p-N203-1~14] 4.1 Plasmonics and Nanophotonics**[7p-N203-2] [JSAP-Optica Joint Symposia Invited Talk] Multiscale Manipulation of Gold Nanocubes: Bridging Colloid Science and Nanophotonics for Tailored Optical Properties**

○Jeong-Eun Park¹ (1.Gwangju Institute of Science and Technology)

キーワード : gold nanocube、high yield、polariton

At the intersection of colloid science and nanophotonics is the potential to unlock fundamental interfacial phenomena for developing advanced materials with unique optical properties. This presentation introduces how strategic manipulation of surface chemistry and assembly dynamics enables advancements in gold nanocube systems across multiple scales. A centrifugal depletion-induced flocculation method achieves exceptional purification of gold nanocubes, with recovery efficiencies exceeding 98% and yields of 98-99% for 60 nm particles, while maintaining high monodispersity, effectively addressing a core challenge in colloidal synthesis. These high-quality gold nanocubes enable the investigation of strong coupling phenomena between plasmonic nanocubes and J-aggregates, where smaller nanocubes demonstrate enhanced coupling strengths further improved by approximately 21% through a layer-by-layer coating technique. This technique overcomes surface area limitations and creates exciton-polaritons for quantum applications. When applied to two-dimensional arrangements, template-assisted self-assembly creates large-area nanoparticle lattices that support high-quality surface lattice resonances. The anisotropic shape and sharp edges of these nanocubes offer additional tunability in plasmonic responses compared to conventional spherical particles. By strategically manipulating interfacial interactions and structural organization, this study highlights the transformative potential of colloid science in crafting advanced nanophotonic materials with tailored properties.

Optical Chirality Enhancement Induced by Lattice Resonances of All-Dielectric Metasurfaces

Kobe Univ.¹, ^oYongan Hu¹, Hiroshi Sugimoto¹, Minoru Fujii¹

E-mail: sugimoto@eedept.kobe-u.ac.jp

1. Introduction

Chiral differentiation is highly required in the fields of pharmaceuticals, biology and chemistry. One of the most widely applied characteristic methods is circular dichroism (CD) spectroscopy. However, due to the scale mismatching between the molecular and the wavelength of the light, the CD of the chiral molecules is weak, and relatively high concentrations ($\sim\mu\text{M}$) of the chiral molecules are required. Nanophotonic materials offer a promising solution to this challenge due to their strong ability to interact with light. To date, plasmonic nanostructures primarily relying on electric resonances have been proposed to chiral “hot-spot” where the optical chirality is locally enhanced and thus improve the sensitivity of the CD characterization¹. However, due to the high Ohmic loss and absence of the magnetic resonance mode, the optical chirality enhancement (OCE) is limited.

In this work, we propose a dielectric metasurface composed with high-refractive-index silicon nanospheres (Si NSs) 2D array. The metasurface possesses collective lattice (CLR) resonance from both the electric and magnetic resonance of the single Si NS. The wavelength of CLR could be modulated by the lattice constant of the array individually. By designing the lattice constant of x and y direction, we achieve ~ 150 -folds point and ~ 85 -folds average OCE at the surface of the Si NS.

2. Results

Optical chirality is defined as $C = -(\omega/2c^2) \text{Im}(\mathbf{E}^* \cdot \mathbf{H})$, where ω is the angular frequency, c is the speed of light, and $\mathbf{E}$ and $\mathbf{H}$ represent the complex electric and magnetic field vectors. Consequently, it is essential to realize the maximized parallel vector components with high in magnitude and optimized offset of phase. These conditions are able to be fulfilled in the structure of Si NSs 2D array as shown in Figure 1, where the dipole moment of electric and magnetic lattice resonance in the x -direction (ED-LRx and MD-LRx) are described as²:

$$p_x = \frac{\varepsilon E^0 \cos \varphi}{\varepsilon / \alpha^E - k^2 G^0}, \quad m_x = -\frac{H^0 \sin \varphi}{\varepsilon / \alpha^M - k^2 G^0}$$

where φ is the angle between the external wave polarization and the x axis, ε is the permittivity, k is the wavevector, G^0 is the Green function which is related to the lattice constant, α^E and α^M are the polarizability of the electric and magnetic dipole moment respectively. At the proper lattice constant, the spectrally overlapping between the ED-LRx and MD-LRx with $\pi/2$ phase difference could be realized.

We perform the Finite-Difference Time-Domain (FDTD) simulation to investigate the optical chirality enhancement of the Si NSs 2D array. The diameter of

the Si NS is 254 nm and the initial lattice constant in x (P_x) and y (P_y) direction is 550 nm. We then increase the P_y to 800 nm while keeping the P_x . From the reflectance contour plot as shown in Figure 1a, we can identify four trends which correspond to ED-LRx, ED-LRy, MD-LRx, and MD-LRy. The maximum of the OCE occurs for the $P_y = 718$ nm and the wavelength of 1046 nm, where the ED-LRx and MD-LRx are overlapped with each other as shown in Figure 2b. We then show the OCE at x - z plane for the single Si NS and the Si NS in the array, respectively. The OCE reaches ~ 150 for the surface of the Si NS in the array which is ~ 15 -folds higher than the single Si NS ones.

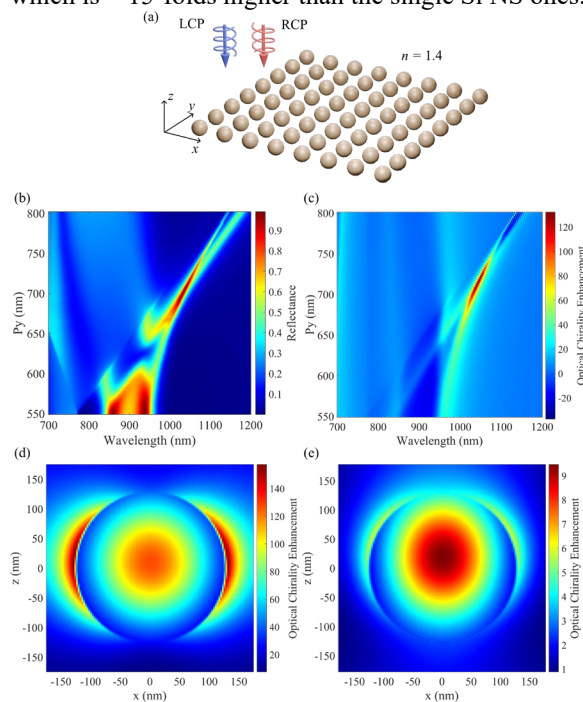


Figure 1. (a) Schematic illustration of Si NSs 2D array under the circular polarized light. (b) Reflectance and (c) OCE for different P_y . OCE distribution in x - z plane for (d) single Si NS (e) Si NS in the array.

3. Summary

We investigate the OCE of the Si NSs 2D array. By modulating the lattice constant of the array, we overlap the ED-LRx and MD-LRx, where the maximized parallel vector components of the $\mathbf{E}$ and $\mathbf{H}$ is achieved. At this condition, we observe the maximum of the OCE of ~ 150 , which is around 15 times higher than the single Si NS.

References

1. Warning, L. A. *et al. ACS Nano* **15**, 15538–15566 (2021).
2. Solomon, M. L. *et al. ACS Photonics* **6**, 43–49 (2019).

Plasmonic Dimer Enhanced Polarized Single Photons Coupled into Optical Nanofiber

Subrat Sahu¹, Kali P. Nayak², and Rajan Jha^{1*}

¹Nanophotonics and Plasmonics Laboratory, IIT Bhubaneswar, Odisha, India -752050

²Department of Engineering Science, University of Electro-Communications, Chofu, Tokyo, Japan-182-8585

Emails: ss99@iitbbs.ac.in, kalipnayak@uec.ac.jp, and rjha@iitbbs.ac.in*

Abstract: A quantum emitter-coupled gold nanorod dimer hybrid system is proposed for channeling plasmon-enhanced polarized single photons into an optical nanofiber-guided mode. We numerically show that the device strongly enhances the spontaneous emission leading to a high Purcell factor ~ 4575 , enhancement factor ~ 588 , with a degree of polarization $\sim 99\%$.

1. Introduction

Single-photon sources (SPS) are crucial for building quantum networks and advancing quantum information science[1]. Different quantum emitters (QE) are suitable candidates for efficient SPS. However, the single photon emission from QEs shows emission bleaching/blinking with a low degree of polarization (*DOP*). On the other hand, optical nanofiber (ONF, a sub-wavelength diameter optical fiber) structure shows a great potential to channel single photons, because they can be easily integrated into existing fiber networks [1,2]. However, for the ONF+QE system the coupling efficiency (η) of $\sim 22\%$, and *DOP* of $\sim 37\%$ archived in the fiber-guided modes[3]. Further, to enhance the performance, a QE coupled to a single gold nanorod (GNR) system is experimentally demonstrated to achieve Purcell factor (*PF*) ~ 360 , enhancement factor (*EF*) ~ 13 , $\eta \sim 3.7\%$, and *DOP* $\sim 97\%$ [1]. Still, the overall *PF* and *EF* are comparable.

In this work, we report for the first time a gold nanorod dimer (GNRD) coupled QE system placed on an ONF using a fiber in-line technique. This device shows high *PF* ~ 4575 , *EF* ~ 588 , $\eta \sim 13\%$, and *DOP* $\sim 99\%$.

2. Proposed Structure and Results

Figure 1 illustrates the schematic of the hybrid structure placed in the waist region of ONF, with different dimensions and the position of QE. The structure has been designed for the QE emission wavelength of around 800 nm, due to the availability of commercial QE. Here, the GNRD structure is formed by placing two GNRs very close to each other in an end-to-end configuration, and minimum $d = 10$ nm is considered due to the finite size of the QE. Different structural dimensions as given in the Fig. 1(a) caption, have been optimized using FDTD simulations for a range of physical parameters to determine the optimized value, before going for experiments. The inset of Fig.1 shows the electric field distribution of the GNRD structure. As can be seen, a high electric field accumulation is observed in the middle of the GNRD structure called, the “Hot Spot” region. Now, if we can place a QE in this region high Purcell enhancement occurs.

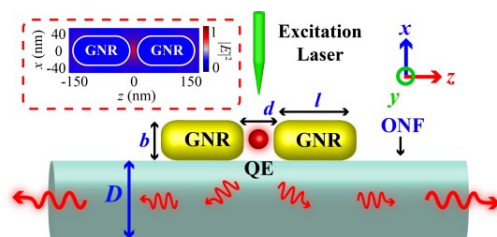


Fig.1: (a) Conceptual diagram of the device with defined dimensions, $D = 400$ nm, $l = 140$ nm, $b = 50$ nm, and d is the separation between two GNRs. A GNRD+QE system is integrated on the ONF. The inset figure shows the electric field distribution of GNRD.

Figure 2 shows the spontaneous emission characteristics of the hybrid structure. Figures 2(a) and 2(b) show the variation of *PF*, and (*EF*, *DOP*) with the d -value. As can be seen, both the *PF* and *EF* responses show a decreasing trend due to the decrease in electric field confinement in the GNRD structure. Maximum *PF* (*EF*) is obtained ~ 4575 (588) at $d = 10$ nm. This yields $\eta = EF/PF \sim 13\%$ in the fiber-guided mode. We have also calculated the *DOP* $\sim 99\%$ for this hybrid system, it shows almost a flat trend for each d -value.

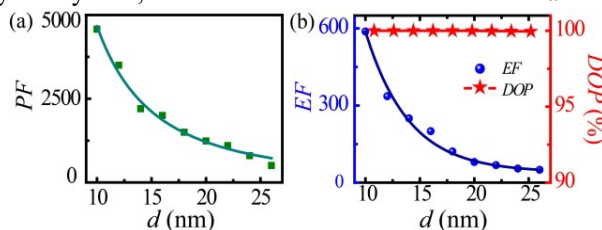


Fig.2: (a), and (b) show variations of *PF* and (*EF*, *DOP*) with the d -value.

3. Conclusions

In conclusion, the proposed GNRD+QE device can yield an order of magnitude more *EF* as compared to the GNR+QE system. This system can be used for quantum cryptography.

4. References

- Shafi et. al., Phys. Rev. Appl. **19**, 34008 (2023).
- Sugawara et.al., Phys. Rev. Res. **4**, 043146 (2022).
- Yalla et.al., Phys. Rev. Lett. **109**, 63602 (2012).

Broadband plasmon nanofocusing for Raman spectroscopy

Yuto Okamura¹, Prabhat Verma¹, Takayuki Umakoshi^{1,2}

¹Dept. of Applied Physics, Osaka Univ.,

²Inst. Adv. Co-Creation Studies, Osaka Univ.,

E-mail: umakoshi@ap.eng.osaka-u.ac.jp

1. Introduction

Plasmon nanofocusing is a phenomenon that generates strong near-field light at the apex of a metallic tapered structure through plasmon propagation and compression toward its apex. Key features include significant light field enhancement and the suppression of background noise, and recently recognized another important advantage is the broadband property. Unlike conventional plasmonic techniques that rely on localized plasmon resonance, plasmon nanofocusing is based on plasmon propagation. This allows to generate near-field light over an extremely broad wavelength range, as previously demonstrated [1], which holds great potential for various nanophotonics applications.

In this study, we applied plasmon nanofocusing for Raman spectroscopy. Raman spectroscopy is a powerful technique to analyze molecular vibrations. Although Raman signals are usually weak, surface-enhanced Raman scattering (SERS) is often employed to drastically increase its intensity. However, since SERS typically uses localized plasmon resonance of metallic nanostructures such as a gold nanoparticle, it can be used only in a narrow wavelength range. Therefore, it is challenging to obtain enhanced Raman signals from the same molecule at different excitation wavelengths, although molecules can show different Raman characteristics due to the resonant Raman effect.

In this study, we used broadband plasmon nanofocusing for plasmon-enhanced Raman spectroscopy at multiple wavelengths. As the exactly same molecules can be studied at different wavelengths at the nanoscale, this approach enables more comprehensive molecular analysis.

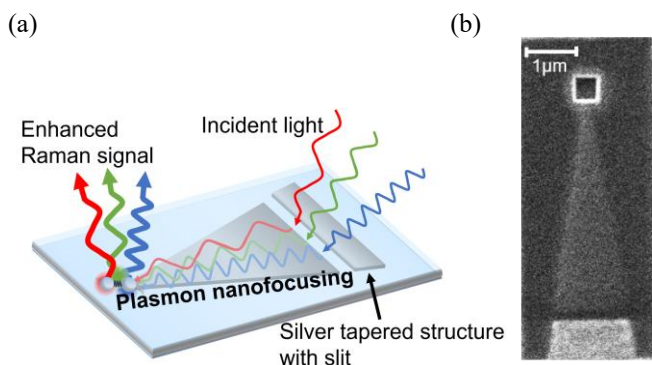


Fig.1 (a) Schematic of this experiment (b) SIM image of tapered silver structure with a slit and a detection hole covered with a PMMA protection layer

2. Experimental results

To demonstrate Raman spectroscopy using broadband plasmon nanofocusing, we used the setup illustrated in Fig.1 (a). A silver tapered structure was fabricated first by depositing a silver thin film via vacuum evaporation, and subsequently by patterning it using a focused ion beam (FIB). A slit structure was fabricated as a plasmon coupler. The entire tapered structure was then covered with a PMMA thin film as a protection layer, and a detection hole was fabricated near the apex using FIB so that samples can be attached only at the apex (Fig.1 (b)).

We performed Raman measurements using plasmon nanofocusing on the fabricated tapered structure. The incident laser was irradiated on the plasmon coupler to excite plasmons. Propagating plasmons generated near-field light at the apex, which was used for Raman measurements. Figure 2 shows Raman spectrum of Rhodamine 6G obtained with the excitation wavelength of 633 nm. A conventional far-field Raman spectrum is also shown for a comparison. We successfully obtained enhanced Raman spectrum using plasmon nanofocusing. We also attempted with different incident wavelengths of 442, 532, and 785 nm. The details of these results will be discussed in the presentation.

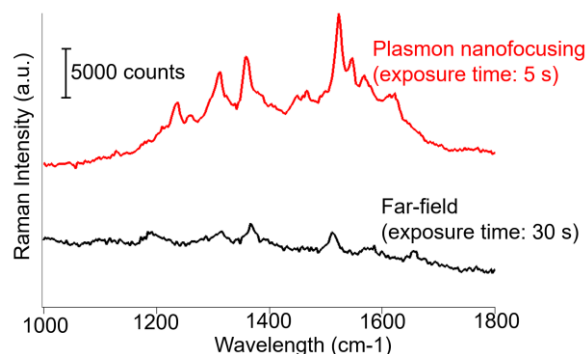


Fig.2 Raman spectra of Rhodamine 6G acquired via far-field excitation and plasmon nanofocusing at the excitation wavelength of 633 nm.

3. Conclusion

We have demonstrated plasmon-nanofocusing-enhanced Raman spectroscopy. This technique would allow highly sensitivity, multi-wavelength Raman analysis.

References

- [1] T. Umakoshi, et al., *Sci Adv.*, **6**, 4179 (2020)

Chirality transfer in Mie-resonant silicon nanoparticle-chiral molecule composites

Hiroki Kasai¹, Kento Shintani¹, Hiroaki Hasebe¹, Shahin Ghamari², Frank Vollmer²
Hiroshi Sugimoto¹, Minoru Fujii¹

¹ Kobe Univ., ² Univ. of Exeter
E-mail: sugimoto@eedept.kobe-u.ac.jp

1. Introduction

Detection of small amounts of chiral molecules ($< \mu\text{M}$) is still challenging due to extremely weak interaction between chiral molecules and circularly polarized light (CPL). Recently, the ways to enhance CD signal by optical chirality enhancement or chirality transfer [1] via nanophotonic effects in optical nanoantenna has been proposed. Here, we experimentally investigate the chirality transfer in Si nanoparticle (Si NP) antenna with chiral molecules film.

2. Results

First, we calculate the differential extinction spectra[2] under right- and left-handed CPL by assuming a chiral medium shell with a refractive index $n = 1.33$ and Pasteur parameter $\kappa = 10^{-5} + 10^{-7}i$. Calculated extinction cross section for incident linearly polarized light (upper panel) and differential extinction for incident left and right CPL (ΔC_{ext})(lower panel) spectra of a bare Si NP with diameter of 150 nm (black solid line) and that covered with a 10 nm chiral shell (red solid line) are shown in Figure 1. In the case of that with chiral shell, an overall extinction spectrum is red-shifted slightly. On the other hand, ΔC_{ext} shows peaks at the wavelengths of electric dipole (ED) and magnetic dipole (MD) resonances for a Si NP with a chiral shell despite of the constant κ . This suggests the chirality transfer from a chiral shell to a Si NP.

We then prepared a monolayer of Si NPs coated with a Cysteine film. Figure 2 shows the measured extinction ($1-T$, T : transmittance) in the upper panel and CD spectra of Si NP (averaged diameter: 199 nm) monolayer coated with L-body of cysteine (L-Cys) (red curve) and bare Si NPs (black curve) in the lower panel. We can see distinct peaks at the wavelengths of the magnetic dipole (MD) resonance and the overlapping resonance of the electric dipole (ED) and magnetic quadrupole (MQ).

3. Summary

Based on the analytical calculations, we demonstrate experimentally the chirality transfer from chiral molecules to Mie resonant Si NPs. In the presentation, we will also discuss the contribution of optical chirality and chirality transfer quantitatively.

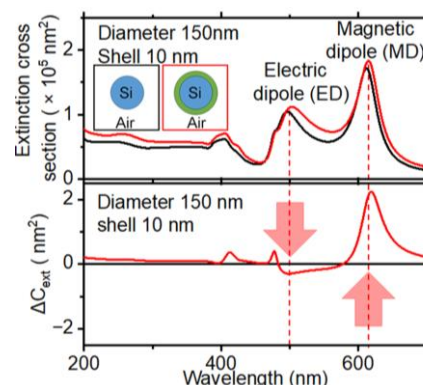


Figure 1. (Upper panel) Calculated extinction spectra of 150 nm silicon nanosphere with (red) and without (black) a 10 nm chiral medium shell ($n = 1.33$ and $\kappa = 10^{-5} + 10^{-7}i$). (Lower panel) Calculated ΔC_{ext} spectra of 150 nm silicon nanosphere with a 10 nm chiral medium shell under right and left handed CPL.

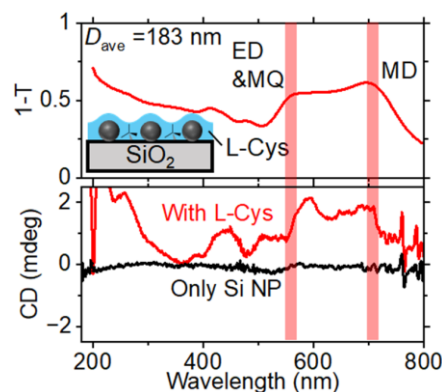


Figure 2. Extinction ($1-T$, T : transmittance, upper panel) and CD spectra (lower) of silicon nanoparticles (183 ± 8.7 nm in diameter) on a silica substrate covered with L-Cys film (red curve). CD spectrum of silicon nanoparticles alone (black curve) is also shown in the lower panel.

Acknowledgements

H.K. acknowledge the support under a Grant-in-Aid for JSPS Research Fellows.

References

- [1] E. Mohammadi et al. *Nano Lett.* **23**, 3978 (2023).
- [2] Kim.T, Park.Q.H., 2022. *Nanophotonics* **11**, 1897

Appendix

Secretariat of the JSAP-Optica Joint Symposia

E-mail: meeting@jsap.or.jp

Landau Polaritons in Nanoslots in the Ultrastrong Coupling Regime: Breakdown of the Electric-Dipole Approximation

Sae R. Endo¹, Dasom Kim¹, Sunghwan Kim², Dukhyung Lee³, Shuang Liang⁴, Geon Lee^{5,6}, Michael J. Manfra⁴, Minah Seo^{5,7}, Dai-Sik Kim^{2,6}, Junichiro Kono¹

¹Rice Univ. (USA), ²Ulsan National Inst. of Sci. and Tech. (Korea), ³Mohammed VI Polytechnic Univ. (Morocco),

⁴Purdue Univ. (USA), ⁵Korea Inst. of Sci. and Tech. (Korea), ⁶Seoul National Univ. (Korea), ⁷Korea Univ. (Korea)

E-mail: kono@rice.edu

1. Introduction

Landau polaritons arise when cavity photons strongly couple, or hybridize, with the cyclotron resonance of two-dimensional electrons in a strong perpendicular magnetic field. These polaritons provide a powerful platform for studying quantum electrodynamical phenomena in the ultrastrong coupling regime, where the Rabi frequency becomes a significant fraction of the bare frequencies of light and matter. Theories of Landau polaritons are well-developed under the electric-dipole approximation, including the selection rules for inter-Landau-level transitions, i.e., from the n -th to the $(n+1)$ -th Landau level with frequency $\omega_c = eB/m^*$, where e , B , and m^* are the elementary charge, magnetic field strength, and electron effective mass, respectively.

Recently, some anomalies have been observed for Landau polaritons in small-mode-volume plasmonic cavities, including the disappearance of the upper-polariton branch, which were interpreted as a result of nonlocal coupling of cavity photons with finite-momentum magnetoplasmons (MPs) [1]. However, the degree of spatial confinement was limited by fabrication constraints to fully investigate the breakdown of the electric-dipole approximation. Here, we explore the behavior of Landau polaritons beyond the electric-dipole approximation by confining light in nanoslots whose widths are smaller than the cyclotron radius.

2. Methods

We fabricated an array of nanoslots with several gap widths d placed close to a single GaAs quantum well (QW) on a GaAs substrate. By employing a combination of photolithography, electron beam evaporation, and atomic layer deposition techniques, we achieved atomic-level control of d down to 20 nm, which is smaller than the cyclotron diameter at the zero-detuning magnetic field (~ 66 nm at 3 T). We performed terahertz time-domain magnetospectroscopy measurements on the GaAs QW embedded in nanoslot cavities at 1.6 K.

3. Results and Discussion

Figure 1 shows color maps of transmittance for different d . At $d = 4 \mu\text{m}$, we observed a splitting of the upper-polariton (UP) branch, attributed to the influence of wavevector-dependent MPs. The electric field distributions

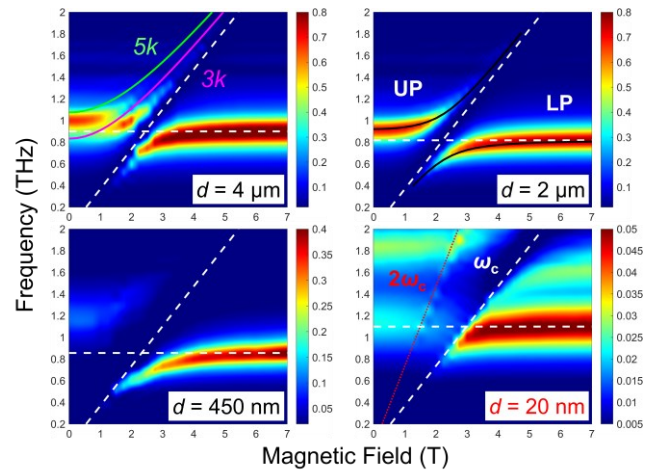


Fig. 1 Color maps of transmittance as a function of frequency and magnetic field for different gap widths, d . The white dashed lines indicate the bare cavity and cyclotron frequencies. The magenta and light green lines for $d = 4 \mu\text{m}$ show theoretical spectra of MPs at $3k$ and $5k$, respectively. The black lines for $d = 2 \mu\text{m}$ are fits to the upper-polariton (UP) and lower-polariton (LP) branches based on the Hopfield model.

exhibit distinct behaviors above and below the $3k$ MP line. As the gap width is reduced to $d = 450$ nm, the UP branch vanishes, confirming the observation by Rajabali *et al.* [1]. However, at $d = 20$ nm, we observed a normally forbidden cyclotron transition with frequency $\omega = 2\omega_c$ (red dashed line, Fig. 1), which we interpret as a signature of the breakdown of the electric-dipole approximation due to the significant spatial variation of the electromagnetic field across the cyclotron radius. The second mode emerging at $d = 20$ nm was not reproduced in COMSOL simulations and suggests the presence of quantum effects.

Acknowledgements

S.R.E. acknowledges support from TOMODACHI-Dow Women's STEM Leadership and Research Program. D.K. and J.K. acknowledge support from the Gordon and Betty Moore Foundation.

References

- [1] Rajabali, S., Cortese, E., Beck, M., Liberato, S. D., Faist, J., and Scalari, G., Nat. Photon. **15** (2021) 690–695.

Engineering Emission Properties of Transition-Metal Dichalcogenide Monolayers by Mie-Resonant Silicon Nanospheres

Kobe Univ. Hiroshi Sugimoto

E-mail: sugimoto@eedept.kobe-u.ac.jp

Controlling the light emission from quantum emitters by nanoantennas is of great importance for photonic applications. Nanostructures of high-index dielectrics such as silicon (Si) have been recently suggested as the highly efficient nanoantennas for the light emission control by Mie resonances. The high-index nanoantennas are capable of not only localizing the incident light in the volume much smaller than the light wavelength but also enhancing the radiative rate of the emitter that is so-called Purcell effect. In this presentation, using the simplest coupled system shown in Fig.(a), we demonstrate how a silicon nanosphere (Si NS)[1] enables emission control of 2D materials through radiative rate enhancement, spectral shaping,[2] and directional emission.[3]

Figure (b) shows a scattering spectrum of the single Si/MoS₂ (diameter of Si NS: 248 nm). The magnetic quadrupole (MQ) Mie resonance around 675 nm is clearly seen. Figure (c) shows photoluminescence (PL) spectra of Si/MoS₂ (red curve) and reference MoS₂ (gray curve). The emission intensity is enhanced approximately ~30 times with respect to the reference and the spectrum becomes very narrow. The full width at half maximum (FWHM) of the spectrum changes from 106 meV (MoS₂) to 55 meV (Si/MoS₂). From the rigorous calculations, we concluded that the PL modification is due to the radiative rate enhancement by the coupling with high-Q MQ resonance.

We will also discuss directional control of the emission by Si NSs[3] in the presentation.

[1] Sugimoto, *et al.*, *Adv. Opt. Mater.* 8, 2000033 (2020)

[2] Shinomiya, *et al.*, *ACS Photonics*, 9, 1741, (2022)

[3] Ozawa, *et al.*, *ACS Appl. Opt. Mater.* 3, 375 (2025)

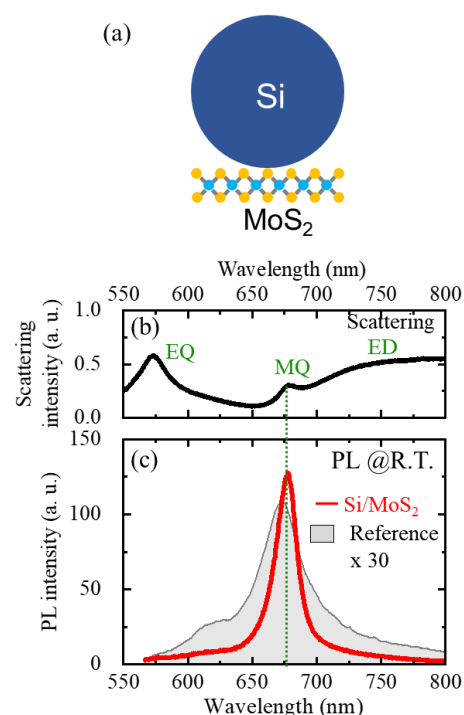


Figure. (a) Schematic of a Si/MoS₂. (b) Scattering spectrum of a Si/MoS₂. The diameter of a Si NS (D_{Si}) is 248 nm. (c) PL spectra of Si/MoS₂ (red curve) and MoS₂ (black curve). The excitation wavelength is 532 nm.

Optical Modulation via Atomically Thin Dielectrics in Membrane Metasurface

Chih-Zong Deng¹, Kuniaki Konishi², Vincent Tung³, Chun-Wei Chen⁴, and Ya-Lun Ho^{1*}

¹ Research Center for Electronic and Optical Materials, National Institute for Materials Science (NIMS)

² Institute for Photon Science and Technology, School of Science, The University of Tokyo

³ Department of Chemical System Engineering, School of Engineering, The University of Tokyo

⁴ Department of Materials Science and Engineering; Center of Atomic Initiative for New Materials, National Taiwan University

E-mail: HO.Ya-Lun@nims.go.jp

1. Introduction

Bound states in the continuum (BICs) offer superior light confinement due to destructive interference, enabling theoretically infinite Q-factors [1]. However, typical substrate-supported BIC designs suffer from symmetry breaking and radiative leakage, which degrades their Q-factors and limits field confinement [2].

Nanomembranes offer a solution as freestanding structures that overcome substrate limitations, facilitating symmetry and preserving BICs for strong field confinement [3]. Our work demonstrates the resonance of the BIC can be precisely modulated by adjusting the membrane thickness at the atomic scale using atomic layer deposition (ALD).

2. Results

Fig. 1 shows simulated transmission spectra for a freestanding SiN membrane metasurface and a SiN metasurface on a SiO₂ substrate, respectively. The metasurface is composed of a triangular lattice of airholes with lattice period $P = 600$ nm and diameter $D = 300$ nm. All modes exhibited a blueshift with decreasing thickness. For the SiO₂-substrate configuration, all resonances undergo attenuation, and the transmission dips progressively lose contrast as the photonic slab thickness decreases. The extinction of both guided modes (GMs) and quasi-BICs at reduced thicknesses was attributed to strong field leakage into substrate radiation channels, preventing sustained resonance. In contrast, the SiN membrane metasurface configuration preserved notably high Q-factors and strong resonance even at thicknesses below 100 nm.

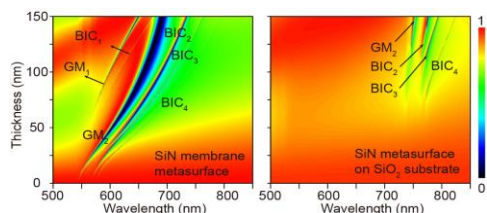


Fig. 1 Simulated transmission spectra as a function of structural thickness for SiN membrane metasurface and SiN metasurface on SiO₂ substrate

Experimental resonance wavelengths closely match simulations (Fig. 2(a)), consistently blue shifting with decreasing thickness. The BIC₄ consistently exhibits significantly higher Q-factors than the GM mode across all thicknesses, often by more than two orders of magnitude. While the Q-factor gradually decreases as thickness is reduced, the BIC₄ maintains an exceptional Q-factor of 5774 at 92 nm and 1480 at 29 nm.

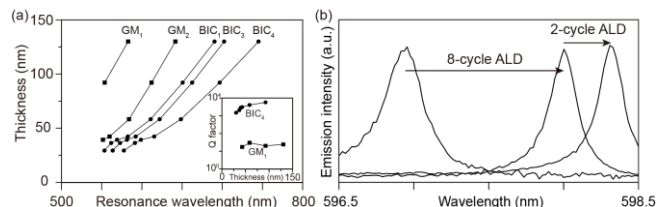


Fig. 2 (a) Measured resonance wavelengths of GMs and quasi-BICs as a function of membrane thickness. Inset: Measured Q-factors for the GM₁ and BIC₄. (b) PL spectra demonstrating spectral shifts of the BIC₄ in the 48-nm-thick membrane metasurface induced by atomic-scale SiN depositions through ALD.

Fig. 2(b) illustrates the PL spectra of a 48 nm-thick membrane metasurface for the BIC₄, before and after atomic layer deposition (ALD). After eight ALD cycles, the BIC₄ exhibited a 1.07 nm redshift, corresponding to an estimated deposited layer thickness of 5.2 Å. An additional two ALD cycles further shifted the mode by 0.30 nm, due to the deposition of an extra 1.3 Å.

3. Conclusions

We demonstrate an ultrathin freestanding membrane metasurface capable of atomic-level modulation of BIC resonances. By eliminating substrate-induced losses, these nanomembranes achieve remarkable Q-factors, preserving strong optical confinement. These membrane metasurfaces, with enhanced surface field sensitivity, are ideal for integrating 2D materials and quantum systems, advancing nanophotonics and providing a powerful tool for sub-Å precision material characterization crucial for advanced semiconductor technologies.

Acknowledgements

This work was supported by JSPS KAKENHI Grant Number JP23K26155, JP25KF0083. A part of this work was supported by Advanced Research Infrastructure for Materials and Nanotechnology in Japan of the Ministry of Education, Culture, Sports, Science and Technology (JPMXP1225NM5090). Financial support by the Center of Atomic Initiative for New Materials, National Taiwan University, from the Featured Areas Research Center Program within the framework of the Higher Education Sprout Project by the Ministry of Education in Taiwan (Grant Number 111L900801), is also acknowledged.

References

- [1] Hsu, C. W., Zhen, B., Stone, A. D., Joannopoulos, J. D., Soljacic, M. Nat. Rev. Mater **1** (2016), 16048.
- [2] Li, M., Li, Q., Brongersma, M. L., Atwater, H. A., Science **386** (2024), 1226.
- [3] Ho, Y. L., Fong, C. F., Wu, Y. J., Konishi, K., Deng, C. Z., Fu, J. H., Kato, Y. K., Tsukagoshi, K., Tung, V., Chen, C.W. ACS Nano **18** (2024), 24173.

Broadband Solar Absorber Design Using Optimization-Driven Nanostructures for Efficient Solar–Thermal Conversion

Chih-Chung Wang^{1,3}, Jia-Han Li^{1,3,4*} and Tadaaki Nagao^{1,2*}

¹ Research Center for Materials Nanoarchitectonics (WPI-MANA), National Institute for Materials Science (NIMS), Japan.

² Department of Condensed Matter Physics Graduate School of Science, Hokkaido University, Japan.

³ Department of Engineering Science and Ocean Engineering, National Taiwan University, Taiwan.

⁴ NTU Radiation Application and Hardness Technology Research Center, National Taiwan University, Taiwan.

E-mail: d09525016@ntu.edu.tw, jiahan@ntu.edu.tw, NAGAO.Tadaaki@nims.go.jp

1. Introduction

The urgent demand for sustainable energy has driven the rapid growth of renewable technologies, with solar energy gaining increasing attention due to its abundance, scalability, and environmental benefits [1]. In solar–thermal systems, refractory metals such as tungsten offer excellent thermal and mechanical stability, making them ideal for high-temperature applications [2]. In contrast, noble metals suffer from low thermal durability and substantial optical losses, limiting their performance in harsh environments. Metal–insulator–metal (MIM) absorbers with periodic nanostructures have been proposed to enhance solar absorption, but they often neglect radiative heat loss in the mid-to-far infrared (IR) region, which reduces overall energy conversion efficiency. In this study, we present an optimized tungsten-based MIM absorber that incorporates nanoscale structural variations. Finite-difference time-domain (FDTD) simulations validate its enhanced spectral selectivity and high photothermal conversion efficiency.

2. Methodology and Results

This study builds on the proposed MIM absorber by integrating nanoscale feature optimization. The structure consists of tungsten (W) and silicon dioxide (SiO₂) layers. Figure 1 illustrates three structural concepts and their corresponding spectral behaviors. Although cone multilayer designs exhibit strong solar absorption, it leads to additional absorption in the mid-infrared (MIR) region, potentially resulting in thermal radiation loss. In contrast, the target structure achieves high absorbance in the 300–2500 nm range and low absorbance in the 2500–20000 nm range, indicating its capability to suppress MIR emission. This spectral selectivity arises from introducing randomly segmented nanostructures into the top metal layer, where specific geometric combinations induce desired resonance modes, gradually approaching the ideal design illustrated in the right panel of Figure 1. In Figure 2, it presents the simulated solar absorption before and after optimization. Based on finite-difference time-domain (FDTD) simulations and particle swarm optimization (PSO) [3], the design can achieve an average solar absorbance above 92%, an IR emittance below 5%, and a total conversion efficiency of 90 or more.

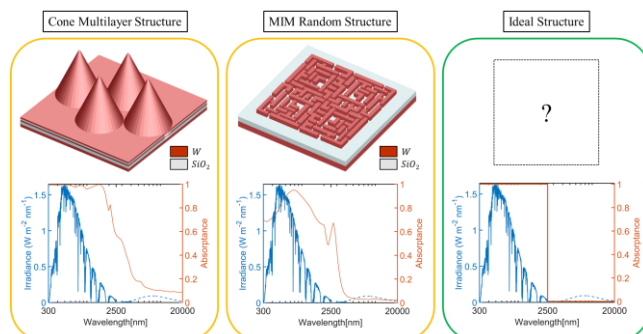


Fig. 1. Simulated absorbances of three structure ideas. Blue: AM1.5 spectrum (solid) and 100 °C blackbody (dashed). Orange: absorbance. **Left:** Cone multilayer—high solar (300–2500 nm), high MIR (2500–20000 nm) absorption. **Middle:** Random-strip MIM—low solar, low MIR absorption. **Right:** Target—high solar, low MIR absorption.

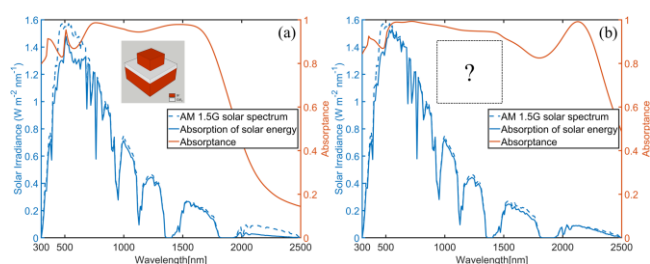


Fig. 2. Comparison of simulated solar absorption before (a) and after (b) optimization. Lines indicate AM1.5 spectrum (blue dashed), absorbed spectrum (blue solid), and absorption rate (orange).

3. Conclusions

The proposed design strategy effectively balances solar absorbance and infrared suppression. This approach provides a promising pathway for developing next-generation broadband solar–thermal absorbers with enhanced photothermal efficiency.

Acknowledgements

We acknowledge Dr. K. Shinozaki, for fruitful discussions and budgetary supports from JAXA. This research was partially funded also by the Dragon Gate Project under grant numbers NSTC 112-2926-I-002-510-G and 114-2926-I-002-505-G.

References

- [1] M. Imtiaz Hussain et al., *Solar Energy Mater. Solar Cells* **187** (2018) 123–139.
- [2] U. Guler et al., *Science* **344** (2014) 263–264.
- [3] J. G. Mutitu et al., *Opt. Express* **16** (2008) 5238.

Flexible and reconfigurable silicon carbide metasurface stickers

Shunsuke Murai^{1,2}, Hiroya Maruyama², Joshua TY Tse², Hongjie Gao², Katsuhisa Tanaka²

¹ Osaka Metropolitan U., ² Kyoto U.

E-mail: murai@omu.ac.jp

Reconfigurable metasurfaces refer to the metasurfaces that change their optical responses by external stimuli. Such tunability is highly advantageous in controlling light, and thus many innovative approaches have been reported. One major approach utilizes adaptable materials, such as liquid crystals, with intrinsically tunable optical properties toward temperature, pressure, electric field and so on. Another and more direct approach is mechanical reconfiguration, which has a broad material applicability. Flexible matrix can serve as a direct platform for mechanically reconfigurable metasurfaces. Based on this concept, several metasurfaces comprising plasmonic metals and dielectrics of high refractive index embedded in flexible polymers have been developed, and tunable structural colors, radiation patterns of photoluminescence (PL) and lasing wavelengths have been reported [1-5].

PL manipulation is one promising application of the metasurface. Both plasmonic and dielectric metasurfaces, in combination with optical emitters, show a notable modulation in PL, i.e., spectral and spatial tuning in radiation patterns. Low absorption (k) and high refractive index (n) are critical prerequisites for dielectric PL enhancers. TiO_2 is one material that satisfies such requirements and is thus mostly used in the visible region for both static and dynamic PL modulation. Silicon carbide (SiC) can be a better substitute because of its higher n and a lower k than those of TiO_2 . Even though some pioneering works have already

applied SiC to nanophotonics, especially in the context of phonon polaritons, it is still far less explored compared to its potential as the dielectric metasurfaces working in the visible.

In this study, we fabricate mechanically reconfigurable SiC metasurface for PL-control application (Fig. 1), starting from a 3C-SiC film epitaxially grown on Si wafer (Air-Water Inc., Japan). The metasurface consists of SiC nanoparticle array embedded in polydimethylsiloxane (PDMS). Due to the self-adhesive properties of PDMS, the flexible metasurface works as a sticker that can be attached to any clean surfaces and act as a metasurface. By mechanically stretching the sticker, the optical resonances due to surface lattice resonances supported by the periodic lattice, spectrally shift in accordance with the change in particle arrangement. Furthermore, we place the sticker on a phosphor plate to observe a directional out-coupling of PL through the sticker.

References

- [1] K. Agata, S. Murai, and K. Tanaka, Appl. Phys. Lett. 118, 021110 (2021).
- [2] T. Lo, S. Murai, and K. Tanaka, ACS Appl. Opt. Mater. 1, 870– 877 (2023).
- [3] T. Takashima, T. Y. Lo, H. Takane, S. Murai, and K. Tanaka, Jpn. J. Appl. Phys. 64, 03SP66 (2025).
- [4] S. Murai, K. Agata, and K. Tanaka, J. Appl. Phys. 129, 183101 (2021).
- [5] H. Maruyama, J. T. Y. Tse, S. Murai, and K. Tanaka, Jpn. J. Appl. Phys. 64, 03SP54 (2025).

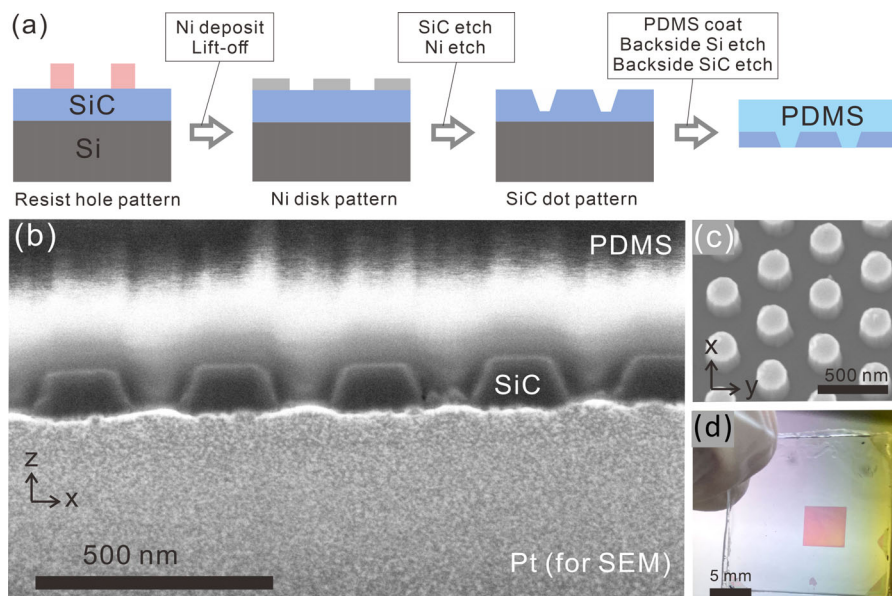


Figure 1. (a) Sketch of the fabrication scheme of the SiC nanoparticle array supported on the PDMS layer. (b,c) SEM images. (b) Cross-sectional view before embedded in the PDMS. (c) Top-view before Ni etching. (d) Optical view of the nanoparticle array embedded in the PDMS layer.

Floquet Matrix Formulation for Dispersive and Dissipative Time-Varying Media

Yuchen Sun¹, Guangwei Hu¹

¹ School of Electrical and Electronic Engineering, 50 Nanyang Avenue,
Nanyang Technological University, Singapore, 639798, Singapore
E-mail: guangwei.hu@ntu.edu.sg

1. Introduction

Photonic time crystals (PTC), consisting of periodic time-varying medium (TVM), have recently attracted considerable attention because it shows exotic properties that cannot be realized in static systems, such as magnetic-free non-reciprocity, Floquet harmonic generation, synthetic frequency dimensions, enhanced spontaneous emission rate and others. Hence it is critical to develop a unified framework to describe the dispersion relation and calculate the eigenmodes in PTC, which can be used to derive the topological invariants in TVM.

2. General Instructions

We consider the plasmonic materials with periodically modulated electron density, which can be realized via “shaking” the metal with pulse etc. The electron motion can be described by the equation of motion [1,2],

$$\left[\frac{\partial^2}{\partial t^2} + \Gamma \frac{\partial}{\partial t} + \omega_p^2(t) \right] \mathbf{P}(\mathbf{r}, t) = \varepsilon_\infty \omega_p^2(t) \mathbf{E}(\mathbf{r}, t)$$

where the plasma frequency and resonance frequency can be time-modulated, corresponding to the time-modulated carrier density and modulating parameter of meta atoms. By introducing the auxiliary field, we can formulate first-order Schrödinger like equation,

$$i \frac{\partial}{\partial t} \begin{pmatrix} \mathbf{E} \\ \mathbf{H} \\ \mathbf{P} \\ \mathbf{J} \end{pmatrix} = i \begin{bmatrix} 0 & \varepsilon_\infty^{-1} \nabla \times & 0 & -\varepsilon_\infty^{-1} \\ -\mu^{-1} \nabla \times & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ \varepsilon_\infty \omega_p^2(t) & 0 & -\omega_r^2(t) & -\Gamma \end{bmatrix} \begin{pmatrix} \mathbf{E} \\ \mathbf{H} \\ \mathbf{P} \\ \mathbf{J} \end{pmatrix}$$

We then follow the Floquet theory, the wavefunction can be formulated as a linear combination of Floquet harmonics with frequency spaced by the modulation frequency. The spatial part is the solution of the static Hamiltonian. The wavefunction can be formulated in this form

$$|n, \alpha\rangle = (\tilde{\mathbf{E}}_{cn}(\mathbf{r}) \quad \tilde{\mathbf{H}}_{cn}(\mathbf{r}) \quad \tilde{\mathbf{P}}_{cn}(\mathbf{r}) \quad \tilde{\mathbf{J}}_{cn}(\mathbf{r}))^T e^{in\Omega t},$$

$$\Psi(\mathbf{r}, t) = e^{-i\omega t} \Phi(\mathbf{r}, t)$$

$$\Phi(\mathbf{r}, t) = \sum_\alpha \sum_n c_{n\alpha} |n, \alpha\rangle$$

We first use the orthonormal condition for the basis, multiplying the left by $\langle \beta, m |$, The Floquet matrix can be formulated as

$$\hat{\mathbf{H}}_F = \begin{bmatrix} \hat{\mathbf{H}}_0 + 2\mathbf{I}\Omega & \hat{\mathbf{H}}_1(\mathbf{r}) & 0 & 0 & 0 \\ \hat{\mathbf{H}}_{-1} & \hat{\mathbf{H}}_0 + \mathbf{I}\Omega & \hat{\mathbf{H}}_1(\mathbf{r}) & 0 & 0 \\ 0 & \hat{\mathbf{H}}_{-1} & \hat{\mathbf{H}}_0 & \hat{\mathbf{H}}_1(\mathbf{r}) & 0 \\ 0 & 0 & \hat{\mathbf{H}}_{-1} & \hat{\mathbf{H}}_0 - \mathbf{I}\Omega & \hat{\mathbf{H}}_1(\mathbf{r}) \\ 0 & 0 & 0 & \hat{\mathbf{H}}_{-1} & \hat{\mathbf{H}}_0 - 2\mathbf{I}\Omega \end{bmatrix}$$

solving the eigenvalues and eigenvectors of the Floquet matrix, we get the quasienergy level and Floquet eigenstates of the PTC. With these eigenstates and biorthonormal relation, we can define the Aharonov-Andndan (AA) phase in PTC to locate the exceptional points (EPs)

$$\theta_\lambda = \int_0^{2\pi} \langle \Psi_\lambda^L(t) | i \frac{\partial}{\partial t} | \Psi_\lambda^R(t) \rangle dt,$$

The results

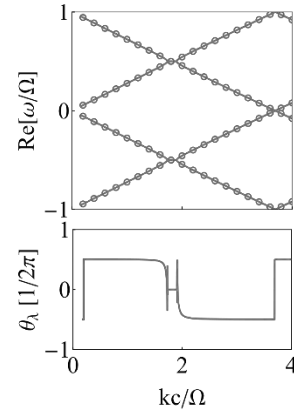


Figure 1. Quasienergy level of PTC with $\omega_p^2(t) = \omega_{p0}^2(1 + \cos(\Omega t))$. The abrupt π phase change of AA phase indicating the location of EPs.

3. Conclusions

We have proposed a unified framework to calculate the quasienergy level and eigenstates in TVM. Using the eigenmodes, we define the Aharonov-Andndan phase and locate the exceptional points.

References

- [1] I. Stefanou, J. Opt. Soc. Am. B **38** (2021) 407.
- [2] G. Ptitcyn, Laser Photon. Rev. **17** (2022) 2100683.
- [3] A. Raman, Phys. Rev. Lett. **110** (2010) 087401.

Helicity-Resolved Raman Spectroscopy on MoS₂ coupled with Mie-Resonant Silicon Nanospheres

Mojtaba Karimi Habil¹, Daisuke Shima¹, Hiroto Shinomiya¹, Hiroshi Sugimoto¹, Minoru Fujii¹

¹ Kobe University, Japan

E-mail: sugimoto@eedept.kobe-u.ac.jp

1. Introduction

In transition metal dichalcogenides (TMDCs) such as MoS₂, the helicity of the Raman-scattered light is preserved or flipped for the out-of-plane chalcogen (OC) or in-plane metal-chalcogen (IMC) vibration modes, respectively [1]. Recently, silicon nanospheres (Si NSs) supporting Mie resonances in the visible range, have been utilized in helicity preserving [2] and controlling the emission directionality of 1L-MoS₂ [3]. In this work, we investigate systematically the helicity and intensity of the Raman signals from MoS₂ coupled to Si NSs. Both theoretical and experimental results demonstrate that when the wavelength of the emitted photon is coupled to the magnetic dipole (MD) or magnetic quadrupole (MQ) modes of the Si NS the Raman scattered light is enhanced while the helicity of the light is unchanged.

2. Results and discussion

Figure 1(a) shows a rotating electric dipole placed at 1 nm from the surface of a Si NS. The degree of circular polarization (DCP) is calculated in the far-field region using the phase and amplitude of the two orthogonal electric fields. Figure 1(b) shows the DCP versus the diameter of Si NSs for a dipole emitting at the wavelength around 544 nm corresponding to the Raman shift of MoS₂ at the OC mode under 532 nm laser excitation. It can be seen that the DCP is maintained unchanged, compared to the isolated dipole (the horizontal dashed line) at the MD mode where the emitted light is also enhanced. For the particle with the diameter of 148 nm, the light is mainly depolarized and the back-scattered intensity is minimal due to the destructive interference of the electric field of the emitting dipole and the scattered field of the Mie modes of Si NS. At the MQ mode strong coupling occurred between the emitted light of the dipole and the Mie mode of Si NS resulting in high intensity while the DCP remains relatively unchanged. Experimentally, colloidal Si NSs prepared in our group [4] were drop-coated on 1L-MoS₂ and then subjected to Ar⁺ etching to remove the outside region of 1L-MoS₂. The intensity of the left (LCP) and right (RCP) circularly polarized light were measured from the substrate side collected by an objective with NA=0.8 under right-circularly polarized wave illumination. As shown in Fig.1(c), the off-resonance particle shows very low intensity. When the excitation wavelength is coupled to the MD or MQ modes of the Si NS the Raman scattering is enhanced with high DCP 0.78 and 0.88, respectively. On the other hand, the back-scattered intensity is substantially decreased for the Si NS of diameter around 148 nm as theoretically predicted.

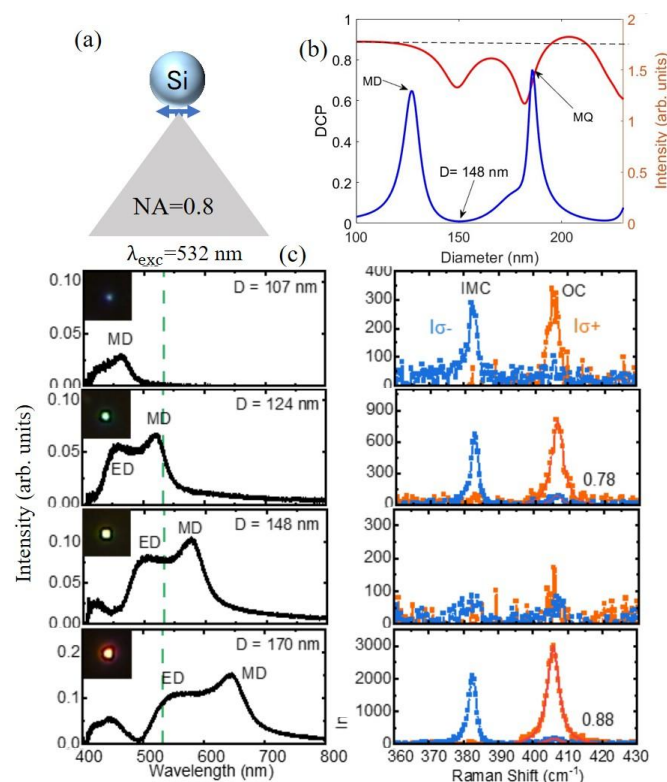


Figure 1: (a) A rotating electric dipole 1 nm from the surface of Si NS. (b) DCP and the intensity collected by the objective with NA=0.8. (c) Scattering (left) and the Raman intensity (right). The dark field image and the DCP at the OC mode are indicated in the figures.

3. Conclusions

The helicity and intensity of the circularly-polarized Raman scattered light from MoS₂ coupled to Si NSs was investigated. We theoretically and experimentally showed that when the wavelength of the emitting dipole at nearfield of the Si NS is coupled to the MD or MQ modes, the Raman scattered light is significantly enhanced while its helicity is preserved.

Acknowledgements

This work was supported by a JSPS Postdoctoral Fellowship for Research in Japan.

References

- [1] S. Y. Chen, *et al.*, Nano Lett. **15** (2015) 2526.
- [2] H. Negoro, *et al.*, Nano Lett. **23** (2023) 5101.
- [3] K. Ozawa *et al.*, ACS Appl. Opt. Mater. **3** (2025) 375.
- [4] H. Sugimoto *et al.*, Adv. Opt. Mater. **8** (2020) 2000033.

Design of Unidirectional Non-Hermitian Multilayer Structures in the Near-Infrared Region

Tokyo Univ. of Agri. and Technol. (TUAT), ○(M) Ayaha Yamamoto, Wakana KUBO*

*E-mail: w-kubo@cc.tuat.ac.jp

Non-Hermitian photonics is known to exhibit unique optical properties and is generally realized through the controlled combination of gain and loss in materials [1]. One prominent optical characteristic of non-Hermitian structures is unidirectional light propagation. If such unidirectionality can be achieved in the near-infrared (NIR) region, which is part of the solar spectrum, it could be applied to functional smart windows that block infrared radiation from the outside while allowing infrared radiation from the inside to pass through.

However, to the best of the authors' knowledge, unidirectional behavior in the NIR region achieved through non-Hermitian control has not been reported. In this study, we aimed to block thermal radiation in sunlight by designing and evaluating a thin-film multilayer structure that exhibits unidirectionality in the NIR region through non-Hermitian control.

We selected graphite (C) as the high-loss material and calcium fluoride (CaF_2) as the low-loss material, both of which exhibit appropriate optical properties in the NIR. Using the transfer matrix method, we designed a multilayer structure that demonstrates unidirectional absorption of near-infrared light at a wavelength of $2\ \mu\text{m}$ (Fig. 1(a)). The resulting structure consists of, from bottom to top: C (300 nm), CaF_2 (167 nm), C (18 nm), and CaF_2 (244 nm). Figure 1(b) shows the absorption spectra for forward and backward incidence calculated using the finite element method. In the wavelength range of $1\text{--}3\ \mu\text{m}$, the structure exhibited over 90% absorption for forward incidence and less than 60% for backward incidence, confirming that the designed multilayer exhibits unidirectional absorption in the NIR. The modulation depth at $2\ \mu\text{m}$ was approximately 50%.

To confirm that the observed unidirectionality originates from non-Hermitian properties, we calculated the power spectrum $S_n (= T + \sqrt{R_f R_b})$ and its spectral derivative $dS_n/d\lambda$ as shown in Fig. 1(c). Here, T is the transmittance, and R_f and R_b are the reflectances under forward and backward incidence, respectively. Around the wavelength of $2\ \mu\text{m}$, S_n reached a minimum, and $dS_n/d\lambda$ showed a sharp phase variation, indicating that this wavelength corresponds to an exceptional point and confirming that the unidirectionality originates from non-Hermitian behavior. Figure 1(d) presents the magnetic field distributions at $2\ \mu\text{m}$ for both forward and backward incidence. In the case of forward incidence, the magnetic field is clearly absorbed within the multilayer structure. In contrast, under backward incidence, interference within the structure leads to reflection. Figure 1(e) presents the photograph of the multilayer structure deposited on a glass substrate. We will plan to discuss its optical properties in the future.

Based on these results, we conclude that by stacking low- and high-loss materials, we successfully designed a non-Hermitian multilayer structure that exhibits unidirectionality in the near-infrared region, as confirmed by numerical analysis.

[1] L. Feng, et al., Opt. Express, 22, 1760-1767 (2014).

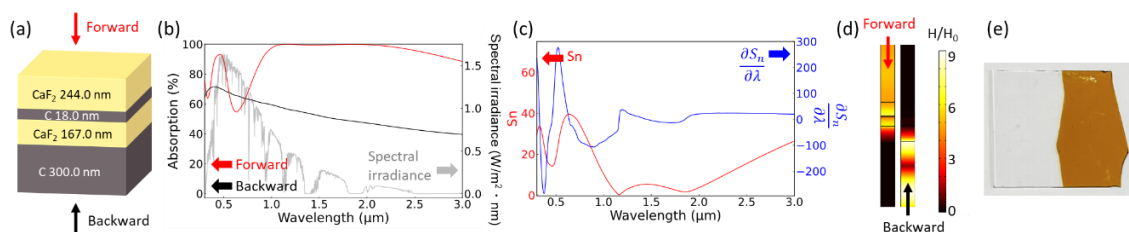


Figure 1(a) Schematic of unidirectional multilayer structure consisting of C and CaF_2 layers. (b) Calculated absorption spectra of the multilayer structure under forward (red) and backward (black) light incidence. (c) Comparison between the generalized total power S_n (red line) and its partial derivative spectrum (blue line). (d) Magnetic field distributions of the multilayer structure calculated at a wavelength of $2\ \mu\text{m}$ under forward and backward light incidence. (e) A photograph of the multilayers deposited on a glass substrate. The brownish part corresponds to the multilayer structure.

4 JSAP-Optica Joint Symposia 2025 | 一般セッション(口頭講演) : 4.1 Plasmonics and Nanophotonics

[8a-N203-1~6] 4.1 Plasmonics and Nanophotonics

[8a-N203-1]

[JSAP-Optica Joint Symposia Invited Talk] Cryo-optical microscopy with on-stage rapid freezing

○Katsumasa Fujita¹ (1.Univ. Osaka)

[8a-N203-2]

[JSAP-Optica Joint Symposia Invited Talk] Information-optimized adaptive optics for biomedical microscopy

Qi Hu¹, Biwei Zhang¹, Jingyu Wang¹, Yuyao Xiao¹, Andrei Enoae¹, OMartin Booth¹ (1.Dept. of Engineering Science, Univ. of Oxford)

[8a-N203-3]

High Resolution Field Emission Scanning Electron Microscopy For Nano-SiC Filled Polymer Matrix Bio-composites For Tibial Spacer in Knee Implants

○(D)Saumya Mishra¹, Swati Gangwar¹ (1.Netaji Subhas Univ. of Tech.)

[8a-N203-4]

Tip-Enhanced Raman Spectroscopy of lipid bilayer in non-gap-mode

○Nao Kuroki¹, Takayuki Umakoshi¹, Prabhat Verma¹ (1.Osaka Univ.)

[8a-N203-5]

Simulation of Extended Depth of Focus Metalens Designed with Intraocular lens Material

○(M1)XIANG-FAN LEE¹, Chih-Chung Wang¹, Jia-Han Li¹ (1.Dept. of ESOE, Natl. Taiwan Univ.)

[8a-N203-6]

Material Advancements and Future Trends in Design of Prosthetic Socket with Biosensor

○(D)ALOK SINGH¹, SWATI GANGWAR¹ (1.Department of Mechanical Engineering, Netaji Subhas University of Technology, Delhi, India.)

Cryo-optical microscopy with on-stage rapid freezing

Univ. Osaka, Katsumasa Fujita

E-mail: fujita@ap.eng.osaka-u.ac.jp

Capturing rapid cellular dynamics with high spatial resolution remains a key challenge in bioimaging, especially when aiming to preserve transient states like ion fluxes or molecular conformations. In this talk, I will present time-deterministic cryo-optical microscopy, a novel method we developed that enables millisecond-scale cryofixation of live cells directly on the microscope stage.

By integrating a rapid cryogen injection system with precise temporal control (± 10 ms), our method “freezes” dynamic events, such as calcium ion waves, at exact timepoints, preserving molecular distribution and chemical state. This approach merges the advantages of live-cell imaging and cryofixation, delivering high signal-to-noise ratio, improved quantitative accuracy, and compatibility with super-resolution and Raman microscopy.

I will demonstrate its power through multimodal imaging of subcellular structures and ion dynamics in cardiomyocytes and HeLa cells, using 3D-SIM and Raman mapping. This method establishes a new paradigm for spatiotemporally resolved, multimodal analysis of living systems with unprecedented precision.

Reference:

1. M. Yamanaka, K. Tsuji, et al., bioRxiv doi: 10.1101/2023.08.01.551103
2. K. Mizushima, et al., Sci. Adv., 10, eadn0110 (2024).

Information-optimized adaptive optics for biomedical microscopy

Qi Hu, Biwei Zhang, Jingyu Wang, Yuyao Xiao, Andrei Enoae, and Martin J. Booth

Department of Engineering Science, University of Oxford, UK

Email: martin.booth@eng.ox.ac.uk

Wavefront aberrations are a prominent issue in microscope imaging. Optical system imperfections and inhomogeneous sample structures introduce phase distortion (or aberration) that lead to compromised image quality. Adaptive optics (AO) are reconfigurable devices that modulate the phase of light to correct aberrations, restoring focusing quality and allowing deep penetration through inhomogeneous tissue samples to facilitate challenging in-vivo imaging for biomedical studies. Particularly useful are indirect – or “sensorless” – AO methods, which do not require a wavefront sensor. They infer wavefront correction from a small set of images, each acquired with a different bias aberration applied with the adaptive correction device. If not well optimized, these methods may require prolonged and repeated sample exposures. We developed a sensorless AO method using embedded machine-learning (ML) based control that considerably improved the efficiency of aberration measurement and estimation. We took steps to further advance information-guided ML-powered AO methods. We used Fisher information to guide AO method design, in particular through the choice of bias aberrations. Further developments included multi-foci for wavefront sensing based on single images. We studied optimised wavefront representations to benefit deep multiphoton microscopy. This showed how alternative modal decompositions can assist the wavefront correction process. These adaptive optics methods have been applied to a range of applications, including super-resolution microscopy and deep tissue imaging for neuroscience.

High Resolution Field Emission Scanning Electron Microscopy For Nano-SiC Filled Polymer Matrix Bio-composites For Tibial Spacer in Knee Implants

Saumya Mishra¹, Swati Gangwar¹

¹ Department of Mechanical Engineering, Netaji Subhas University of Technology, Delhi, India

E-mail: saumya.mishra.phd22@nsut.ac.in, swati.gangwar@nsut.ac.in

1. Introduction

In recent years, materials have been reinforced with natural fibres. Natural fibres are used to create polymer-based composite structures and are currently receiving a lot of attention in the research community because they are readily available, simple to process and have mechanical qualities than that synthetic fibres [1]. The matrix, often referred to as the composites' binder preserves the alignment and position of the reinforced elements, while reinforcement particles contributes the necessary strength and stiffness[2]. Excellent mechanical qualities provided by silicon carbide include high hardness, excellent wear resistance, acid resistance, thermal resistance and superior thermal conductivity [3]. The goal of this investigation is to create a bio-composite material that is promising and reinforced with natural fibre for use in knee implants. In this study, the compression moulding method was used to investigate the structural properties of a bio-composite made from jute, kenaf and kevlar fibre with varying fiber contents (0, 2, 4, 6, 8 and 10wt%) and an ultra high molecular weight polyethylene resin matrix. The bonding of microstructure between matrix and fibre at the outer surface is studied using the field emission scanning electron microscope (FESEM). The result revealed that the n-SiC particles were evenly distributed and contained evenly in the composite.

2. Fabrication Method

The proposed composite resin was made by stirring UHMWPE powder (20wt%), ethanol (10wt%), and nano silicon carbide particles (3wt%) and sonicated for 60 minutes at 20°C and 350 rpm using a magnetic stirrer. Fabrication of proposed composites was done by using the compression molding process. The produced composite plates measure 300 by 300 mm³ and have an average thickness of 4 mm. Fig.1 displays a schematic illustration of the prepared composite manufacture process.

The Nova Nano FE-SEM 450(FEI) equipment was used to perform FESEM investigations at 1 kv and 1.6 nm resolution. It offered a micrograph of the manufactured composites with extremely high resolution(500X). All six powdered samples were examined using a low vacuum imaging setup.

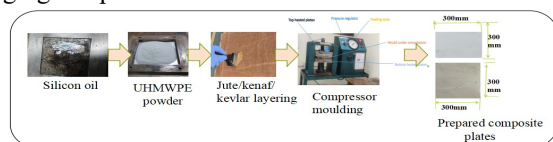


Fig. 1: Steps of fabrication for proposed composites

3. Result and Discussion

The existence of silicon in all six composites (0, 2, 4, 6, 8 and 10 wt%) proved the successful treatment of n-SiC filler. Fig. 2a) and 2b) shows representative FE-SEM images of fabricated hybrid composites. Based on the morphology, it can be inferred from these figures that the n-SiC particles are evenly contained and spread throughout the composite.

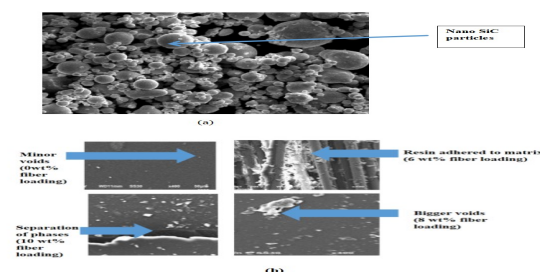


Fig.2. FE-SEM images of (a) treated n-SiC particles (b) micrographs of fabricated composite at 500X Magnification

The silica layer, when combined with the resin matrix, created a homogeneous distribution of nanoparticles in the composite. This is because the Si and C atoms in a SiC crystal create strong tetrahedral covalent connections with a bond energy of 4.6 eV. The Si-C atoms have a bond length of 1.89 Å. Additionally, the composites micrograph (500 magnification) displays variance in the weight percentage of manufactured composites' void contents.

4. Conclusions

It was observed that the determined mechanical strength parameters were comparable to the patient's bone strength, with the knee tibia's acceptable medical range being 65-190 MPa as per ISO 14243. Thus, according to the study's findings, the proposed n-SiC treated jute/kenaf/kevlar filled UHMWPE composite based knee implants serves as a safe and comfortable alternative for patients.

References

- [1] Kumar S, Bhatt I K and Patnaik A, Novel Dental Composite Material Reinforced with Silane Functionalized Microsized Gypsum Filler Particles. J. Mater. Des. Appl. **11**(2015) pp1-12.
- [2] Yadav S and Gangwar S, A Critical Evaluation of Tribological Interaction for Restorative Materials in Dentistry. Int. J. Polym. Mater. Polym. Biomater **10**(2018).:pp1-14
- [3] Mishra Saumya, and Swati Gangwar. "Thermal analysis of jute/kenaf/kevlar hybrid-filled UHMWPE composite-based tibial spacer using ANSYS-22R1 for total knee replacement Machining and Tribology of Advanced Materials: From Coatings, Lubrications, Surface Treatments to Modeling and Simulation **12** (2025): 39

Tip-Enhanced Raman Spectroscopy of lipid bilayer in non-gap-mode

Nao Kuroki¹, Takayuki Umakoshi¹, Prabhat Verma¹

¹Dept. of Applied Physics, Osaka Univ.

E-mail: verma@ap.eng.osaka-u.ac.jp

1. Introduction

The cell membrane is a platform for many vital cellular processes. Depending on the cellular process, the distribution of biomolecules, such as protein and lipid, changes in the cell membrane at the nanoscale. Therefore, in order to determine the distribution of biomolecules, a nanoscale detection technique is required. One of the best tools for the observation of the biomolecule distribution in the cell membrane is tip-enhanced Raman spectroscopy (TERS) [1]. In TERS, nanoscale near-field light is generated by irradiating a metallic tip with incident light. By shining a sample with the nanoscale near-field light, one can detect Raman scattering at the nanoscale. Because Raman scattering reveals the intrinsic chemical properties of materials through their vibrational modes, TERS enables nanoscale visualization of biomolecular distributions. Lipid bilayers can be used as a model of the cell membrane. Lipid bilayers have been investigated by gap-mode TERS in previous studies, where a gold substrate is used in combination with a metallic tip. This configuration induces strong plasmonic coupling between the tip and the substrate, thereby significantly enhancing the near-field light. However, since gap-mode is not suitable for a thicker sample such as a cell, we focus on measuring TERS without the gap-mode. Here, in this study, we measured non-gap-mode TERS spectra from lipid as a model of the cell membrane by overcoming the challenge of low enhancement.

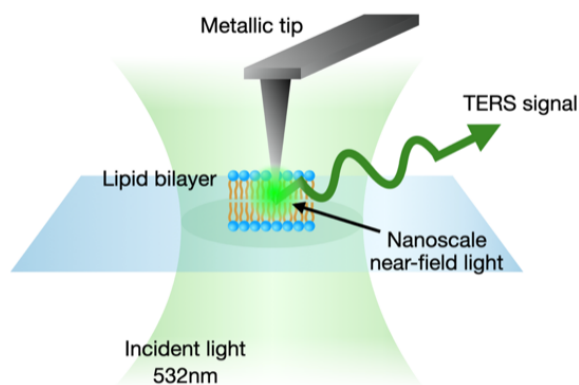


Figure 1 The schematic of TERS set up.

2. Experimental results

For TERS measurements, a metal-covered AFM tip is utilized. To induce plasmonic activity, a 20-nm-layer of silver was deposited onto the AFM tip.

The key parameter for a better enhancement is the surface roughness of the silver layer. A corrugated surface with specific roughness can effectively generate strongly enhanced localized surface plasmons. Therefore, to obtain such a surface morphology, silver was evaporated at a low deposition rate of 0.05 nm/s. By using this tip, we detected TERS signal from lipids. For comparison, a normal Raman spectrum was also acquired, as shown in Figure 2. The red spectrum shows Raman signal acquired when the tip approached the lipid bilayers (TERS spectrum), while the black spectrum shows Raman signal obtained when the tip was away from the substrate (normal Raman spectrum). In contrast to the black spectrum, which displays no noticeable Raman peaks, the red spectrum exhibits several peaks, both in the fingerprint region, such as the CH₂ and C=C modes, and in the C-H stretching region. These results demonstrate that TERS signal from lipid can be successfully detected using non-gap-mode TERS. In the poster, we will discuss more about TERS spectra of the lipid bilayer.

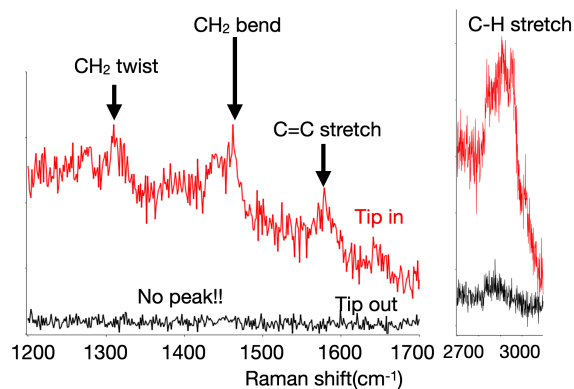


Figure 2 TERS and Raman spectra of lipid.

3. Conclusion

We successfully confirmed non-gap-mode TERS signal enhancement from lipid bilayers. This result demonstrates the potential of non-gap-mode TERS for detecting cell membranes. Therefore, in order to detect more natural molecular behavior in vitro, measuring the cell membrane with TERS in a liquid environment is expected to be a valuable approach.

References

- [1] P. Verma, *Chem. Rev.*, **117**, 6447-6466 (2017)

Simulation of Extended Depth of Focus Metalens Designed with Intraocular lens Material

Xiang-Fan Lee, Chih-Chung Wang, and Jia-Han Li*

Department of Engineering Science and Ocean Engineering, National Taiwan University, Taipei 10617, Taiwan

E-mail: r13525097@ntu.edu.tw, d09525016@ntu.edu.tw, *: jiahan@ntu.edu.tw

1. Introduction

Currently, metalens technology has been widely used in wearable devices and optical sensing [1], demonstrating its high potential for miniaturization and integration. This study aims to design a metalens structure with extended depth of focus (EDOF) characteristics for potential use in intraocular applications. A dielectric material suitable for ophthalmic implantation is employed as the substrate, and the design is evaluated using finite-difference time-domain (FDTD) simulation. The proposed metalens consists of a nanocolumn array, and its optical phase distribution, focusing behavior, and depth of focus performance are analyzed to assess its feasibility for integration into implantable optical components in ophthalmology.

2. Methodology and Results

In this study, we designed a planar metalens to focus green light, with focal length and aperture size proportionally scaled from a human eye model. Based on anatomical data by Brown (1974) and the Liou and Brennan model [2], the crystalline lens has a radius of approximately 5 mm. To represent the retinal imaging plane, we set a target focal length of 16 mm. For numerical simulation, the design was downscaled to a 31 μm radius and a proportional focal length of 100 mm. As shown in Figure 1, this miniaturized, biologically inspired configuration enables efficient simulation and potential integration into ophthalmic systems.

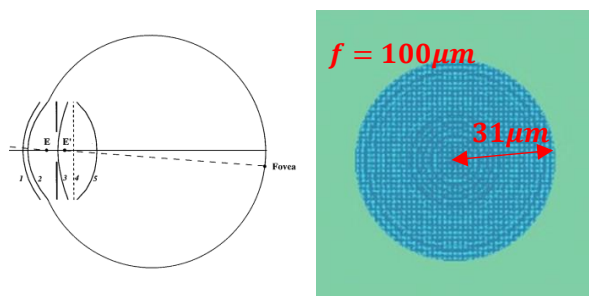


Fig.1 (Left) Schematic of the anatomical eye model based on Liou and Brennan. (Right) Scaled metalens design with a target radius of 31 μm and a focal length of 100 μm , proportionally derived from the human crystalline lens geometry for numerical simulation purposes.

The metalens of the phase distribution [3] $\varphi(x, y)$ need to follow:

$$\varphi(x, y) = \frac{2\pi}{\lambda_d} (f - \sqrt{x^2 + y^2 + f^2}) + \frac{\alpha}{R^3} (x^3 + y^3)$$

where λ_d is the design wavelength, x and y denote the spatial coordinates of each nanopillar, f is the nominal focal length, R is the lens radius, and α is the strength of the cubic phase term. The first term corresponds to a conventional

focusing phase profile, while the additional cubic term modulates the wavefront to generate an EDOF effect. The cubic phase modulation results in a longitudinally extended, enabling the optical system to maintain more consistent imaging performance across an extended axial range and increasing tolerance to defocus.

simulation results are shown in Figure 2. Using PMMA nanopillars as the unit structure, the metalens was simulated under identical material and geometric conditions. By varying the cubic phase coefficient α , different axial focusing behaviors were observed, indicating that the EDOF performance is influenced by the value of α .

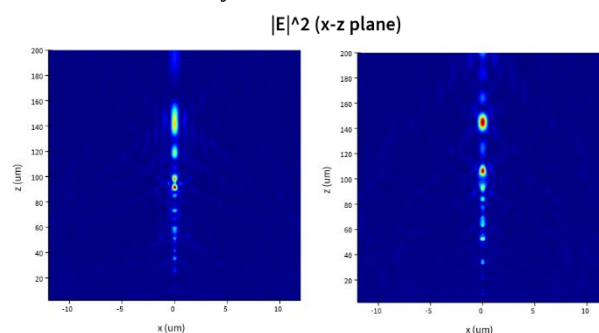


Fig.2 (Left) $\alpha = 55\pi$ (Right) $\alpha = 30\pi$

3. Conclusions

We employed the FDTD method to simulate the far-field focusing behavior of an EDOF metalens. In this study, green light was selected as the design wavelength due to its high sensitivity in human vision. From a biomedical perspective, the proposed EDOF metalens design holds promise for potential applications in IOLs [4], particularly in enhancing imaging performance over an extended depth range.

Acknowledgements

This research was funded by Ministry of Science and Technology of Taiwan under grant number 112-2221-E-002-201-MY2.

References

- [1] Li, B., Piyawattanametha, W., & Qiu, Z. (2019). Metalens-Based Miniaturized Optical Systems. *Micromachines*, 10(5), 310. <https://doi.org/10.3390/mi10050310>
- [2] Hwey-Lan Liou and Noel A. Brennan, "Anatomically accurate, finite model eye for optical modeling," *J. Opt. Soc. Am. A* 14, 1684-1695 (1997)
- [3] Majumdar, "Design and analysis of extended depth of focus metalenses for achromatic computational imaging," *Photon. Res.* 8, 1613-1623 (2020)
- [4] Kanclerz P, Toto F, Grzybowski A, Alio JL. Extended Depth-of-Field Intraocular Lenses: An Update. *Asia Pac J Ophthalmol* (Phila). 2020;9(3):194-202. doi:10.1097/APO.0000000000000296

Material Advancements and Future Trends in Design of Prosthetic Socket with Biosensor

Alok Singh^{1,*}, Swati Gangwar¹

Department of Mechanical Engineering, Netaji Subhas University of Technology, Delhi, India.

E-mail: alok.singh.phd24@nsut.ac.in ; swati.gangwar@nsut.ac.in

1. Introduction

Prosthetic sockets function as the important connection between a residual limb and an artificial limb because they affect ease, operation, and recovery. Materials innovations improved adaptability with strength-to-weight ratios [1],[2]. Composite polymers, shape memory alloys, and 3-D printed lattice structures stand as some examples within these innovations. An enhancement that is promising has emerged as implantable biosensors in recent times. Because they offer real-time data to personalize fit, reduce complications, and improve clinical decision-making [6], these biosensors can monitor parameters like pressure, strain, plus temperature at the limb–socket interface.

2. Materials Used in Prosthetic Sockets

Polyethylene and polypropylene such as thermoplastics were regularly used. Their shaping was quite easy, and also their affordability was prominent [3]. However, modern research has stressed about the use of composite materials such as carbon fiber-reinforced polymers, polyamide (PA-12), and shape memory alloys (SMAs), because these materials offer superior mechanical strength, reduced weight, and tailored stiffness [4]. Additive manufacturing allows customization of lattice structures. This customization improves ventilation along with mechanical performance.



Fig. 1 Progress and Trends in Prosthetic Materials [1]

3. Limitations of Current Materials

Even with these advancements that exist, current sockets still often fail to accommodate daily stump volume fluctuations that happen, and that leads to discomfort as well as pressure sores. Inadequate thermal qualities do dissipate excessively and cause sweating, particularly some skin conditions in much warmer climates [5]. Rigid sockets can create pressure hotspots and limited adaptability especially for patients with high-mobility or long-term use [3].

4. Future Directions and Material Innovations

For prosthetic development, the integration by socket systems of implantable biosensors represents a promising avenue. These are biosensors that can measure biophysical parameters like pressure or strain and temperature at that limb–socket interface. They provide continuous data for clinical evaluation and adaptive control. For instance, strain biosensors embedded in the residual limb interface can detect load distribution along with socket misalignment during ambulation. These sensors are useful to optimize the socket geometry or the material stiffness. Wireless sensor technology that is biodegradable offers monitoring options that are low-profile and long-term for user comfort. Smart sensing with materials science fuse to align with personalized rehabilitation strategies and may greatly reduce complications like pressure ulcers or implant rejection [6].

5. Conclusion

The performance of prosthetic sockets continues on improving because it uses advanced materials along with fabrication techniques. Biosensors are integrated thus prosthetic systems are data-driven so adaptability is introduced and personalization occurs. For ensuring long-term safety, efficacy, and user comfort, future work should focus on validating biosensor-based sockets in clinical settings.

References

- [1] P. Patel and P. Gohil, *Int. J. Lightweight Mater. Manuf.*, vol. 8, pp. 205–227, 2025.
- [2] P. Rai et al., *Mater. Today Proc.*, vol. 70, pp. 454–464, 2022.
- [3] N.A. Razak et al., *Biocybern. Biomed. Eng.*, vol. 35, pp. 100–105, 2015.
- [4] M.H. Wang et al., *IRBM*, vol. 44, 100731, 2023.
- [5] C.M. Webber and B.L. Davis, *J. Biomech.*, vol. 48, pp. 1294–1299, 2015.
- [6] K.E. Nash, K.G. Ong, and R.E. Guldberg, **Connective Tissue Research**, vol. 63, no. 3, pp. 228–242, 2022.
- [6] K.E. Nash, K.G. Ong, and R.E. Guldberg, **Connective Tissue Research**, vol. 63, no. 3, pp. 228–242, 2022.

4 JSAP-Optica Joint Symposia 2025 | 一般セッション(口頭講演) : 4.2 Photonics Devices, Photonic Integrated Circuit and Silicon Photonics

[8p-N203-1~11] 4.2 Photonics Devices, Photonic Integrated Circuit and Silicon Photonics

[8p-N203-1]

[JSAP-Optica Joint Symposia Invited Talk] 300mm Silicon Photonics Platforms from Datacommunication to LiDAR

○Frederic Boeuf¹, Louise-Eugenie Bataille¹, Leopold Viro¹, Lorenzo Lazzari¹, Stephane Monfray¹, Eva Kempf¹, Sebastien Cremer¹ (1.STMicroelectronics)

[8p-N203-2]

On-chip vibrational circular dichroism spectrometer using topological photonics

○LIYAN HU¹, Sho Okada², Qianshuo Wang¹, Xing-Xiang Wang¹, Xiao Hu³, Tomohiro Amemiya¹ (1.Inst. of Sci. Tokyo, 2.NICT, 3.Shanghai Univ.)

[8p-N203-3]

Feedback in Mach-Zehnder Interferometer for Higher Order Optical Differentiation

○CheeFai Fong¹, Guangwei Cong¹ (1.PEIRC, AIST)

[8p-N203-4]

Indium Tin Oxide-based Transparent Electrode Memristor for Integrated Photonic Phase Modulation on Silicon Nitride Platforms

○(M2)Min Kang^{1,2,3}, Minsik Kong^{1,2,3}, Soo-Yeon Lee^{1,2,3} (1.Elect. & Comp. Eng., 2.ISRC, 3.Seoul Nat'l Univ.)

[8p-N203-5]

[JSAP-Optica Joint Symposia Invited Talk] Membrane InP-based Optical Modulators and Lasers on Si Platform

○Tatsuro Hiraki^{1,2}, Takuma Aihara^{1,2}, Takuro Fujii^{1,2}, Yoshiho Maeda^{1,2}, Tomonari Sato^{1,2}, Shinji Matsuo² (1.NTT Device Innovation Center, 2.NTT Device Technology Labs)

[8p-N203-6]

[JSAP-Optica Joint Symposia Invited Talk] High Power SOA-integrated DFB Lasers for Co-packaged Optics

○Daisuke Inoue^{1,2}, Konosuke Aoyama¹, Takashi Matsui¹, Shinya Iizaka¹, Shigenori Toyoshima¹, Shinsuke Yanagida¹, Kotaro Hoshino¹, Naoki Fujiwara², Daisei Shoji¹, Harold Kamisugi¹ (1.Sumitomo Electric Device Innovations, Inc., 2.Sumitomo Electric Industries, Ltd.)

[8p-N203-7]

Passive Radiative Cooling Employing Vanadium Dioxide-based Metasurface

Muhammad Faizan¹, Muhammad Abuzar Baqir¹, Muhammad Saqlain¹, ○Pankaj Kumar Choudhury² (1.COMSATS Univ., 2.Zhejiang Univ.)

[8p-N203-8]

Energy Enhancement in Solar Cells Employing InP Nanorods-assisted Metasurface

M. Ghasemi¹, A. Dehzangi², A. -B. M. A. Ibrahim³, ○Pankaj Kumar Choudhury⁴ (1.S. B. Univ., 2.Univ. Texas Dallas, 3.Univ. Teknol. MARA, 4.Zhejiang Univ.)

[8p-N203-9]

Tailoring AgBi₄ Lead-Free Solar Cells Using Alkali Halide Additive

○(DC)Shanas fatima Fatima^{1,2}, Khadka B Dhruba¹, Masatoshi Yanagida¹, Sunil Kumar Singh², Yasuhiro Shirai¹ (1.NIMS, Tsukuba, Japan, 2.IIT BHU, Varanasi)

[8p-N203-10]

Enhanced Luminescent Properties of Sm³⁺-Doped Niobate-Based Phosphors for Opto-Electronic Applications

○(DC)Kanishk Poria¹, Sanjana Bhatia¹, Nisha Deopa² (1.Panjab Univ., 2.Ch. Ranbir Singh Univ.)

[8p-N203-11]

Virtual Vernier Effect-Based Nano-Displacement Sensing Using Single-Cavity Interferometry

○(DC)Arvind Kumar Maurya¹, Rajan Jha¹ (1.IIT Bhubaneswar)

300nm Silicon Photonics Platforms from Datacommunication to LiDAR

Frédéric Boeuf, Louise-Eugenie Bataille, Leopold Virot, Lorenzo Lazzari, Stephane Monfray, Eva Kempf
and Sebastien Cremer

STMicroelectronics, 850 rue Jean Monnet, Crolles, France

E-mail: frederic.boeuf@st.com

Introduced nearly 40 years ago, Silicon Photonics has gradually emerged at the industrial level to address the need for low-cost, high-speed transceivers [1]. Today, commercial pluggable modules delivering aggregated bandwidths of 800 Gbits/s and even 1.6 Tbits/s are available. In addition, research into efficient systems for high-bandwidth switches and GPU-to-GPU communication has gained significant traction, driven by the increasing demand for AI clusters. While the Silicon Photonics market is predominantly driven by data communications, it also holds immense potential for other applications, such as automotive (e.g., LiDAR), healthcare, and quantum communications. Consequently, the versatility of device offerings in platform development is critical to ensuring compatibility across a wide range of applications. In recent years, we have developed Silicon Photonics platforms tailored to both R&D (PIC50) and the manufacturing of photonic integrated circuits (PIC100). To support diverse applications, both platforms are designed to meet essential requirements, including the availability of multiple process options for flexible configurations of optical passive devices, low propagation loss, efficient edge and surface coupling, and high-performance modulators. To achieve this, our waveguide process relies on immersion lithography for patterning the 300 nm thick SOI layer, utilizing multiple slab thicknesses (150 nm, 50 nm, and full etch) as well as SiN layers optically coupled to the Si layer [2] (Fig. 1). This combination enables the co-integration of various device types, such as low-loss rib waveguides (<0.6 dB/cm) and SiN-based optical devices. In the PIC100 technology (Fig.2), which targets 200 Gbps/lane applications, we have implemented a high-speed Germanium photodetector (PD) with a 3 dB bandwidth exceeding 90 GHz and a responsivity of 1 A/W. Furthermore, an efficient phase modulator has been integrated, delivering a 2x improvement in efficiency compared to our previous platform [1]. To explore applications beyond data communications, we have designed Optical Phase Arrays (OPA) and optimized antennas within our PIC50 platform to support LiDAR applications. Low-power consumption OPAs based on PN junction phase shifters with 256 channels have been demonstrated [3], along with millimeter-long antennas featuring enhanced far-field performance [4]. Lastly, we have investigated the compatibility of our platform with the heterogeneous integration of III-V materials. As an example, we will discuss the feasibility of a hybrid III-V/SOI entangled photon source [5] for quantum communication application.

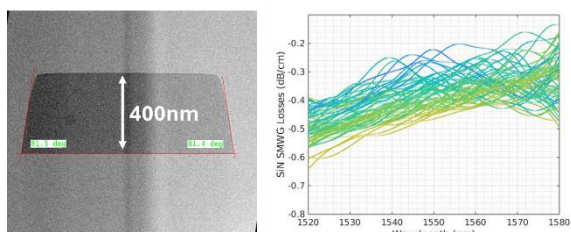


Fig.1 : SiN patterning and single mode waveguide performance in C-Band

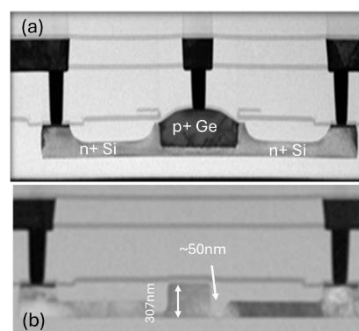


Fig.2 : (a) Ge High-Speed Photo-Detector (b) High Speed Phase Modulator on PIC100G platform

References [1] F.Boeuf et al., J. Lightwave Technol. 34, 286-295 (2016), [2] F. Boeuf et al., IEDM 2019, [3] L-E Bataille et al., CLEO 2023 [4] L-E Bataille et al. IEEE Si-Photonics 2024 [5] J Schuhmann et al., PRX Quantum 5, 2024 .
Acknowledgement: this work has been partially supported by the Institut de Recherche Technologique (IRT),

On-chip vibrational circular dichroism spectrometer using topological photonics

Liyan Hu¹, Sho Okada², Qianshuo Wang¹, Xing-Xiang Wang¹, Xiao Hu^{1,3} and Tomohiro Amemiya¹

¹ Institute of Science Tokyo, ² National Institute of Information and Communications Technology,

³ Shanghai University

E-mail: hu.l.eb23@m.isct.ac.jp

1. Introduction

Circular dichroism (CD) analysis is a standard method to measure the difference in absorbance properties between left and right circularly polarized (LCP and RCP) light chiral molecules. However, the size of the conventional system tends to be large, and the operating bandwidth is limited to the visible range[1]. In topological photonics systems, light can propagate while maintaining circular polarization[2-5]. In this study, we measured infrared circular dichroism (VCD; vibrational circular dichroism) at the chip level for a very small amount of sample.

2. Device concept and measurement

An overview of the device for measuring VCD is shown in Fig. 1(a). The device is based on silicon photonics, and a honeycomb lattice structure with C_{6v} symmetry is adopted as the topological photonic crystal (PhC) (Fig. 1(b)). The propagating light is divided and incident to two symmetrical topological waveguides. In this case, either LCP light or RCP light is scattered upward from each topological waveguide. By dropping a sample to be evaluated on this area and observing the intensity difference of the scattered light, VCD can be measured. Since the above measurement is possible as long as the dropped sample is present in the topological region, the amount of sample required for the measurement is much smaller than that required for a typical CD spectrometer using free-space optics. For operating

wavelengths around 1400 nm, we varied R and L and measured the bandgap wavelengths for the trivial and topological PhC using infrared photonic band microscope[6]. From the result we determined the (R, L) to (247nm, 272nm) and (275nm, 278nm) for trivial and topological PhCs, respectively.

Fig. 2(a) shows the optical microscope and scanning electron microscope (SEM) images of the device. Fig. 2(b) is an infrared camera image of the device w/ and w/o a drop of (-)-borneol at a wavelength near 1400 nm. As a result, at 1400 nm, the ratio of the intensity of scattered light at measurement area of A and B before dropping (-)-borneol is 0.649, while after dropping the ratio is 1.893. The difference of scattered light intensity between A and B is consistent with the reference data of (-)-borneol[7].

Acknowledgments

This work is supported by JST CREST (JPMJCR24R1), JST ASPIRE (23837157), and JST A-STEP (JPMJTR22RG).

References

- [1] <https://jascoinc.com/products/spectroscopy/circular-dichroism/>
- [2] L.-H. Wu and X. Hu, *Phys. Rev. Lett.* **114**, 223901(2015).
- [3] J. Kang *et al.*, *Appl. Phys. Express* **7**, 032202 (2014).
- [4] Y. Wang *et al.*, *Jpn. J. Appl. Phys.* **59**, 052004 (2020).
- [5] T. Tomiyasu *et al.*, *Appl. Phys. Express* **11**, 012704 (2018).
- [6] T. Amemiya *et al.*, *Opt. Lett.* **47**, 2430 (2022).
- [7] S. Abbate *et al.*, *Chirality* **21**, E242 (2009).

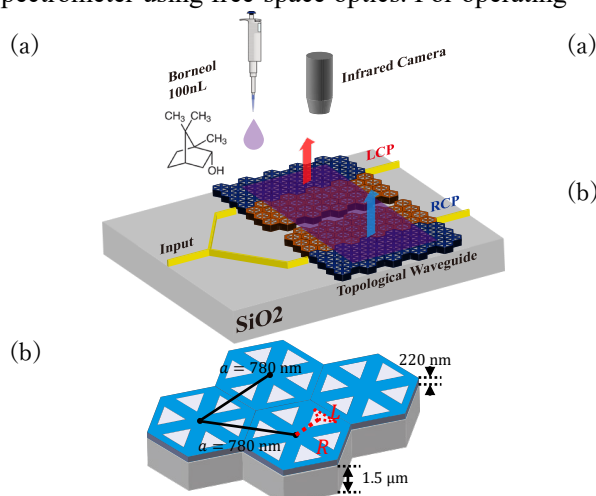


Fig. 1 (a) An overview of the device for measuring VCD. (b) Honeycomb lattice structure with C_{6v} symmetry used in this work.

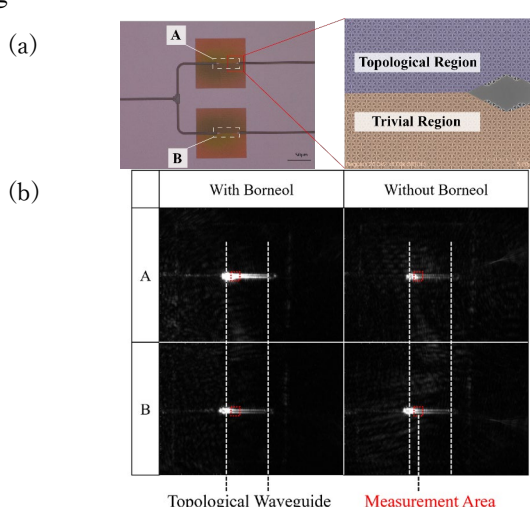


Fig. 2(a) Optical microscope and SEM image of the fabricated device. (b) infrared camera image of the device w/ and w/o a drop of [(1S)-endo]-(-)-borneol at a wavelength near 1400 nm.

Feedback in Mach-Zehnder Interferometer for Higher Order Optical Differentiation

Photonics-Electronics Integration Research Center, AIST¹, °Chee Fai Fong¹ and Guangwei Cong¹

E-mail: cheefai.fong@aist.go.jp

The Mach-Zehnder interferometer (MZI), despite its simple structure, is a highly versatile optical component used in a wide range of applications, including filtering, modulation, sensing, and signal processing [1-3]. Since its operation is typically analyzed under continuous-wave (CW) excitation, its potential as an optical differentiator, particularly under pulsed conditions, has remained relatively overlooked. In this work, we explore the MZI's capability to perform temporal differentiation in numerical simulations by introducing an appropriate path delay between its two arms. We further propose two advanced configurations: an MZI with a single feedback loop and a cascaded double-MZI structure to realize higher-order optical differentiation.

In the first configuration, an asymmetric MZI (AMZI) is designed with a fixed path-length difference that introduces a temporal delay between the two arms, allowing constructive and destructive interference of input pulses to output signal of the first temporal derivative. By considering a train of Gaussian pulses, we show that the output closely resembles the time derivative of the input waveform. To realize second-order differentiation, we incorporate a feedback loop that routes one output of the AMZI back into one of its input arms. This feedback-induced interference enhances temporal resolution and enables the generation of second-order derivative-like features. Extending this concept, we cascade the feedback-enabled AMZI with a second-stage AMZI, resulting in a composite system capable of producing third-order derivative-like pulse shapes. These designs demonstrate the potential of MZI for ultrafast analog signal processing, offering a compact and efficient platform for implementing temporal derivatives in the optical domain.

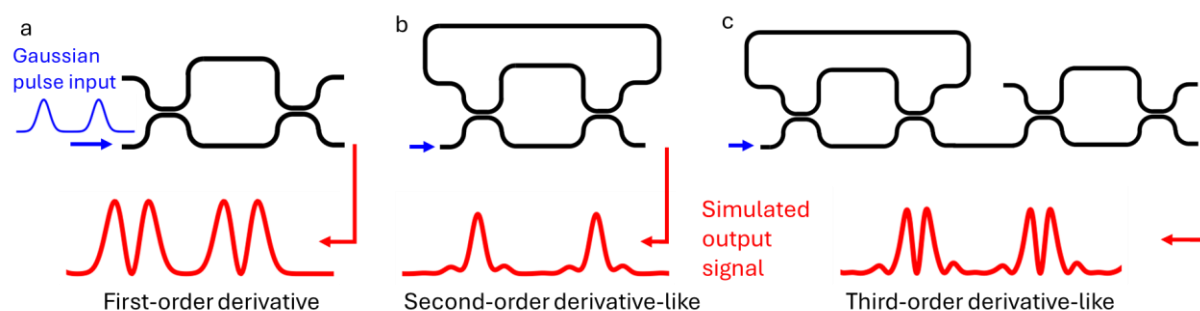


Fig. 1(a) Schematic of an asymmetric MZI (AMZI) and the simulated first-derivative output signal when considering a Gaussian pulse train input. (b) AMZI with a feedback loop connecting the top output and input arms to enable output of second-order derivative-like signals (c) Cascade of the AMZI with feedback loop and an AMZI to generate third-order derivative-like output signals.

This work is supported in part by JSPS KAKENHI (JP24K17627) and JST CREST (JPMJCR24R3).

[1] Wang, M., Chen, X., Khan, U. & Bogaerts, W., *Sci Rep* 12, 1482 (2022).

[2] Han, J.-H. *et al. Nature Photon* 11, 486–490 (2017).

[3] Goodwin, M. J. *et al. ACS Appl. Bio Mater.* 3, 4566–4572 (2020).

Indium Tin Oxide-based Transparent Electrode Memristor for Integrated Photonic Phase Modulation on Silicon Nitride Platforms

Min Kang^{1,2,3}, Minsik Kong^{1,2,3} and Soo-Yeon Lee^{1,2,3}

¹ Department of Electrical and Computer Engineering, ² Inter-university Semiconductor Research Center,

³ Seoul National University, 1, Gwanak-ro, Gwanak-gu, Seoul, 08826, Republic of Korea

E-mail: sooyeon.lee@snu.ac.kr

1. Introduction

Photonic computing is a promising next-generation computing paradigm to overcome the von Neumann bottleneck[1]. Among the essential components for photonic computing, photonic memristors enable to provide energy-efficient, non-volatile, and reconfigurable optical phase modulation[2]. In particular, resistive random-access memory (RRAM) offers multi-level switching capability, low power consumption, and CMOS compatibility[3]. While noble metals such as Platinum (Pt) are commonly used as RRAM electrodes, their optical opacity limits their application in photonic platforms. In contrast, Indium Tin Oxide (ITO) enables both electrical switching and optical modulation due to its transparency[4]. However, ITO-based RRAMs face challenges such as interfacial instability and uncontrolled oxygen vacancy (V_o) formation[4]. In this work, O_2 annealing was applied to ITO electrodes to ensure stable switching behavior of the device. Simulations demonstrated that, by leveraging the optical transparency of ITO, RRAM could be monolithically integrated onto a Si_3N_4 waveguide, achieving optical phase modulation through the engineering of V_o filaments.

2. Methods

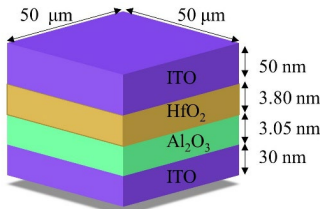


Figure 1 | Schematic of ITO-based HfO₂/Al₂O₃ RRAM stack.

ITO (30 nm, sputtered) / Al₂O₃ (3.05 nm, ALD) / HfO₂ (3.80 nm, ALD) / ITO (50 nm, sputtered) multilayer structures were fabricated on a thermally oxidized SiO₂ substrate. Oxygen vacancies in ITO electrodes were modulated through O_2 thermal annealing to enhance interfacial stability. To evaluate optical modulation characteristics, Al₂O₃ and HfO₂ films were treated with N₂O plasma, and refractive index changes were measured using ellipsometry. For optical analysis, the RRAM stack was modeled on a Si_3N_4 waveguide (200 nm height, 1.5 μm width), and optical confinement factors (Γ) were extracted using eigenmode simulations. These values were used to calculate the effective index shift (Δn_{eff}) and simulate the phase modulation in an asymmetric Mach-Zehnder Interferometer (a-MZI) via FDTD simulations.

3. Results and Discussions

The RRAM with ITO electrodes exhibited bipolar resistive switching under a compliance current of 10 μA with a low forming voltage. O_2 annealing improved switching uniformity by stabilizing the electrode/dielectric interface and regulating V_o concentration in the ITO layers (Fig. 2a). Refractive index reductions of 0.213 (Al₂O₃) and 0.068 (HfO₂) at 1550 nm after N₂O plasma treatment confirmed effective optical modulation via V_o control (Fig. 2b).

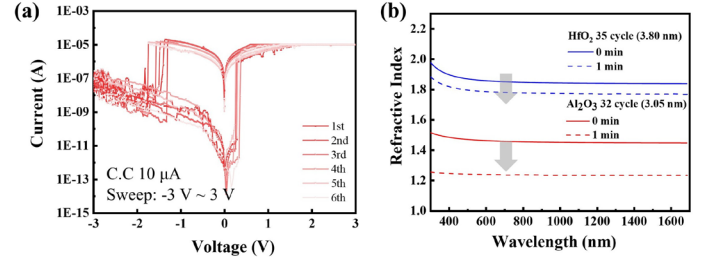


Figure 2 | (a) I-V characteristics of the device in set and reset states. (b) Refractive index variation of Al₂O₃ and HfO₂ thin films upon N₂O plasma treatment.

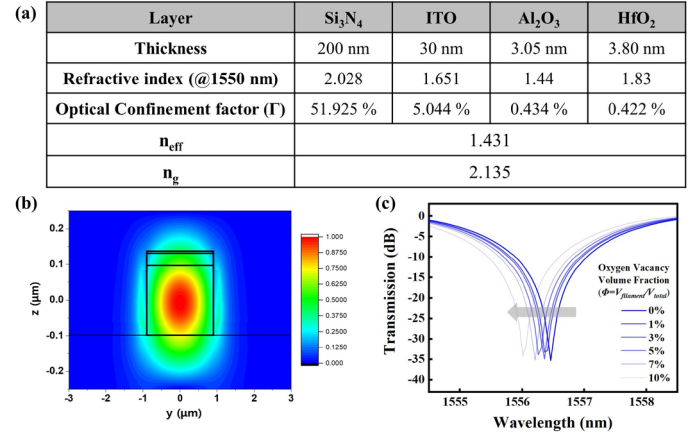


Figure 3 | (a) MODE solver results for a Si_3N_4 waveguide with the RRAM stack integrated on top. (b) Optical mode profile for the Si_3N_4 waveguide with the RRAM. (c) Optical transmission spectra from a MZI structure incorporating the RRAM-integrated Si_3N_4 waveguide.

MODE simulation of the RRAM-stacked Si_3N_4 waveguide revealed the effective index modulation according to $\Delta n_{eff} \approx \Gamma_{Al_2O_3} \cdot \Delta n_{Al_2O_3} \cdot \Phi_{Al_2O_3} + \Gamma_{HfO_2} \cdot \Delta n_{HfO_2} \cdot \Phi_{HfO_2}$ where Φ denotes the volume fraction of V_o filaments (Fig. 3a,b). FDTD simulations showed that the change of effective index (Δn_{eff}) resulted in an optical phase shift (Fig. 3c), confirming the potential for electrically programmable optical phase modulation using the engineered ITO-based RRAM.

4. Conclusions

We fabricated RRAM with ITO electrodes and investigated its electrical switching characteristics. To explore its potential for photonic integration, we performed simulations of a monolithic structure integrating the RRAM onto a Si_3N_4 waveguide. The dual role of ITO as both electrical contact and an optical modulator enables compact photonic integration. Despite interfacial limitations, O_2 annealing successfully stabilized switching behavior. These results highlight the potential of the proposed structure as a building block for photonic integrated circuits.

Acknowledgements

This work was supported by the Basic Research Laboratory (RS-2024-00397664) funded by the Korean Government (MSIT).

[1] Zhang, G. et al., Light, Sci.&Appl. 13(1), 206-212 (2024).
[3] Cheung, S. et al., Commun. Eng. 3(1), 49-12 (2024).

[2] Tossoun, B. et al., Nat. Commun. 15(1), 551 (2024).
[4] Chen, K.-H. et al., Nanoscale Res. Lett. 11(1), 52 (2016).

Membrane InP-based Optical Modulators and Lasers on Si Platform

Tatsuro Hiraki^{1,2}, Takuma Aihara^{1,2}, Takuro Fujii^{1,2}, Yoshiho Maeda^{1,2}, Tomonari Sato^{1,2},
and Shinji Matsuo²

¹ NTT Device Innovation Center, NTT Corporation, ² NTT Device Technology Labs, NTT Corporation
E-mail: tatsuro.hiraki@ntt.com

As datacenter traffic increases, there is a growing demand for high-capacity and low-power-consumption optical interconnections. Optical transceivers with optical modulators achieve high-baudrate modulation, making them essential components for high-capacity optical interconnections. A silicon photonics platform is widely used for integrating Si Mach-Zehnder modulators (MZMs) and GeSi-based electro-absorption modulators (EAMs) with compact Si-waveguide circuits. On silicon-on-insulator (SOI) substrates, Si waveguides have a high refractive index contrast of about 40%, allowing for high-density integration. Furthermore, SOI substrates have been developed up to 300 mm in diameter, providing an excellent platform for mass production. However, compared to InP-based materials, Si and GeSi are not necessarily ideal as optical modulator materials. Recent Si MZMs have already reached their performance limits due to the inherent properties of Si, yet their performance does not surpass that of reported InP-based MZMs. Additionally, high-speed GeSi-bulk EAMs face challenges in O-band operation because of the limited range of bandgap variability. Furthermore, since Si and GeSi are indirect-bandgap materials, integrating optical modulators with lasers remains difficult.

To overcome these issues, heterogeneous integration of InP-based materials on Si has attracted much attention. The inherent properties of InP-based materials are beneficial for fabricating high-performance MZMs, O-band EAMs, and lasers. Among various types of InP-based photonic devices, we have focused on membrane InP-based photonic devices, consisting of 200-300-nm-thick lateral p-i-n diodes with buried active regions. This configuration allows for high optical confinement and low junction capacitance, enabling the development of high-efficiency and high-speed optical modulators. Additionally, because the effective refractive indices of the membrane InP layer and the Si layer are similar, optical coupling between the InP and Si layers is facilitated, allowing for the integration of high-performance InP-based lasers and optical modulators on Si-waveguide circuits. Using the membrane structure, we have developed high-efficiency carrier-depletion-type MZMs and high-speed EAMs, and integrated them with membrane laser diodes [1, 2].

In this paper, we review recent progress in membrane InP-based modulators and lasers. Fig. 1 (a) shows a schematic of a membrane EAM-integrated distributed feedback (EADFB) laser [2]. Fig. 1 (b) and (c) shows the cross-sectional images of the DFB laser and EAM. Both the DFB laser and EAM feature a lateral p-i-n diode structure with a 230-nm-thick InP layer and a buried InGaAlAs multiple-quantum-well (MQW) core. The EAM enables intensity modulation through the Franz-Keldysh effect when a reverse bias voltage is applied. The EAM is 100 μm in length. The DFB laser has a supermode waveguide in which the MQW core is optically coupled with a low-loss Si core. This design reduces internal losses, enabling high output power with the relatively long active length of 300 μm . The EAM and DFB laser are connected to the Si waveguide through 50- μm -long InP and Si tapers. The fabricated EADFB laser exhibited 3-dB bandwidth of more than 67 GHz without power-consuming termination resistors. A side mode suppression ratio of 47 dB was confirmed at a lasing wavelength near 1260 nm. The EADFB laser demonstrated 100-Gbit/s non-return-to-zero operation. These results suggest that membrane photonic devices are promising for compact, high-speed, and low-power-consumption optical transceivers.

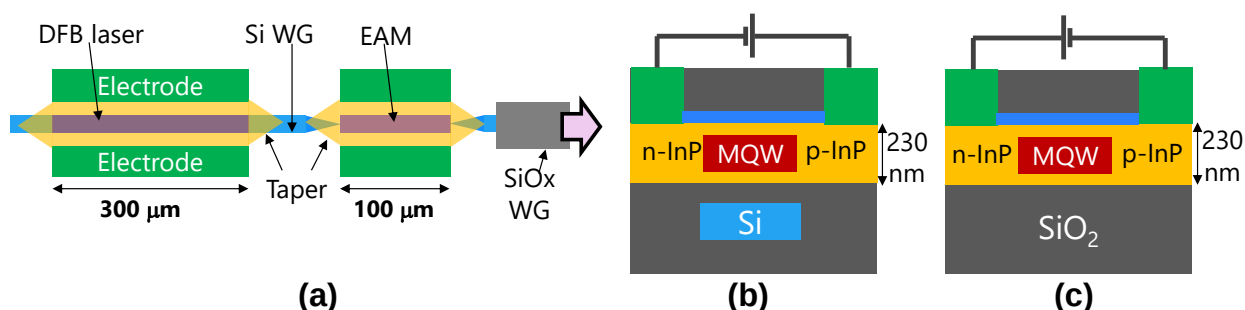


Fig. 1 (a) Top view of membrane EADFB laser, and cross-sectional images of (b) DFB laser and (c) EAM.

References

- [1] T. Hiraki, et al., Opt. Express **29** (2021) 2431-2441.
- [2] T. Hiraki, et al., J. Light. Technol. **41** (2023) 880-887.

High Power SOA-integrated DFB Lasers for Co-packaged Optics

Sumitomo Electric Device Innovations, Inc.¹, Sumitomo Electric Industries, Ltd.²

[○]Daisuke Inoue^{1,2}, Konosuke Aoyama¹, Takashi Matsui¹, Shinya Iizaka¹, Shigenori Toyoshima¹,
Shinsuke Yanagida¹, Kotaro Hoshino¹, Naoki Fujiwara², Daisei Shoji¹ and Harold Kamisugi¹

E-mail: inoue-daisuke@sei.co.jp

1. Introduction

Exponential growth of AI and machine learning applications drives the demand for interconnect bandwidth in data centers. These applications require the optical interconnect to be low-power and low-latency characteristics at the same time. Co-packaged optics (CPO) and related packaging methods are expected to significantly reduce signal attenuation caused by RF electrical losses. CPO systems typically incorporate silicon photonics (SiPh)-based transmitters along with external laser sources [1]. In this configuration, continuous-wave (CW) high-power operation is required in order to divide the output light into the multiple optical channels. We developed high power 1.3 μm semiconductor optical amplifier (SOA) integrated DFB lasers for external laser sources [2–6]. The basic idea is that the SOA section controls the output power and the DFB section offers stable single-mode operation. In this paper, we will review the recent progress in our development of high-power lasers for CPO applications.

2. Device structure and results

Figure 1 shows a schematic view of the SOA-integrated DFB laser. A light output from the DFB laser is used as a seed light to be amplified by the SOA section. The lasing wavelength and the other properties are mainly determined by the DFB laser. To suppress the facet back reflection, the SOA is terminated with a 7° tilted facet. The straight DFB laser section and the tilted SOA section are connected via a curved waveguide. A high-reflection (HR) and anti-reflection (AR) coatings are formed on the rear side of DFB laser and the front facet of SOA, respectively. DFB laser and SOA sections share identical active layers consisting of InGaAsP quantum wells. To increase the optical volume, the width of the SOA section is expanded beyond transverse single-mode conditions. The fabricated device is evaluated in a *p*-side down configuration. AlN sub-mount is used to bonding the laser chip. Figure 2 shows optical output versus SOA current characteristics measured at various temperatures. A bias current to the DFB laser is fixed at 300 mA. The device exhibits CW optical power exceeding 500 mW at 45°C, and maintains optical power above 300 mW at 70°C. The power conversion efficiency (PCE) at 45°C is 25% with optical power range from 200 to 440 mW. Spectrum measurements show side-mode suppression ratio (SMSR) of greater than 50 dB. Laser linewidth measurements revealed that the device has narrow linewidth of less than 200 kHz.

3. Conclusion

We presented a high-power SOA-integrated DFB laser as an external laser source for CPO application. The results indicate this laser is promising for high-power and power efficient external laser source.

References: [1] J. E. Johnson et al., OFC2022, Tu2D.1 (2022). [2] D. Inoue et al., OFC2023, M4C.4 (2023). [3] D. Inoue et al., OECC2024, TuC2.5 (2024). [4] K. Aoyama et al., SEI Tech. Rev., 83, 40 (2024). [5] D. Inoue et al., ISLC2024, MC2 (2024). [6] D. Inoue et al., OFC2025, W1G.7 (2025).

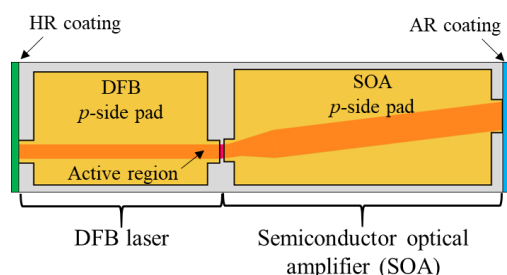


Fig. 1 Top view of an SOA-integrated DFB laser.

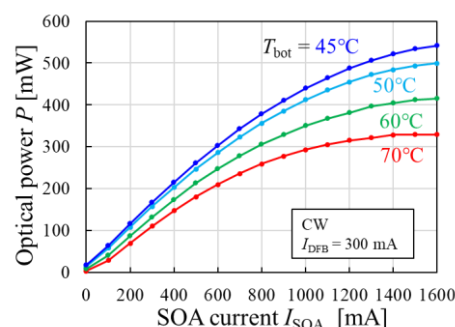


Fig. 2 Light output characteristics.

Passive Radiative Cooling Employing Vanadium Dioxide-based Metasurface

Muhammad Faizan¹, Muhammad Abuzar Baqir¹, Muhammad Saqlain¹, and Pankaj K. Choudhury^{2*}

¹Departement of Electrical Engineering, COMSATS University Islamabad, Sahiwal Campus, 57000 Pakistan

²College of Optical Science and Engineering, International Research Center for Advanced Photonics, Zhejiang University, Haining, Zhejiang 314400, P. R. China

*E-mail: pkchoudhury@ieec.org

1. Introduction

Passive radiative cooling (PRC) involves spontaneous heat emission by an object as a thermal radiation into the outer space [1] – an innovative and environmentally sustainable energy-efficient cooling technology that reduces the electrical energy consumption for cooling purposes. PRC is now in the global research limelight and various R&D approaches pivoted to PRC has been reported in the literature [2]. In the context of radiative heat transfer [3–5], the night-time radiative cooling can be achieved by attaining high emissivity of an object or surface in the mid-infrared band (8–13 μm). In the context of this scenario, vanadium dioxide (VO_2) possesses significant advantages in passive radiative cooling due to its phase-changing attributes [6]. At low temperatures (i.e., $< 68^\circ\text{C}$), VO_2 exhibits high emissivity within the atmospheric window (8–13 μm), whereas at elevated temperatures (i.e., $> 68^\circ\text{C}$), it has low emissivity but high reflectance in the solar spectrum. The potential of VO_2 in passive radiative cooling needs to be further explored for effective and practical industrial use.

This study aims at presenting the emissivity of a specially designed VO_2 -assisted metasurface and its overnight radiative cooling performance. The obtained results indicate a significant reduction in temperature, thereby determining the configuration to be of potential in PRC system applications.

2. The Design Feature

Figure 1 presents the design of the proposed metasurface-based PRC device comprising three layers. The top layer consists of periodically arranged squared VO_2 structures with the dimensions of $3 \times 3 \mu\text{m}^2$ and thickness of 1 μm ; the spacing between squared patches being $S = 4 \mu\text{m}$. The middle layer is a planar MgF_2 having a thickness of 1.5 μm , placed above a reflective tungsten (W) layer with a thickness of 0.04 μm . The unit cell period is $P = 10 \mu\text{m}$.

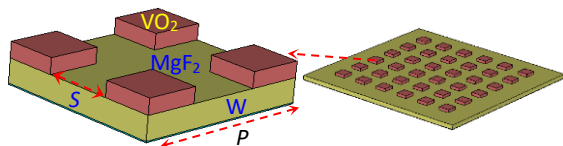


Fig. 1. Schematic of PRC device using VO_2 metasurface.

3. Results and Discussion

The PRC device captures heat from the solar light and other atmospheric sources such as the convection and conduction, and simultaneously emits the infrared radiation in a range of 8 to 13 μm . The PRC operation primarily relies on the emissivity of the device in the atmospheric window (i.e., 8–13 μm) [7], and the maximum emissivity accounts for the direct

release of energy into the space, due to which the radiative cooling takes place. During night, in absence of solar radiation, the net cooling power is independent of solar radiation [8].

Figure 2a depicts the emissivity of the device, with an average value of 97% within the 8–13 μm range, indicating a notably good performance; which is almost equivalent to the ideal blackbody radiation. As such, the proposed device efficiently emits the radiation in the atmospheric transmission window of the earth. Figure 2b shows the net cooling power (NCP) of the device for different ambient temperatures to evaluate thermal performance. It is estimated by assuming the device temperature T_s to be equal to the ambient temperature T_a ; and the difference ΔT in these is established under the condition of vanishing NCP, with $h_c = 8 \text{ W/m}^2$ [9]; h_c being the non-radiative heat transfer co-efficient. At an ambient temperature of 300K, the NCP attains a value of 149.56 W/m^2 , which leads to a temperature decrease of up to 6.722K. For ambient temperature of 310K, the NCP is 174.73 W/m^2 with a decrease of 8.388K in temperature.

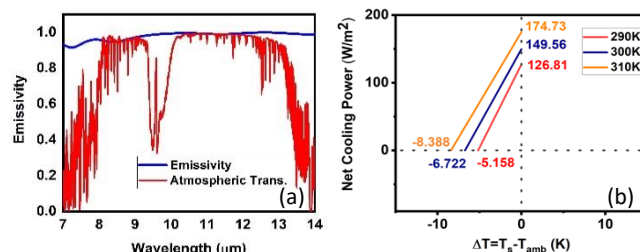


Fig. 2. (a) The emissivity plot of VO_2 -based metasurface in mid IR range and (b) the alculated values of net cooling power and ΔT at different ambient temperatures.

4. Conclusion

The VO_2 -based metasurface exhibits strong emissivity in the atmospheric window of 8–13 μm , that makes it useful in the applications of night-time PRC. Further, the NCP of this material greatly depends on the thermal ambience. With the increase in ambient temperature, the NCP and the total temperature drop also increase, which makes it useful in practical applications.

References

- [1] Z. Ding, H. Li, *et al.*, Adv. Mater. Interf. **11** (2024) 2300603.
- [2] G. Huang, *et al.* Nature Commun. **15** (2024) 3798.
- [3] Yuxuan Li, *et al.*, Nature Commun. **15** (2024), 5465.
- [4] Yongdi Dang, *et al.*, Appl. Phys. Lett. **123** (2023) 222201.
- [5] Xinran Li, *et al.*, ACS Photon. **12** (2025) 1432–1440.
- [6] J. Keum, J. Choi, S. Kim, *et al.*, Mater. Today Phys. **52** (2025) 101665.
- [7] L. Liang, S. Bai, K. Lin, *et al.*, Sustainability **16** (2024) 2346.
- [8] L. Wu, S. Chen, and C. Lin, IEEE Access **12** (2025) 181116.
- [9] H. Zhang, M. Luo, *et al.*, Opt. Mater. Express, **10** (2020) 484.

Energy Enhancement in Solar Cells Employing InP Nanorods-assisted Metasurface

M. Ghasemi¹, A. Dehzangi², A. -B. M. A. Ibrahim³, and Pankaj K. Choudhury^{4*}

¹Laser and Plasma Research Institute, Shahid Beheshti University, Daneshju Blvd., Evin, 19839 69411 Tehran, Iran
²Department of Electrical and Computer Engineering, University of Texas at Dallas, Richardson, 750803021 Texas, USA
³School of Physics, Faculty of Applied Sciences, Universiti Teknologi MARA, Shah Alam, 40450 Selangor, Malaysia
⁴College of Optical Science and Engineering, Zhejiang University, Haining, Zhejiang 314400, P. R. China
*E-mail: pkchoudhury@ieee.org

1. Introduction

In nanosized non-semiconductor materials and semiconductors (which is the InP nanorods in our case), the Mie frequency is determined by the dielectric constant and electron density of the material [1–5]. The localization of Mie resonance in nanostructured semiconductors can lead to enhanced optical and electronic properties, such as increased absorption and emission rates, and improved device performance [6]. In solar cell technology, enhancing efficiency through quantum optics is the research target for reducing the overall cost of solar power systems. In this study, we present a p-n junction-based solar cell, consisting of four layers of TiO₂, InP nanorods, Si, and Ag, to examine the influence of InP nanorods on Mie resonance, carrier generation rate, and photon current.

2. Model and Design Features

Figure 1 illustrates the schematic of a p-n junction-based solar cell having the InP nanorods in the form of a metasurface. We used a TiO₂ anti-reflector above a 1 μm thick Si layer, with the InP rods-based (20 nm thick and varying radius in a range of 5–40 nm) layer etched in between them. A 200 nm thick TiO₂ absorber layer was optimized for high absorption in the visible spectrum, maximizing the light absorption and conversion into electricity. The efficiency of energy conversion in solar cells is primarily determined by the semiconductor properties, including the ability to effectively suppress rapid electron/hole recombination. A 0.5 μm thick Ag back reflector further enhances light absorption, thereby improving the overall efficiency of the solar cell.

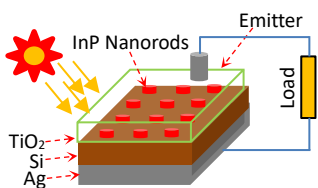


Fig. 1. Schematic of the InP nanorods-based solar cell.

We utilized the ANSYS FDTD and Charge Solvers to analyze the solar cell configuration in fig. 1. This analysis allows us to generate the current density-voltage characteristic plots. By employing the steady-state mode and applying the active electrical boundary conditions to all the defined parameters, we could accurately assess the performance of the proposed solar cell configuration.

3. Discussion

The Mie resonance characteristics, as figs. 2a and 2b depict, becomes weak for nanorods with 5 nm and 20 nm radii,

when the solar cell employs 20 nm thick InP nanorods. The use of smaller sized InP nanorods increases light scattering due to Mie resonance, resulting in an increased optical path length within the Si medium. The quantum size of the nanorods acts as a charge transport pathway, reducing the distance that charge carriers must travel before recombination.

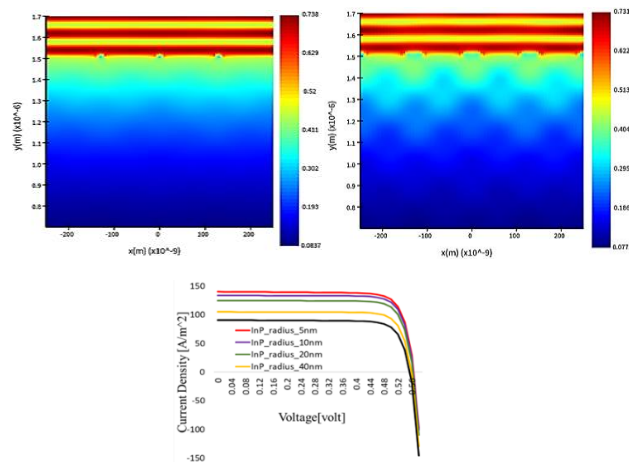


Fig. 2. 2D electric field distribution with the InP nanorods of 20 nm height and varying radii of 20 nm and 5 nm, at a wavelength of 450 nm.

Figure 2c shows the I-V curves for the solar cell. In Quadrant I of this figure, both the voltage and current are positive, indicating that the solar cell is operating in the power generation mode. The photogenerated carriers result in a free current flow even in the absence of an applied voltage. Increasing the voltage in a range of 0 to ~0.5V shows almost no change in photon generation. The current remains positive and depends solely on the incident light intensity. It enters Quadrant IV when the applied voltage cancels out the photocurrent in the voltage range of ~0.5 to 0.7V.

4. Conclusion

Using the TiO₂ antireflection layer reduces surface reflection in the solar cell. InP nanorods at the TiO₂-Si interface further minimizes the reflection loss through introducing a graded refractive index profile. Smaller sized InP nanorods enhance light scattering due to Mie resonance and act as a charge transport pathway through quantum confinement of photons, thereby pronouncing the solar energy generation.

References

[1] M. Ghasemi, *et al.*, Plasmonics **14** (2019) 1189–1195.
[2] J. Wang and Y. Jiang, Opt. Exp. **25** (2017) 5206–5216.
[3] M. Ghasemi, *et al.*, J. Nanophoton. **11** (2017) 043505.
[4] M. A. Baqir, *et al.*, IEEE Photon. Technol. Lett. **31** (2019) 735–738.
[5] M. A. Baqir, *et al.*, IEEE Access **8** (2020) 84850–84857.
[6] V. E. Babicheva and A. B. Evlyukhin, Adv. Opt. Photon. **16** (2024) 539–658.

Tailoring AgBiI₄ Lead-Free Solar Cells Using Alkali Halide Additive

Shanas Fatima^{1,2*}, Khadka B Dhruba¹, Masatoshi Yanagida¹, Sunil Kumar Singh², Yasuhiro Shirai¹

¹National Institute for Materials Science, Tsukuba, Japan

²Indian Institute of Technology (BHU) Varanasi, UP, India

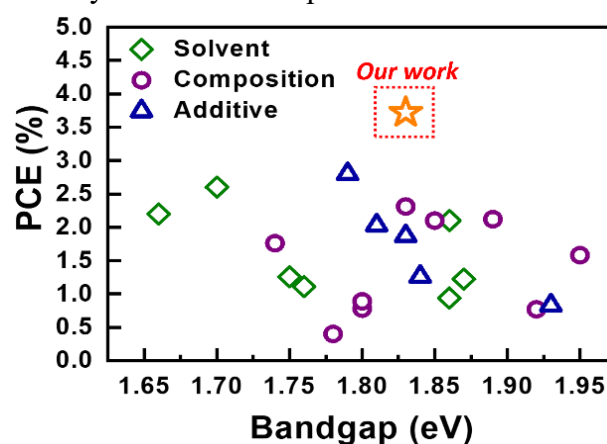
*shanasfatima.rs.phy21@itbhu.ac.in

Introduction:

Halide perovskites have demonstrated a startling power conversion efficiency (PCE) of over 26% for single junction devices. Despite having such remarkable properties, the presence of toxic lead and instability towards moisture, air, and temperature is a major limitation.¹ Ternary Ag-Bi-I materials have been explored as potential Pb-free candidates as light-absorbing materials for photovoltaic applications due to their lower toxicity and relatively high stability against air and moisture. These silver bismuth iodides are known as rudorffites.² Although rudorffites are quite stable, the efficiency of the Ag-Bi-I-based solar cell is quite low compared to the ideal value. This underscores the need for further advancements in material and transport engineering to achieve competitive performance in rudorffite-based solar cells. Other than compositional and solvent engineering, multiple reports demonstrated that additive engineering, such as inorganic halide derivatives and functional molecular additives, benefits both hybrid perovskites and rudorffites-based devices in terms of improving the kinetics of reactions and device performance.

Results: In this work, we have investigated the effect of alkali halide additive on AgBiI₄ with a bandgap of approximately 1.82 eV as a Pb-free light-absorbing material. The NaI additive regulates the crystallisation of AgBiI₄ crystals and helps in the formation of a highly compact and pinhole-free surface, leading to significantly improved AgBiI₄ film quality. The fabricated solar cell with ITO/SnO₂/AgBiI₄ NaI/poly[bis(4-phenyl) (2,4,6-trimethylphenyl) amine] (PTAA)/Ag configuration achieved a PCE of 3.72% with the introduction of the Na⁺ additive. The film with NaI additive also modulated the surface chemistry of the AgBiI₄ film by quenching the metallic content of Bi⁰ ions, which otherwise is detrimental to the device's performance. The chart (Fig.1) shows that we have achieved one of the best PCEs for rudorffite-based solar

cells³. Furthermore, non-radiative relaxations are also suppressed after the introduction of NaI, which is evidenced by increased PL intensity and PL lifetime of NaI-based films. The stability of the unencapsulated NaI additive-



based device is also better than the control device.

Figure: Summary of PCE of rudorffite-based solar cells.

Acknowledgement:

Shanas Fatima acknowledges the support from the International Cooperative Graduate Program (NIMS), Japan, and the Prime Minister Research Fellowship (PMRF), Ministry of Education, Government of India.

References:

- (1) Khadka, D. B.; Shirai, Y.; Yanagida, M.; Ryan, J. W.; Song, Z.; Barker, B. G.; Dhakal, T. P.; Miyano, K. Advancing Efficiency and Stability of Lead, Tin, and Lead/Tin Perovskite Solar Cells: Strategies and Perspectives. *Solar RRL* **2023**, 7 (21), 2300535. <https://doi.org/https://doi.org/10.1002/solr.202300535>.
- (2) Turkevych, I.; Kazaoui, S.; Ito, E.; Urano, T.; Yamada, K.; Tomiyasu, H.; Yamagishi, H.; Kondo, M.; Aramaki, S. Photovoltaic Rudorffites: Lead-Free Silver Bismuth Halides Alternative to Hybrid Lead Halide Perovskites. *ChemSusChem* **2017**, 10 (19), 3754–3759. <https://doi.org/https://doi.org/10.1002/cssc.201700980>.
- (3) Fatima, S.; Khadka, D. B.; Yanagida, M.; Singh, S. K.; Shirai, Y. Effect of Alkali-Metal Additive on Rudorffite AgBiI₄-Based Pb-Free Solar Cells. *ACS Applied Energy Materials* **2025**, 8 (7), 4601–4608.

Enhanced Luminescent Properties of Sm^{3+} -Doped Niobate-Based Phosphors for Opto-Electronic Applications

Kanishk Poria¹, Sanjana Bhatia¹, Nisha Deopa²

¹ Department of Physics, Panjab University, Chandigarh-160014 India

² Department of Physics, Chaudhary Ranbir Singh University, Jind-126102 India

E-mail: kanishk.chaudhary15@gmail.com

Phosphors are luminescent materials that emit light upon excitation by ultraviolet (UV) radiation or electron bombardment. They are composed of a host matrix doped with activator ions, which act as luminescent centers [1]. Rare-earth ions such as Eu^{3+} , Sm^{3+} , Dy^{3+} , and Tm^{3+} are commonly employed as activators due to their sharp emission characteristics.

Experimental Procedure

Samarium-doped niobate-based phosphors were synthesized via a conventional high-temperature solid-state reaction route, with varying Sm^{3+} concentrations. High-purity precursor materials were thoroughly mixed, mechanically milled, and subjected to calcination. The calcined powders were then finely ground to obtain homogenous phosphor samples. Characterization involved X-ray diffraction (XRD) to investigate the crystalline structure and steady-state photoluminescence (PL) spectroscopy to analyze luminescent behavior.

Results and Discussion

XRD patterns confirmed the formation of a filled tetragonal tungsten bronze (TTB) structure, which remained structurally stable upon the incorporation of Sm^{3+} ions. The successful substitution of Sm^{3+} for La^{3+} was attributed to the comparable ionic radii and minimal lattice distortion. Photoluminescence analysis exhibited well-defined excitation and emission transitions characteristic of Sm^{3+} . The optimal doping concentration was determined to be 7.0 mol%, beyond which luminescence intensity decreased due to concentration quenching effects. CIE 1931 chromaticity coordinates indicated high color purity in the range of 98.5%–99.0%, highlighting the potential applicability of these phosphors in optoelectronic and display technologies. This study presents a systematic approach to the development of Sm^{3+} -doped niobate phosphors with promising optical performance for commercial use.

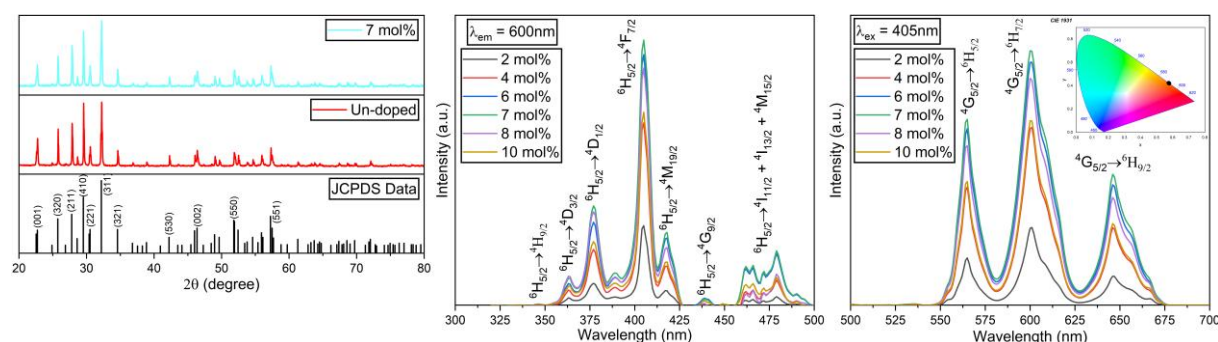


Fig 1. (a) XRD pattern. (b) PL Excitation spectra. (c) PL Emission spectra. Inset: CIE chromaticity diagram.

- [1] Poria, K., et.al, "Lumino-structural properties of Dy^{3+} activated $\text{Na}_3\text{Ba}_2\text{LaNb}_{10}\text{O}_{30}$ phosphors with enhanced internal quantum yield for w-LEDs," RSC Adv., vol. 13, pp. 11557-11568, April 2023.

Virtual Vernier Effect-Based Nano-Displacement Sensing Using Single-Cavity Interferometry

Arvind Kumar Maurya¹, and Rajan Jha^{1*}

¹ Nanophotonics and Plasmonics Laboratory, Indian Institute of Technology Bhubaneswar, Odisha, India-752050

E-mail: rjha@iitbbs.ac.in

1. Introduction

The advancement of nanotechnology has necessitated the development of highly sensitive measurement techniques capable of detecting minute displacements at the nanoscale [1]. One promising approach is the vernier effect, which leverages optical interferometry to achieve exceptional resolution and accuracy. This method is particularly advantageous in applications where precise measurements are critical, such as in materials science, biomedical devices, and micro-electromechanical systems (MEMS) [1]. In traditional vernier systems [2-3], two interferometers are used to enhance measurement precision. Whereas this proposed virtual vernier effect replicates this principle through computational techniques, allowing for the creation of a second interferometer using a single cavity interferometry setup. This innovative approach not only simplifies the measurement apparatus but also significantly improves sensitivity, achieving a remarkable resolution of 10 nm. By utilizing this compact configuration, researchers can effectively monitor nanoscale displacements with enhanced reliability and hence represent a significant step in the field of high-resolution metrology [3].

2. Methodology and Results

To achieve the virtual vernier effect, we first established a cavity interferometer setup using a gold mirror and a sharply cleaved fiber tip. In this configuration, the fiber tip acts as a second reflecting surface, exhibiting a reflectivity of approximately 4% due to Fresnel reflection. This arrangement forms a low finesse external fiber Fabry-Perot interferometer (EFFPI). To realize the vernier effect, an additional interferometer must be cascaded either in series or in parallel with the existing setup. We accomplish this virtually by generating an interference spectrum with a slightly detuned free spectral range (FSR). The creation of this virtual spectrum involves analyzing the envelopes of the fabricated interferometer's spectrum along with its FSR value. Since this interference spectrum adheres to a two-beam interference model (characteristic of low finesse FPIs), it enables the generation of another interferometric spectrum with a chosen FSR, thus allowing for controlled magnification factors and sensitivity. The optical spectra generated both experimentally and computationally are illustrated in Fig. 1(a). When these two interferometric spectra are cascaded serially, they produce the vernier effect, resulting in an envelope that is more sensitive to cavity changes than that of a single cavity interferometer. In this setup, the fabricated interferometer functions as the sensing interferometer, while the virtual spectrum serves as the

reference. To evaluate its sensitivity to nano displacement, we introduced a 10 nm change in cavity length using a nano-displacement stage. The spectra recorded before and after this displacement are shown in Fig. 1(b), which demonstrates negligible shift and thus no sensitivity to nano-displacement. To enhance sensitivity further, we formed the virtual spectrum and achieved the virtual vernier effect. The corresponding spectrum, illustrating the vernier envelope shift, is presented in Fig. 1(c), revealing a sensitivity of 37 pm/nm, an state of art for nano-displacement sensing using fiber cavity-based systems.

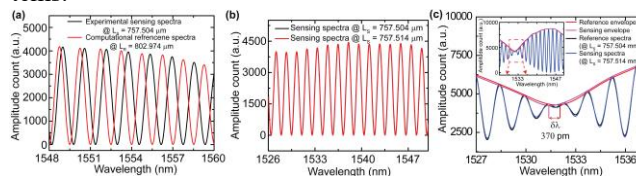


Fig. 1 (a) Optical spectrum of single cavity interferometer and virtually constructed interferometer with detuned FSR. (b) Experimentally observed single cavity interferometer's sensitivity measurement towards nano-displacement. (c) Vernier spectrum showing envelope shift corresponding to a 10 nm displacement.

3. Conclusions

In this paper, a virtual Vernier effect-based nano-displacement sensing system is demonstrated using single-cavity interferometry, achieving a resolution of 10 nm. This approach leverages the generation of a virtual Fabry-Perot (FP) cavity interferometer, which, when cascaded with a physical interferometer, produces the Vernier effect. By utilizing a virtual reference rather than a physical reference arm, the system reduces the number of optical components, resulting in lower noise, increased compactness, and improved cost-effectiveness. This streamlined setup enables enhanced measurement accuracy, making it particularly suitable for applications in nanotechnology and precision engineering.

Acknowledgements

RJ acknowledges the funding from NTTM, and NQM. AKM acknowledges fellowship from UGC.

References

- [1] T. Liu, F. Pagliano, R. van Veldhoven, V. Pogoretskiy, Y. Jiao, and A. Fiore, Nat. Commun. 11 (2020) 2407.
- [2] A. K. Maurya, K. Chatterjee, and R. Jha, Opt. Lett. 49 (2024) 3588-3591.
- [3] J. Chae, S. An, G. Ramer, V. Stavila, G. Holland, Y. Yoon, et al., Nano Lett. 17 (2017) 5587-5594.

4 JSAP-Optica Joint Symposia 2025 | 一般セッション(ポスター講演) : 4.3 Laser sources and Laser applications

[8p-P07-1~6] 4.3 Laser sources and Laser applications

[8p-P07-1]

DOPING ENGINEERING IN LEAD HALIDE PEROVSKITES FOR OPTOELECTRONIC APPLICATIONS

○(D)Ankit Sharma¹, Shaona Bose², Samit K Ray², K V Adarsh¹ (1.IISER Bhopal India, 2.IIT Kharagpur India)

[8p-P07-2]

Effect of Correlated and Uncorrelated Randomness on Localization of Polarized Light in One-dimensional Photonic Superlattice

○(D)Ashiq Kaniyandi Meethal¹, Anirban Sarkar¹ (1.NIT Calicut)

[8p-P07-3]

Highly polarized Amplified Spontaneous Emission from a D-A-D Organic Dye in CBP-Host Blended Films

○(M1)Hsin-Yi Wei¹, Ja-Hon Lin¹, Yu-Cheng Hou¹, Yin-wen Lee¹, Tzu-Chau Lin², Chihaya Adachi³ (1.Natl. Taipei Univ. of Tech., 2.Natl. Cent. Univ., 3.Kyushu Univ.)

[8p-P07-4]

Wavelength Switching in Mode-Locked Fiber Lasers via Bend-Induced Loss and Transmission Tilt Tuning

○(D)Yuanjun Zhu^{1,2}, Bowen Liu³, Maolin Dai^{1,2}, Yifan Ma^{1,2}, Shinji Yamashita^{1,2}, Sze Yun Set² (1.Tokyo Univ., 2.Tokyo Univ, RCAST, 3.Keio Univ.)

[8p-P07-5]

Broad-band yellow-green light source generated by diode-pumped Ce:YAG crystal fiber

○Yin-Wen Lee¹, Sz-Hau Chen¹, Sheng-Lung Huang², Ja-Hon Lin¹, Rui-Lun Huang¹ (1.National Taipei University of Technology, 2.National Taiwan University)

[8p-P07-6]

Band-edge lasing from a re-filled cholesteric liquid crystal polymer template with 1D photonic crystal structure

○Ja-Hon Lin, Hsuan-Li Huang¹, Yu-Tong Yang¹, Hsin-Yi Wei¹, Chiung-Cheng Huang² (1.Natl. Taipei Univ. of Tech., 2.Tatung Univ.)

DOPING ENGINEERING IN LEAD HALIDE PEROVSKITES FOR OPTOELECTRONIC APPLICATIONS

Ankit Sharma*¹, Shaona Bose², Samit K Ray², K V Adarsh*¹

¹ Department of Physics, Indian Institute of Science Education and Research, Madhya Pradesh, India, 462066

² Department of Physics, Indian Institute of Technology Kharagpur, West Bengal, India, 721302,

Email id: ankits19@iiserb.ac.in and adarsh@iiserb.ac.in

ABSTRACT

This study systematically explores the optoelectronic properties of pristine and Cu-doped CsPbI₃ nanocrystals (NCs), with a particular emphasis on their carrier thermalization dynamics and relevance to optoelectronic device performance. Pristine CsPbI₃ NCs exhibit rapid carrier thermalization attributed to a quantum bottleneck effect following above-bandgap excitation, which promotes efficient radiative recombination at the band edge, a favorable characteristic for light-emitting applications. Conversely, Cu-doped CsPbI₃ NCs display markedly slower carrier thermalization, which is beneficial for photovoltaic devices as it facilitates improved charge extraction and reduces thermalization-associated energy losses. Furthermore, femtosecond laser excitation at 400 nm with a pulse width of 120 fs, generated via second harmonic generation of the fundamental 800 nm wavelength, was employed to investigate hot carrier dynamics. Fluence-dependent transient absorption measurements revealed signatures of many-body interactions and thermalization processes. At higher excitation fluences ($\geq 150 \mu\text{J}/\text{cm}^2$), pristine CsPbI₃ nanocrystals exhibited a rapid decay component, indicative of the breakdown of the phonon bottleneck effect due to carrier-carrier scattering. In contrast, Cu-doped CsPbI₃ nanocrystals exhibited a slower thermalization profile, indicating the suppression of many-body interactions and prolonged hot carrier lifetimes. The findings highlight the key role of dopant engineering in tailoring the excited-state behavior of lead halide perovskites, providing valuable insights for the rational design of materials with targeted optoelectronic functionalities.

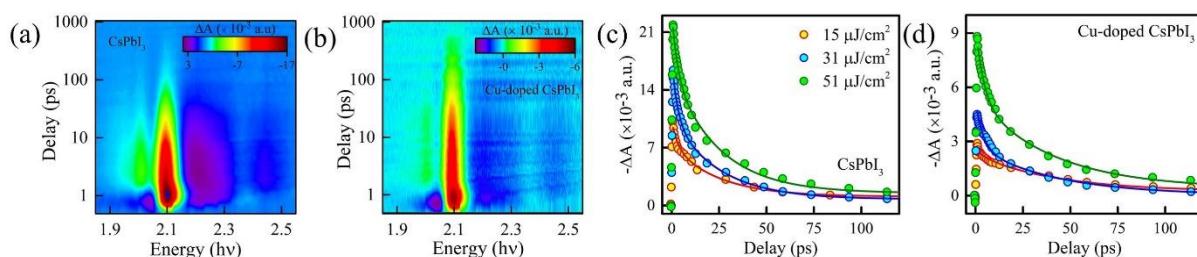


Figure 1: 2D contour plot for (a) pristine CsPbI₃ and (b) Cu-doped CsPbI₃ NCs showing excited state carrier dynamics. Temporal evolution of (c) pristine CsPbI₃ and (d) Cu-doped CsPbI₃ NCs at different fluences depict fast and slow excitonic decay, respectively.

References:

1. H. Baker, C. M. Perez, C. Sonnichsen, D. Strandell, O. V. Prezhdo, and P. Kambhampati, ACS Nano, **17** (2023) 3913.
2. A. Dutta, R. K. Behera, P. Pal, S. Baitalik, and N. Pradhan, Angew. Chem. Int. Ed., **58** (2019) 5552.
3. Y. Yang, D. P. Ostrowski, R. M. France, K. Zhu, J. Van De Lagemaat, J. M. Luther, and M. C. Beard, Nat. Photonics., **10** (2016) 53.
4. K. Miyata, D. Meggiolaro, M. T. Trinh, P. P. Joshi, E. Mosconi, S. C. Jones, F. De Angelis, and X.-Y. Zhu, Sci. Adv., **3** (2017) e1701217.
5. Richter, J. M., Abdi-Jalebi, M., Sadhanala, A., Tabachnyk, M., Rivett, J. P. H., Pazos-Outón, L. M., Gödel, K. C., Price, M. B., Deschler, F., and Friend, R. H, Nat. Commun, **8**, (2017) 376.

Effect of Correlated and Uncorrelated Randomness on Localization of Polarized Light in One-dimensional Photonic Superlattice

Ashiq K M¹ and Anirban Sarkar¹

¹Department of Physics, National Institute of Technology Calicut, Kozhikode - 673601, Kerala, India

E-mail: anirban@nitc.ac.in

1. Introduction

The photonic superlattice (SL) is an array of multiple photonic crystals (PCs), where each PC is called a subcell, and the repeating unit in the system is called a supercell. The SL structures possess multiple bandgaps and their harmonics. Since PCs are their building blocks, these systems are vulnerable to any kind of randomness present in their structural properties [1]. Here, we explore the effect of correlated and uncorrelated randomness on light localization in SL structures by monitoring the photon decay length for transverse electric (TE) and transverse magnetic (TM) polarizations of light.

2. Simulations and results

We investigate the propagation and localization of light in one-dimensional (1D) random SL structures, consist of four subcell and four supercells, using the transfer matrix method [2]. The subcells are quarter wave stacks having fundamental bandgap centered around 580 nm and 500 nm respectively. Since the random structures generated at each instant are different, an ensemble-averaged decay length (ξ) of 1000 structures are computed for correlated and uncorrelated disorder using the intensity function, $I(x) = I_0 e^{-x/\xi}$ [3]. Figures 1 and 2 shows the decay

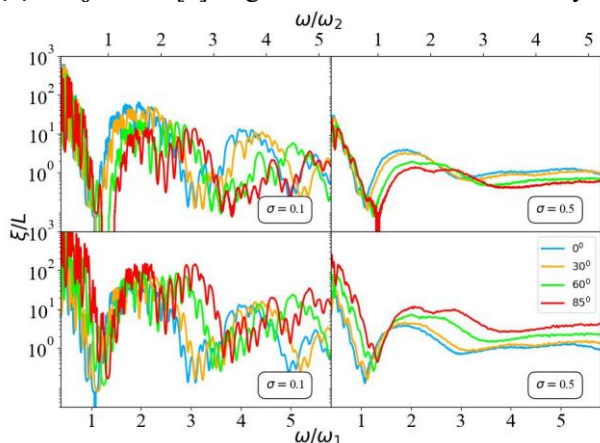


Fig. 1: Spectra of averaged decay length of uncorrelated random SLs with the strength of randomness as 10%, and 50%. ω_1 and ω_2 are the central frequencies of fundamental bandgaps of the constituent PCs. The first row is for TE polarization while the second row is for TM polarization.

length of electromagnetic waves with TE and TM polarizations for uncorrelated and correlated random systems respectively. The light localization is better within the bandgap region and much worse outside of the bandgap in the weakly randomized regime. As the randomness increases, the systems evolve to have a better localization as it reaches 50% strength of randomness. The evolution

of light localization is much faster in the case of correlated random systems. The localization length reaches close to the length of the structure at higher frequencies because the randomness is accumulated along the correlated system. The mode of polarization also has effect on light localization. The TM polarized light, irrespective of type and strength of randomness, has lower localization than the TE polarized light at all frequencies. This variation in localization of light is due to the dependence of Fresnel coefficients on the polarization.

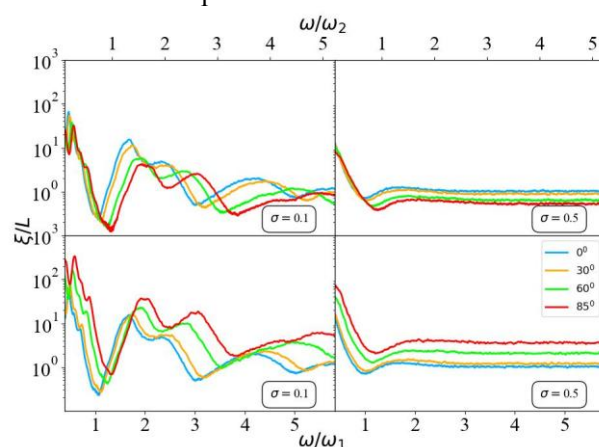


Fig. 2: Spectra of averaged decay length of correlated random SLs with the strength of randomness as 10%, and 50%. The first and second rows are for TE and TM polarizations respectively.

3. Conclusions

We have investigated the effect of correlated and uncorrelated randomness in the light localization in SL structures for TE and TM polarized light. Randomness in the periodic systems causes degradation of bandgap but it can be used to achieve better light localization. The light localization depends on mode of polarization, strength of randomness as well as type of randomness. The systems with correlated randomness are more vulnerable against randomness compared to the uncorrelated systems. Also, the TE polarized light has better localization at higher incident angles. The results would be useful for developing lasers with random cavity.

Acknowledgements

SERB (Grant: SRG/2023/001940), NIT Calicut (Grant: NITC/(R&C)/2023-24/FRG/Phase III/(9)).

References

- [1] I. S. Panyae *et al.*, Appl. Opt. 60 (2021) 1943.
- [2] X. Jiang and C. M. Soukoulis, Phys. Rev. B 59 (1999) 6159.
- [3] S. F. Liew and H. Cao, J. Opt. 12 (2010) 024011.

Highly polarized Amplified Spontaneous Emission from a D–A–D Organic Dye in CBP-Host Blended Films

Hsin-Yi Wei,¹ Ja-Hon Lin,^{1,*} Yu-Cheng Hou,¹ Yin-wen Lee,¹ Tzu-Chau Lin^{2,*}, Chihaya Adachi^{3,*}

1. Department of Electro-Optical Engineering, National Taipei University of Technology, Taipei 106, Taiwan
 2. Department of Chemistry, National Central University, Taoyuan City 32001, Taiwan
 3. Center for Organic Photonics and Electronics Research (OPERA), Kyushu University, Fukuoka 819-0395, Japan
- jhlin@ntut.edu.tw, tclin@ncu.edu.tw, adachi@cstf.kyushu-u.ac.jp

Since the first demonstration of lasing using Rhodamine 6G doped in polymethyl methacrylate (PMMA) in 1967[1], organic solid state lasers have become a great interest topic. Compared with conventional chromophores, the chromophore with donor-acceptor-donor (D-A-D) structures exhibit superior properties [2], such as excellent solution-processability favorable film-forming capability, high fluorescence efficiency, shorter lifetime, and the wide range of emission wavelength tunable possibility [3]. To mitigate aggregation-caused quenching (ACQ) in the solid state, 4,4'-Bis(9H-carbazol-9-yl)biphenyl (CBP) is commonly used as a host material in blended films to enhance emission efficiency through the Förster resonance energy transfer (FRET) effect. However, their polarization characteristics have rarely been discussed. In this study, we investigate the polarization characteristics of ASE from blended films by doping a self-synthesized D–A–D skeleton organic dye (2DFL-2Tp-PT-C6) into CBP.

Here, the blend films were fabricated by dissolving the different concentrations (3.0 ~ 12.0 wt%) of dye with CBP in chloroform and spin-coated onto pre-cleaned glass substrates. Figure 1(a) shows the molecular structure of chromophore, consisting of a bis(4-methoxyphenyl)amino and 2-hexyl-2H-[1,2,3]triazolo[4,5-c]pyridine as the core and bis(4-methoxyphenyl) amino (diphenyl-amino groups) as acceptor. The absorption and PL emission spectra of the chromophore in solution (toluene, 10^{-3} M), shown at the Fig. 1(b), exhibit an absorption peak at 484 nm, attributed to intermolecular charge transfer (ICT) from the donor to the acceptor, and a PL emission peak at 547 nm. Figure 1(c) shows the setup used to study ASE and its polarization behavior, where a 337.1 nm nitrogen laser (10 Hz) was focused onto the sample using a cylindrical lens ($f = 75$ mm). Side-emission spectra were collected using a monochromator (iHR320, Horiba Inc.) equipped with CCD detector (Syncerity, Horiba Inc.). In order to confirm the polarization of ASE, a linear polarizer is used in front of fiber tip.

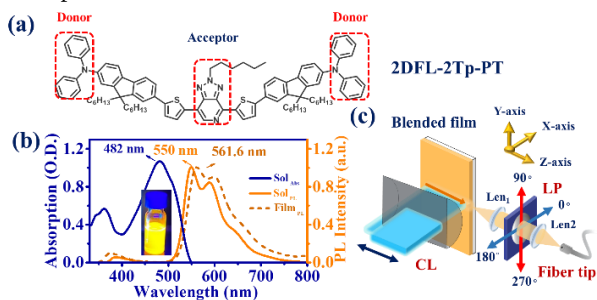


Fig.1 (a) molecular structure of 2DFL-2Tp-PT-C6, (b) Absorption and PL spectrum of dye in solution phase (inset: photo of dye solution), (c) the setup of side emission from blended solid-state film

Owing to the re-absorption, the ASE peak wavelength of the blended film shifts from 597 nm to 605 nm as the dye doping concentration increases in Fig. 2(a). Figure 2(b) shows the peak intensity of ASE in the solid-state film as a function of pump fluence, which is used to determine the threshold via bilinear fitting. Due to the spectral overlap between the PL of CBP and the absorption of the chromophore, the ASE threshold in the solid film is significantly reduced compared to that in the solution phase ($\sim 440 \mu\text{J cm}^{-2}$), due to efficient FRET. As the dye concentration decreases from 12.0 wt% to 3.0 wt%, the threshold of the blend film further decreases by a factor of three, attributed to improved film quality and reduced light scattering. The polar plot in Fig. 2(c) shows the output intensity of ASE as a function of rotation angle θ of LP relative to x-axis. The dumbbell shape indicates the linear polarization with higher degree of polarization (DOP) around 93.4% that can be attributed to the gain guiding effect.

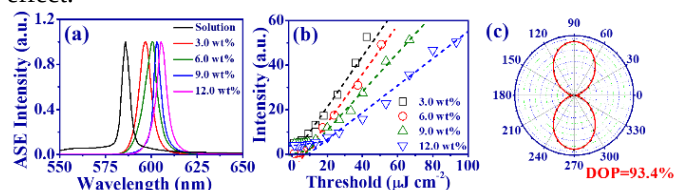


Fig.2 (a) ASE from blended film with different concentration of dye, (b) in-out relation of blended film with different concentration of dye.

In conclusion, we investigated ASE performance of D-A-D dye blended with CBP matrix to achieve a minimum threshold of $7.03 \mu\text{J cm}^{-2}$ at 3.0 wt% doping because of the FRET effect and better film quality. Besides, the higher polarized ASE from solid film with DOP around 93.4% is attributed to the gain-guiding effect.

Acknowledgement

This work was supported by the National Science Council of Taiwan, Republic of China, under grants NSC 113-2112-M-027-001- and NSTC 113-2221-E-027-038.

Reference

1. B. Soffer, and B. McFarland, "Continuously tunable, narrow - band organic dye lasers," *Applied physics letters* **10**, 266-267 (1967).
2. T.-C. Lin, S.-T. Cho, C.-L. Wu, N. E. Setyatama, P.-H. Tung, B.-Y. Hung, J.-H. Lin, P.-E. Jan, P.-H. Tsai, and H.-W. Lin, "Dual-state emission and two-wavelength amplified spontaneous emission behaviors observed from symmetric dyes based on functionalized fluorene and benzotriazole units," *Chemical Communications* **60**, 5948-5951 (2024).
3. X. Tang, Y.-T. Lee, Z. Feng, S. Y. Ko, J. W. Wu, V. Placide, J.-C. Ribierre, A. D'Aléo, and C. Adachi, "Color-tunable low-threshold amplified spontaneous emission from yellow to near-infrared (NIR) based on donor-spacer-acceptor-spacer-donor linear dyes," *ACS Materials Letters* **2**, 1567-1574 (2020).

バンド損失および透過傾斜の調整による波長切替可能なモードロックファイバレーザ

Wavelength Switching in Mode-Locked Fiber Lasers via Bend-Induced Loss and Transmission Tilt Tuning

東大工¹, 東大先端研², 慶応義塾³ ○(D)朱元軍^{1,2}, 柳博文³, 戴茂林^{1,2}, 麻一凡^{1,2}
山下真司^{1,2}, セットジイヨン²

Tokyo Univ.¹, RCAST, Tokyo Univ.², keio univ.³ ○Yuanjun Zhu^{1,2}, Bowen Liu³, Maolin Dai^{1,2}

Yifan Ma^{1,2}, Shinji Yamashita^{1,2}, Sze Yun Set²

E-mail: yuanjunzhu@g.ecc.u-tokyo.ac.jp

We experimentally demonstrate a wavelength-switchable mode-locked fiber laser by employing a bent section of polarization-maintaining fiber (PMF) to introduce controlled intra-cavity loss and transmission spectral tilt. The fiber bending modifies both the insertion loss and the effective gain profile through transmission shaping, enabling selective lasing at different wavelengths. This provides a passive and compact approach for wavelength switching without the need for active components or complex filters.

Figure 1(a) shows the measured and fitted bend loss as a function of bending diameter. The steep increase in loss for tight bending (<10 mm) provides a straightforward mechanism to suppress certain wavelength components. More importantly, the transmission spectrum is also wavelength-dependent under bending. Figure 1(b) presents simulated transmission tilt for various bend diameters, showing increasing spectral slope and attenuation as the bend becomes tighter. [1, 2] These features were also confirmed experimentally in Fig. 1(c), where the transmission curve under different bend diameters exhibits clear spectral shaping effects.

We applied this mechanism to an all-PM mode-locked ring cavity. Without bending, single-wavelength operation at 1558 nm is observed. Tight bending (~6 mm) suppresses this mode and enables operation at 1532 nm. For intermediate bending (~9 mm), dual-wavelength mode-locking at 1532 and 1554 nm is achieved, with a repetition-rate offset of ~1.1 kHz due to group delay mismatch. This demonstrates tunable wavelength selection as well as dual-wavelength generation using a single passive control element.

This technique offers a compact and cost-effective solution for wavelength-switchable and dual-wavelength ultrafast sources, compatible with polarization-maintaining cavity designs and promising for dual-comb applications.

Reference:

- [1] Dietrich Marcuse, "Curvature loss formula for optical fibers," *Opt. Soc. Am.* **66**, 216-220 (1976).
- [2] R. Renner, "Bending losses of coated single-mode fibers: A simple approach," *Opt. Lett.* **19**, 1994.

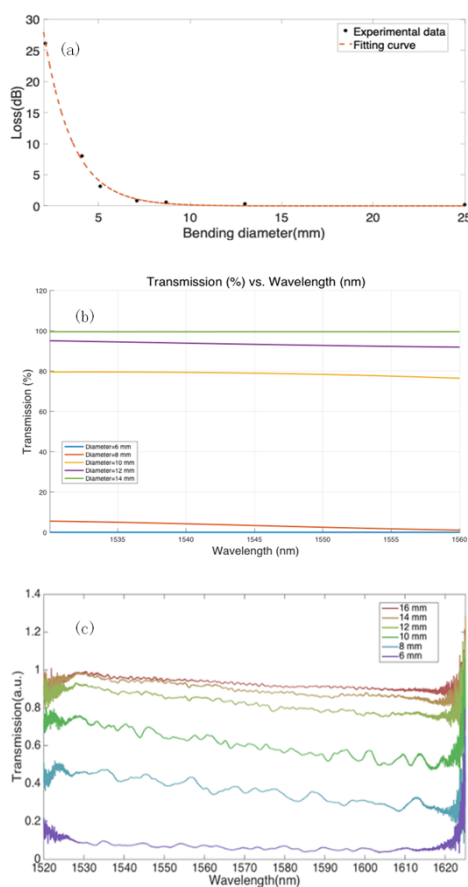


Figure 1. (a) Bend loss vs. bending diameter (experimental data and fitting curve). (b) Simulated transmission vs. wavelength for different bend diameters. (c) Measured spectral transmission under different bend diameters.

Broad-band yellow-green light source generated by diode-pumped Ce:YAG crystal fiber

Yin-Wen Lee^{1,*}, Sz-Hau Chen¹, Sheng-Lung Huang², Ja-Hon Lin¹, and Rui-Lun Huang¹

¹Department of Electro-optical Engineering, National Taipei University of Technology, 106, Taiwan

²Graduate Institute of Photonics and Optoelectronics, National Taiwan University, 106, Taiwan

Email:ywlee@ntut.edu.tw

Introduction

Optical Coherence Tomography (OCT) is a non-invasive imaging technique providing micrometer-scale resolution [1]. Higher axial resolution can be achieved with broadband light sources, and performance is further enhanced in visible-light OCT (vis-OCT), which offers submicron resolution and superior contrast for superficial tissues. However, the development of suitable broadband sources for vis-OCT remains a challenge. Conventional supercontinuum sources are often costly and noisy, while superluminescent diodes have limited spectral coverage in the critical yellow-green range. To address this gap, we demonstrate a high-brightness yellow-green light source utilizing a novel Ce:YAG crystal fiber. This approach offers key advantages, including high luminance, excellent thermal stability, and a smooth, peak-free spectral profile that is essential for high-quality imaging.

Experimental setup

The experimental setup is illustrated in Fig. 1. A 440nm semiconductor laser with a maximum output power of 600 mW was employed as the pump source. The active medium was a 10.45 mm-long, single-clad Ce³⁺:YAG crystal fiber fabricated in-house using the laser-heated pedestal growth (LHPG) method [2]. The fiber featured a 60μm core and a 180μm cladding diameter. Before entering the fiber, the pump beam was passed through a 490nm short-pass filter and a 450nm band-pass filter to eliminate wavelengths above 520nm. Two short-focal-length lenses were used to efficiently couple the pump light into the fiber core and to collimate the generated broadband emission. Finally, the output power and spectrum were measured using a power meter (Thorlabs, PM100USB-S405C) and a spectrometer (Ocean Optics, USB2000).

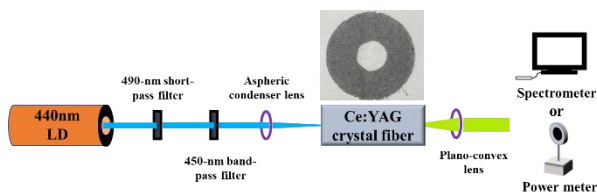


Fig.1. Schematic of the experimental setup. The inset shows the end face of the Ce:YAG fiber sample.

Experimental results and analysis

Figure 2 shows the fluorescence power and emission spectrum of the broadband yellow-green light source. At a maximum pump power of 600 mW, the source produced 16.9 mW of fluorescence power, corresponding to an optical-to-optical efficiency of 2.7%. The output spectrum has a central wavelength, λ_0 , at 552 nm with a full-width-half-maximum (FWHM) bandwidth, $\Delta\lambda$, of 112.3 nm. Notably, despite a slight wavelength redshift observed in the pump laser at high power, the output power curve remained linear and was stable over several hours of continuous operation. These characteristics make the source highly suitable for OCT. The theoretical axial resolution in OCT, δz , is determined by the source's spectral properties according to the equation:

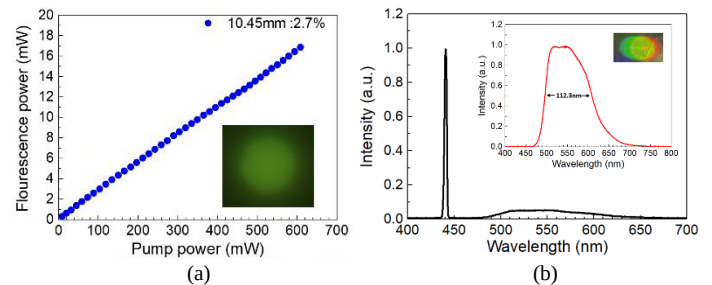


Fig.2 The measured (a) fluorescence power and (b) spectrum generated from the Ce: YAG crystal fiber.

$$\delta z = 0.44 \lambda_0^2 / \Delta\lambda \quad (1)$$

using the measured values, the axial resolution δz is calculated to be 1.2 μm. In addition, this light source exhibits high spatial mode quality, low background noise, and a Gaussian-like spectrum, which allows for low image pixel crosstalk [3].

Furthermore, a white light source can be formed by combining the emitted yellow-green fluorescence with the 10.2% residual blue pump light. Given the fiber's core and cladding refractive indices of 1.835 and 1.52, respectively, the combined 78.1 mW output yields a total luminous flux of 15.2 lm, composed of 8.06 lm from the yellow-green emission and 7.22 lm from the residual blue light. For an estimated solid angle (Ω) of 6.283, this corresponds to a luminance of 8.3×10^8 cd/m².

Conclusions

We have demonstrated a broadband yellow-green light source based on a Ce: YAG crystal fiber. The source produced a maximum output power of 16.9 mW centered at 550 nm, achieving an optical-to-optical efficiency of 2.7% and a broad FWHM bandwidth of 112.3 nm. The source's high brightness is advantageous for high-resolution visible OCT. Furthermore, by incorporating the residual blue pump light, the system can function as a white light source, generating a high luminous flux of 15.2 lm and a luminance of 8.3×10^8 cd/m².

Acknowledgement

This work was supported by the National Science and Technology Council, Taiwan, under grants NSTC 113-2221-E-027-038, 113-2112-M-027-001, and 110-2634-F-002-031.

Reference

- [1] D. Huang, E. A. Swanson, C. P. Lin, J. S. Schuman, W. G. Stinson, W. Chang, M. R. Hee, T. Flotte, K. Gregory, C. A. Puliafito, and J. G. Fujimoto, "Optical coherence tomography," *Science*, 254, 1178 (1991).
- [2] K. Y. Huang, K. Y. Hsu, D. Y. Jheng, W. J. Zhuo, P. Y. Chen, P. S. Yeh, and S. L. Huang, "Low-loss propagation in Cr⁴⁺:YAG double-clad crystal fiber fabricated by sapphire tube assisted CDLHPG technique," *Opt. Express* 16, 12264 (2008).
- [3] C. C. Tsai, Y. S. Lin, T. H. Chen, Y. T. Wang, W. Chang, P. K. Hsu, Y. H. Chang, E. Sun, and S. L. Huang, "Ultrahigh Resolution Optical Coherence Tomography via Ce³⁺:YAG Double-clad Crystal Fiber Source" in *Conference on Lasers and Electro-Optics* (2010).

Band-edge lasing from a re-filled cholesteric liquid crystal polymer template with 1D photonic crystal structure

Ja-Hon Lin,^{1,*} Hsuan-Li Huang,¹ Yu-Tong Yang,¹ Hsin-Yi Wei,¹ Chiung-Cheng Huang^{2,*}

¹Department of Electro-Optical Engineering, National Taipei University of Technology, Taipei 106, Taiwan

² Department of Chemical Engineering and Biotechnology, Taipei 104, Tatung University

jhlin@ntut.edu.tw, chchhuang@gm.ttu.edu.tw

In recent years, there has been a growing demand for flexible and stretchable optical devices. However, the flexibility of conventional cholesteric liquid crystal (CLC) devices [1] is inherently limited by the use of rigid ITO-coated glass substrates. Fortunately, this limitation has been successfully addressed through the development of free-standing cholesteric liquid crystal polymer (CLCP) films. In parallel, band-edge lasers have been demonstrated in stretchable cholesteric liquid crystal elastomers (CLCEs) [2] and flexible CLCP films [3] by incorporating organic dyes as gain media. In this work, we demonstrate a flexible band-edge laser by embedding an organic dye into a nanoporous CLCP (DE-NPCLCP) film.

The fabrication process of the DE-NPCLCP film is illustrated in Fig. 1. First, a nanoporous CLC (NPCLCP) template was prepared using a mixture of the nematic diacrylate monomer RM257, nematic liquid crystals (NLCs) E7, chiral dopant S811, and a photoinitiator. The mixture was heated and stirred on a hotplate using a magnetic stir bar. It was then infiltrated into a custom-fabricated liquid crystal cell via capillary action. Photopolymerization was carried out by exposing the cell to ultraviolet (UV) light, forming a polymerized CLCP film. After curing, the film was immersed in ethanol to extract the unreacted E7, resulting in a nanoporous CLCP (NPCLCP) template. This NPCLCP film was then immersed in a PM597 dye solution, allowing the dye to infiltrate the nanoporous structure. After removing the substrate, a flexible DE-NPCLCP film was obtained. Band-edge lasing from the sample was achieved by optically pumping it with a 532 nm Q-switched Nd:YAG laser. The laser pulses had a repetition rate of 10 Hz and a pulse duration of 2.2 ns. The pump beam was focused onto the sample using a lens with a 10 cm focal length. The emitted band-edge lasing signal from the dye-refilled CLCP template was collected using a fiber tip and analyzed with a spectrometer.

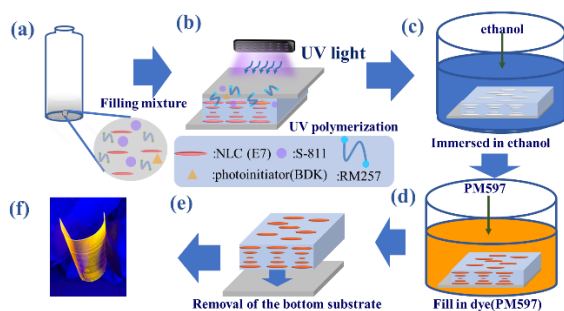


Fig.1 Manufacturing process of the DE-NPCLCP film, including: (a) mixing of LC components, (b) UV-induced photopolymerization, (c) immersion in ethanol to extract unreacted LC, (d) dye infiltration, (e) substrate removal, and (f) resulting flexible DE-NPCLCP film (photograph shown).

To verify the presence of the photonic bandgap (PBG), the transmittance spectrum of the pristine CLCP film reveals a distinct transmission dip, indicating the successful formation of a PBG. Theoretically, the short- and long-wavelength edges of the PBG are determined by the extraordinary (n_e) and ordinary (n_o) refractive indices, as well as the helical pitch (Λ) of the cholesteric structure. Figure 2a shows the lasing spectrum (in pink) of the pristine DE-NPCLCP film under excitation by a Q-switched laser. Band-edge lasing is observed at the short-wavelength edge of the PBG, which can be attributed to the high density of optical states and zero group velocity at the band edge. Figure 2b presents the corresponding variation in lasing peak intensity as a function of excitation pump energy. Based on the intersection of two linear fits, the lasing threshold is determined to be 1.29 $\mu\text{J}/\text{pulse}$. The inset shows the conical far-field emission pattern of the band-edge laser projected onto a screen.

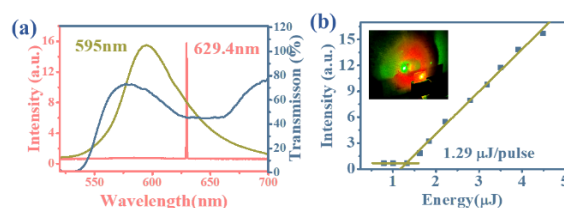


Fig.2 (a) Transmission spectrum (blue), lasing spectrum (pink) of the DE-NPCLCP film, and photoluminescence (PL) spectrum of PM597. (b) Lasing peak intensity as a function of pump energy. (Inset: projected lasing pattern on the screen).

We demonstrated band-edge lasing from a free-standing dye-embedded nanoporous cholesteric liquid crystal polymer (DE-NPCLCP) film. Upon excitation by a frequency-doubled Q-switched laser, the DE-NPCLCP film exhibited band-edge lasing with a peak wavelength of approximately 629.4 nm. The beam steering properties of the laser emission will be further investigated by applying mechanical stress in future work.

Acknowledgement

This work was supported by the National Science Council of Taiwan, Republic of China, under grants NSC 113-2112-M-027-001- and NSTC 113-2221-E-027-038.

Reference

- [1] Lin, J.-H.; Shih, W.-C.; Xie, Z.-H.; Tsay, S.-Y.; Huang, C.-C. Thermal control band edge lasing toward near IR from dye-doped cholesteric liquid crystal: Relatively stable operation at high temperatures. *Opt. Laser Tech* 2024, 174, 110592 (2024).
- [2] Finkelmann, H.; Kim, S. T.; Munoz, A.; Palffy-Muhoray, P.; Taheri, B. Tunable mirrorless lasing in cholesteric liquid crystalline elastomers. *Adv. Mater.* 13, 1069–1072 (2001).
- [3] Matsui, T.; Ozaki, R.; Funamoto, K.; Ozaki, M.; Yoshino, K. Flexible mirrorless laser based on a free-standing film of photopolymerized cholesteric liquid crystal. *Appl. Phys. Lett.*, 81, 3741–3743 (2002).

[9a-N203-1~9] 4.3 Laser sources and Laser applications

[9a-N203-1]

[JSAP-Optica Joint Symposia Invited Talk] Electro-Optic Frequency Comb based fast and precise LiDAR

○Guanhao Wu¹, Weiwei Yang¹, Xingyu Jia¹ (1.Tsinghua Univ.)

[9a-N203-2]

Dual-comb interferometric vibrometry for absolute vibration amplitude measurement with picometer precision

○Shinichi Watanabe¹, Kazuki Maezawa¹, Riku Shibata¹ (1.Keio Univ.)

[9a-N203-3]

Realization of a Stable Broadband 2 μm Supercontinuum Light Source and Its Application to Highly Sensitive OCT○(D)Rongjie Zhang¹, Jacob Kokinda¹, Shotaro Kitajima¹, Norihiko Nishizawa¹ (1.Nagoya Univ.)

[9a-N203-4]

Accurate Multi-Gas Thermometry via Dual-Comb Spectroscopy Based on Integrated Absorbance

○Naoki Takeshi¹, Ryusei Uchiyama¹, Takumi Takahoshi¹, Yoshiaki Nakajima¹ (1.Toho Univ.)

[9a-N203-5]

THz-TDS System Using a Mechanically Shared Dual-Comb Fiber Laser

○Takumi Takahoshi¹, Naoki Takeshi¹, Masahiko Tani², Hideaki Kitahara², Takeshi Yasui³, Shinichi Matsubara⁴, Yoshiaki Nakajima¹ (1.Toho Univ., 2.Univ. Fukui, 3.p-LED, 4.JASRI)

[9a-N203-6]

Integrating Raman spectroscopy and DFT to probe the photophysics of optically active materials

○(DC)Elkhansa Elbashier^{1,2,3}, Keith Gordon^{1,2,3}, David Officer⁴, Pawel Wagner⁴ (1.University of Otago, 2.Dodd Walls Centre, 3.MacDiarmid Institution, 4.University of Wollongong)

[9a-N203-7]

[JSAP-Optica Joint Symposia Invited Talk] Low-noise frequency synthesis and terahertz wireless communication driven by compact turnkey Kerr combs

○Zhenda Xie¹, Kunpeng Jia¹, Chenye Qin¹, Xinwei Yi¹, Zexing Zhao¹, Shining Zhu¹ (1.Nanjing University)

[9a-N203-8]

Frequency-multiplexed photonic reservoir computing using single soliton microcomb

○Jonathan Cuevas¹, Yue Hu², Baoqi Shi², Jinqiu Liu^{2,3}, Kaoru Minoshima^{4,5}, Naoya Kuse⁵ (1.Tokushima Univ., 2.IQA, 3.USTC, 4.UEC, 5.pLED)

[9a-N203-9]

Fiber cavity implementation of a wavelength-tunable, repetition-rate-fixed fiber optical parametric oscillator

○Qingcheng Song¹, Shun Takahashi¹, Yasuyuki Ozeki^{1,2} (1.EEIS, UTokyo, 2.RCAST, UTokyo)

Electro-Optic Frequency Comb based fast and precise LiDAR

Tsinghua Univ.¹, °Guanhao Wu¹, Weiwei Yang¹, Xingyu Jia¹

E-mail: guanhaowu@mail.tsinghua.edu.cn

1. Introduction

Frequency-Modulated Continuous Wave (FMCW) LiDAR is a high-sensitivity 3D ranging technology. The resolution, acquisition rate, and accuracy of FMCW systems are limited by the laser's tuning range, Fourier transform processing, and lack of frequency traceability, respectively [1–2].

Here, based on the unique advantages of electro-optic frequency combs (EOFCs), such as high sideband power, broad bandwidth, and fast tunable repetition rate, we optimize the FMCW system. This is achieved by using a pair of frequency-shifted EOFCs for swept lasers nonlinearity calibration, employing EOFCs with slightly different repetition frequencies for equivalent large bandwidth, and enabling absolute distance measurement at a gigahertz acquisition rate through an EOFC with high modulation depth.

2. Nonlinear calibration for FMCW LiDAR

Firstly, we present a calibration method for swept lasers using a pair of frequency-shifted EOFCs generated by cascading electro-optic modulators (Fig. 1A, 1B). The system achieves 0.61 μm precision at a 1 kHz rate (Fig. 1C), with FMCW ranging results compared before and after calibration (Fig. 1D).

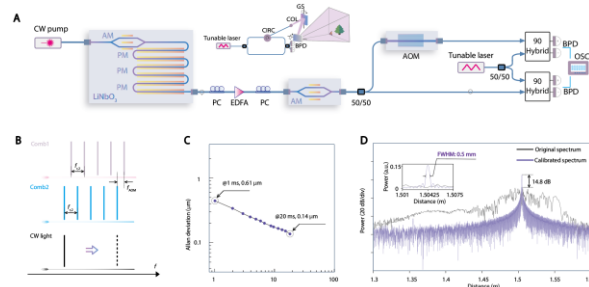


Fig. 1 Setup and results for nonlinear calibration.

3. Resolution-Enhanced FMCW LiDAR System

Secondly, we present a method using integrated lithium niobate on insulator (LNOI) EOFCs as the

light source for the FMCW LiDAR system (Fig. 2A). This approach achieves a resolution of 1 mm, five times higher than conventional FMCW LiDAR with the same scan range (Fig. 2B), and a measurement accuracy of 27.3 μm (Fig. 2C).

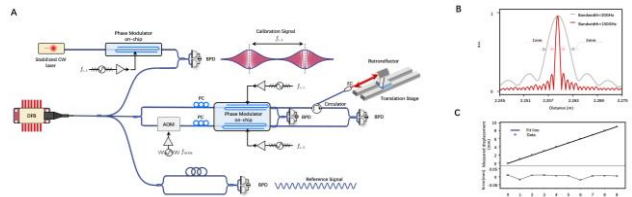


Fig. 2 Setup and results for resolution enhancement.

4. Distance measurement with 1.79-GHz acquisition rate

Finally, we demonstrate a precise distance measurement method using a repetition rate-modulated frequency comb (RRMFC) with a gigahertz acquisition rate (Fig. 3A). The RRMFC resolves distance in the time domain, achieving 1.79 GHz (Fig. 3B) and 15.2 μm Allan deviation (Fig. 3C) at 14.9 μs averaging. Using the RRMFC, we achieved high-speed 3D imaging with millimeter-level precision (Fig. 3D).

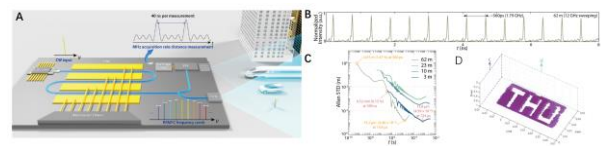


Fig. 3 Setup and results for RRMFC LiDAR.

Acknowledgments

This work was supported by National Natural Science Foundation of China (52327805, 62227822).

References

- [1]. Burdick, J. S. *Radar Signal Analysis*, Prentice-Hall, 1968.
- [2]. Royo, S. & Ballesta-Garcia, M. "An overview of lidar imaging systems for autonomous vehicles," *Appl. Sci.* **9**, 4093 (2019).

Dual-comb interferometric vibrometry for absolute vibration amplitude measurement with picometer precision

Shinichi Watanabe¹, Kazuki Maezawa¹, and Riku Shibata¹

¹ Keio University

E-mail: watanabe@phys.keio.ac.jp

1. Introduction

Recently, energy conversion processes between quasiparticles with different forms of energy have attracted growing attention. In particular, surface vibrations, or surface phonons, offer unique advantages such as long lifetimes and long propagation lengths. These properties make them ideal candidates for coupling with other degrees of freedom, such as magnons, enabling magnon-mediated excitations to persist over extended distances. Against this background, precise measurement of surface-vibration profiles is demanded, because it is essential for accurately sensing the underlying energy-conversion processes.

Here, we show that dual-frequency-comb interferometry is an ideal tool for this task, offering picometre-level determination of surface-vibration profiles and thereby accelerating studies of energy-conversion phenomena such as magnon-phonon coupling.

2. Methods and results

One major advantage of optical-frequency-comb technology is its ability to transfer the stability of a microwave reference to the optical domain, thereby providing a highly accurate optical-frequency standard [1]. In addition, dual-comb interferometry allows nanometer-level absolute-distance measurements over long distances by combining time-of-flight information with optical-phase comparison [2]. We have applied dual-comb interferometry to the measurement of absolute vibration amplitudes of the surface vibration and have pushed the axial precision to the picometer level [3], surpassing the performance of conventional absolute-distance techniques.

Figure 1(a) illustrates the operating principle of our dual-comb vibrometry [3]. A pulse from one of the two optical frequency combs is split into two paths—Beam 1 and

Beam 2—which reflect from the sample surface at different times, corresponding to the vibration's peaks and troughs induced by the surface acoustic wave (SAW) propagation. By comparing the optical phases of Beam 1 and Beam 2 with dual-comb interferometry, we determine their absolute displacement difference. The key to achieving picometer-level precision is that the two beams share the same optical path but propagate in opposite directions within a Sagnac geometry, greatly suppressing the effect of vibrations of the optical components. Figure 1(b) plots the displacement difference between Beam 1 and Beam 2 versus position [3], clearly revealing the sinusoidal oscillation profile of the surface phonon vibration.

This high-precision surface-vibrometry technique can be leveraged to probe magnon-phonon coupling, where the energy of surface phonons is transferred to magnons [4]. We are presently constructing a fiber-based Sagnac interferometer [5], which will allow dual-comb vibrometry to be integrated seamlessly into more advanced experiments.

3. Conclusions

We have developed a dual-comb-based absolute vibrometry technique that maps surface-vibration profiles with picometer precision. This capability will greatly advance investigations of energy-conversion processes mediated by surface phonons.

Acknowledgements

We would like to thank Ms. Iwasaki and Prof. Okano for their collaboration during the initial stage of this study. This work was partially supported by JSPS KAKENHI (Grant Numbers 25H02153, 24K21743, and 23K26165), JST CREST (JPMJCR19J4), and MEXT Q-LEAP (JPMXS0118067246).

References

- [1] T. Udem, R. Holzwarth, and T. W. Hänsch, "Optical frequency metrology," *Nature* **416**, 233–237 (2002).
- [2] I. Coddington, W. C. Swann, L. Nenadovic, and N. R. Newbury, *Nat. Photonics* **3**, 351–356 (2009).
- [3] A. Iwasaki, D. Nishikawa, M. Okano, S. Tateno, K. Yamanoi, Y. Nozaki, and S. Watanabe, *APL Photonics* **7**, 106101 (2022).
- [4] K. Maezawa, S. Fujii, K. Yamanoi, Y. Nozaki, and S. Watanabe, *Phys. Rev. Appl.* **21**, 044047 (2024).
- [5] K. Maezawa *et al.* "Measurement of surface acoustic waves using a fiber-based Sagnac interferometer," presented at the 86th Japan Society of Applied Physics Autumn Meeting, Meijo University, Sep. 2025 (in Japanese).

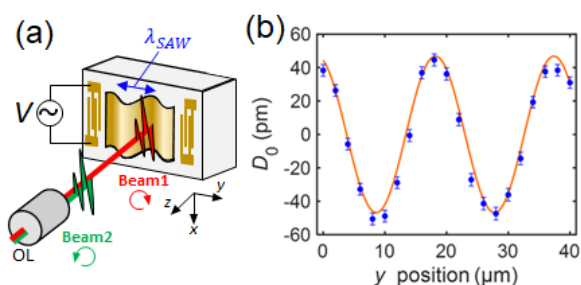


Fig. 1: Surface vibration profile of a SAW device measured by dual-comb interference measurement with a Sagnac geometry. (a) Schematic of the measurement principle. (b) Experimental result. (Reprinted from [3], licensed under CC BY 4.0. © 2022 Author(s).)

Realization of a Stable Broadband 2 μm Supercontinuum Light Source and Its Application to Highly Sensitive OCT

Nagoya University¹ [○](D)Rongjie ZHANG¹, Jacob KOKINDA¹, Shotaro KITAJIMA¹ and Norihiko NISHIZAWA¹

E-mail: zhang.rongjie.i6@s.mail.nagoya-u.ac.jp

1. Abstract

Owing to its low scattering in biological tissues, the broadband 2 μm light source enables enhanced penetration depth, making it a compelling candidate for optical coherence tomography (OCT). In this study, we developed a polarization-maintaining (PM), all-fiber ultrashort pulse fiber laser to generate a highly stable supercontinuum (SC) light in the 2 μm band. Utilizing this SC light as the source for time-domain OCT (TD-OCT), we achieved a high sensitivity of 97 dB, demonstrating its potential for high-performance OCT applications.

2. Experimental setup

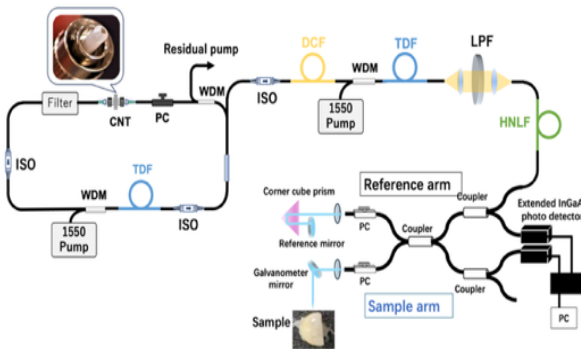


Fig.1. Schematic diagram of experimental setup

Figure 1 shows the schematic of our system. Seed pulses were generated by an all-PM ring cavity operating in the anomalous dispersion regime, where mode-locking was achieved using a carbon nanotube saturable absorber. The soliton pulses underwent soliton self-frequency shift (SSFS) during amplification in a Thulium-doped (TDF) amplifier, red-shifting their wavelength into the 2 μm spectral region. The pulses were then coupled into a highly nonlinear fiber (HNLF) to generate a broadband SC. This SC light source was subsequently utilized in TD-OCT for imaging.

3. Result

Figure 2(a) and figure 2(b) show the spectra of output soliton before and after the TDF, where the pulse is red-shifted following the SSFS. Figure 2(c)

illustrates the broadband SC spectrum generated after nonlinear spectral broadening in the HNLF, spanning over 140 nm in the 2 μm region. Figure 2(d) presents the interferogram obtained from the TD-OCT system using the SC source.

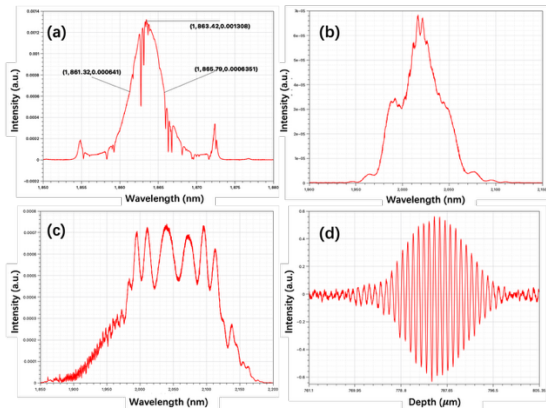


Fig.2. Optical spectra of (a)Seed pulse, (b)Shifted pulse and (c)SC

The detector output exhibited a signal-to-noise ratio (SNR) of 37 dB (Figure 3(a). Accounting for the 60 dB optical attenuation introduced by the ND filter, the calculated system sensitivity reached 97 dB. Finally, Figure 3(b) showcases a cross-sectional OCT image of adhesive tape, where distinct layer interfaces are resolved, validating the SC source's effectiveness for high-resolution imaging.

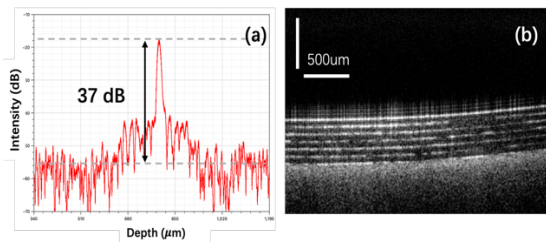


Fig.3. (a)Logarithmically demodulated signal and (b)OCT image of tape

4.Reference

[1] R. Zhang, F. Osaki, S. Kitajima and N. Nishizawa, "Development of OCT in 2-um Spectral Region by Using an All-fiberized Ultrashort Tm-Ho Co-doped Fiber Laser," Proc. Advanced Lasers and Photonics (ALPS), 2023.

Accurate Multi-Gas Thermometry via Dual-Comb Spectroscopy Based on Integrated Absorbance

Toho Univ.¹, ^oNaoki Takeshi¹, Ryusei Uchiyama¹, Takumi Takahoshi¹, Yoshiaki Nakajima¹

E-mail: yoshiaki.nakajima@sci.toho-u.ac.jp

The evaluation of gas temperature is becoming increasingly important in industrial applications, environmental science, and reaction chemistry. In particular, non-contact measurements of multi-component gases enable detailed and accurate analysis under complex conditions. Dual-comb spectroscopy (DCS) [1] has emerged as an attractive tool for this purpose offering broadband spectra acquisition with high resolution and rapid measurement times. Temperature measurement using DCS is based on the principle that molecular absorbance spectra follow the Boltzmann distribution. This approach, known as Rotational-state Distribution Thermometry (RDT) [2], has been experimentally demonstrated using acetylene ($^{12}\text{C}_2\text{H}_2$). However, RDT is limited to specific molecular species, restricting its broader applicability. To overcome this limitation, we propose a new model that relaxes these constraints.

In this study, we introduce Integration Log RDT (ILRDT), a temperature evaluation model that focuses on the integrated absorbance of molecular spectra. Based on the Lambert-Beer law, this method allows for quantitative estimation of thermodynamic temperature. We conducted experiments using a phase-locked dual-comb spectroscopy system composed of two mode-locked Er-doped fiber lasers. Gas cells containing $^{12}\text{C}_2\text{H}_2$ and H^{13}CN were connected in series. Figure 1 shows the temperature estimation results obtained by applying ILRDT to the measured integrated absorbance. The estimated gas temperatures were compared with reference values measured by platinum resistance thermometers (PRTs) attached to the walls of each gas cell. While the PRTs indicated a temperature of 293.1 K, the ILRDT-estimated temperatures were 294.0 K for $^{12}\text{C}_2\text{H}_2$ and 292.8 K for H^{13}CN , demonstrating good agreement with the reference.

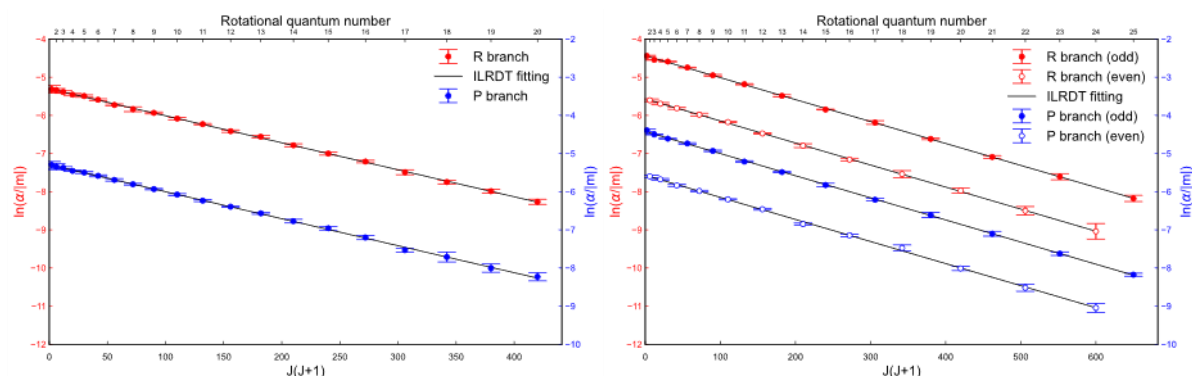


Fig. 1 Temperature estimation results using ILRDT: (a) $^{12}\text{C}_2\text{H}_2$, (b) H^{13}CN

[1] I. Coddington, et al., *Optica* **3**, 414-426 (2016).

[2] Y. Shimizu, et al., *Appl. Phys. B* **124**, 71 (2018).

THz-TDS System Using a Mechanically Shared Dual-Comb Fiber Laser

°Takumi Takahoshi¹, Naoki Takeshi¹, Masahiko Tani², Hideaki Kitahara², Takeshi Yasui³,

Shinichi Matsubara⁴, Yoshiaki Nakajima¹

Toho Univ.¹, Univ. Fukui², p-LED³, JASRI⁴

E-mail: yoshiaki.nakajima@sci.toho-u.ac.jp

Terahertz (THz) waves are valuable for evaluating non-metallic materials due to their strong penetrative capabilities. Conventional THz time-domain spectroscopy (THz-TDS) systems based on asynchronous optical sampling (ASOPS) use ultrashort pulse lasers however require a mechanical delay stage, resulting in a trade-off between spectral resolution and acquisition time. Dual-comb spectroscopy (DCS) eliminates the need for delay stage, enabling broadband, high-resolution, and rapid measurements [1], and has been applied to ASOPS THz-TDS systems [2]. However, conventional DCS systems are typically large and complex, as they require precise stabilization of two independent lasers.

To address this limitation, we developed an ASOPS THz-TDS system based on an all polarization-maintaining dual-comb fiber laser with a mechanically shared cavity [3]. This design simplifies the system by eliminating the need for active stabilization, as the shared cavity ensures that the two frequency combs remain intrinsically phase coherent, effective functioning as a single dual-comb laser. Figure 1(a) shows the experimental setup. Each laser output was amplified to approximately 100 mW using an Er-doped fiber amplifier (EDFA) and split using a 10/90 coupler. The 10% port provided the trigger signal, while the 90% port underwent second-harmonic generation (SHG) and was used for THz generation and detection via a photoconductive antenna (PCA). Figure 1(b) shows the time-domain THz waveform transmitted through a high-resistivity Si plate. Fourier transform analysis yielded the amplitude and phase spectra, from which the transmittance (Fig. 1(c)) and phase difference (Fig. 1(d)) were calculated. This work was supported by Paloma environmental technology development foundation.

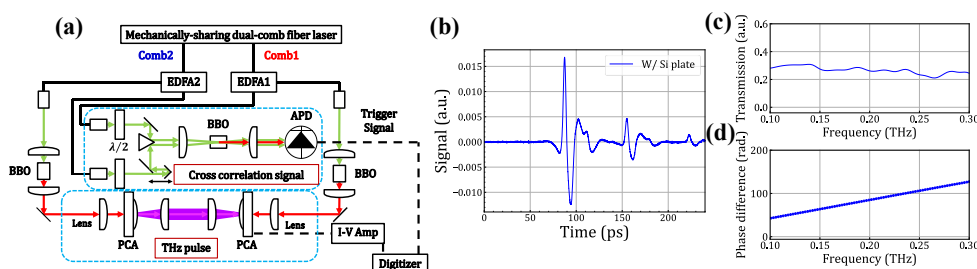


Fig.1 (a) Experimental setup, (b) THz pulses after passing through the Si-plate, (c) Transmission spectrum of Si-plate, (d) Phase difference spectrum.

- [1] I. Coddington, et al., *Optica* **3**, 414 (2016).
- [2] T. Yasui, et al., *Appl. Phys. Lett.* **88**, 241104 (2006).
- [3] T. Yumoto, Y. Nakajima, et al., *Opt. Continuum* **2**, 1867 (2023).

Integrating Raman spectroscopy and DFT to probe the photophysics of optically active materials

Otago University¹, University of Wollongong², Elkhansa Elbashier¹, Keith C. Gordon¹,

David L. Officer², Pawel Wagner²

E-mail: elbel670@student.otago.ac.nz



Optically active materials, including donor-acceptor systems, polymers, and porphyrin derivatives, are central to applications in photovoltaics, nonlinear optics, sensing, and bioimaging. Understanding their photophysical behavior is key to guiding molecular design and optimizing performance. In our laboratory, we combine Fourier-transform Raman spectroscopy (FT-Raman, 1064 nm), Resonance Raman (RR) spectroscopy, and Density Functional Theory (DFT) to investigate ground- and excited-state properties. This integrated approach enables us to probe vibrational modes, electronic transitions, and environment-dependent behavior. In donor-acceptor systems, FT-Raman and solvatochromic shifts reflect intrinsic ground-state polarity, supported by DFT-based geometry and charge-density analysis. In porphyrin derivatives, RR and TD-DFT uncover low-lying charge-transfer states that are not evident in UV-Vis spectra. In π -extended systems, enhanced light absorption is linked to a new π - π^* excited state rather than additional charge transfer, as demonstrated by RR profiles and orbital analysis. These examples illustrate how spectroscopy theory collaboratively provides deep insight into the structural and electronic factors governing optical activity, enabling more informed development of photoactive materials.

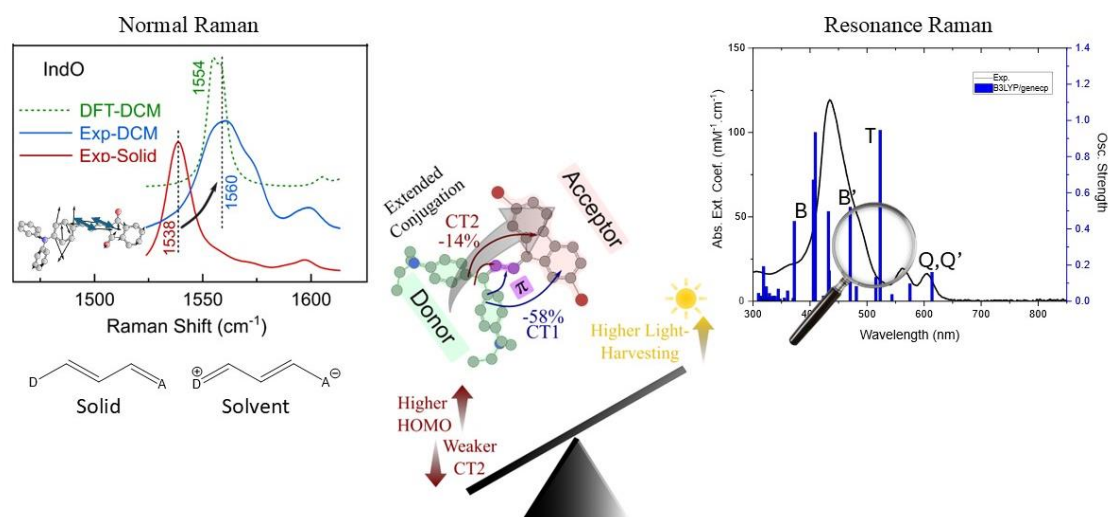


Figure 1: Schematic illustration of various case studies integrating Raman and DFT techniques to study the photophysical properties of materials.

[9a-N203-1~9] 4.3 Laser sources and Laser applications**[9a-N203-7] [JSAP-Optica Joint Symposia Invited Talk] Low-noise frequency synthesis and terahertz wireless communication driven by compact turnkey Kerr combs**

OZhenda Xie¹, Kunpeng Jia¹, Chenye Qin¹, Xinwei Yi¹, Zexing Zhao¹, Shining Zhu¹ (1.Nanjing University)

キーワード : Kerr comb、Low-noise frequency synthesis、Terahertz wireless communication

The high-frequency microwave, spanning up to terahertz frequencies, stands as the pivotal technology propelling next-generation wireless communication, remote sensing, and radar systems. However, fundamental limit exists for low noise microwave generation, especially when the frequency is pushed towards the boundary of the conventional electronic technologies. Microresonator-based optical frequency comb (microcomb) has the potential to break the bottleneck. Here we demonstrate a low-noise and broadband frequency synthesizer based on compact turnkey microcombs, ranging from 10.1 GHz to 384 GHz and operating close to its low quantum-limited phase noise, within a compact setup size of 85 mm × 90 mm × 25 mm. This works open avenues for diverse applications in the high-frequency microwave photonic technologies, leveraging taking advantage of the near quantum-limited performance inside an electric-driven compact package. Such unprecedented low noise performance warrants a high signal-to-noise ratio, facilitating 64QAM modulation in terahertz wireless communication and enabling record high data rate of 240 Gbps without need for carrier phase estimation. Based on above results, this high-frequency microwave photonic device can serve as a key building block for the future information technology.

Frequency-multiplexed photonic reservoir computing using single soliton microcomb

Jonathan Cuevas¹, Yue Hu², Baoqi Shi², Jinqiu Liu^{2,3}, Kaoru Minoshima^{4,5}, Naoya Kuse⁵

¹ Graduate School of Sciences and Technology for Innovation, Tokushima University, Tokushima, Japan ² International Quantum Academy, Shenzhen, China ³ Hefei National Laboratory, University of Science and Technology of China, Hefei, China ⁴ Graduate School of Informatics and Engineering, The University of Electro-Communications, Chofu, Japan ⁵ Institute of Post-LED Photonics, Tokushima University, Tokushima, Japan
E-mail: kuse.naoya@tokushima-u.ac.jp

Reservoir computing (RC) is a machine learning algorithm that can perform a variety of tasks such as chaotic time series data prediction [1]. Photonic implementations of RC have been demonstrated recently using time-multiplexing [2], spatial multiplexing [3], and frequency multiplexing [4]. Frequency multiplexing overcomes the limitations of the previously mentioned methods such as requirement of an input mask, 2D camera, and photodetector array, which increases processing time. Previously demonstrated examples of frequency multiplexing, however, use a long fiber cavity, which can affect processing speed and increases the complexity of the setup, making it difficult to integrate by silicon photonics technologies. In this report, we demonstrate a new type of frequency-multiplexed RC using a microresonator, which addresses the drawbacks of previously demonstrated methods of frequency-multiplexed RC.

RC consists of three main layers: the input layer, the reservoir, and the output layer. For our RC as shown in Fig 1, a continuous-wave (CW) laser is frequency-modulated with input data and is then coupled into a microresonator, which functions as the nonlinear reservoir.

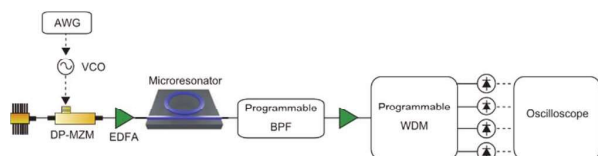


Figure 2: Experimental setup used for RC.

Through a nonlinear four-wave mixing process, a soliton comb is generated. This nonlinear process enables high-dimensional mapping of the input, while the photon storage time in the microresonator provides short-term memory. For our experiment, we use a microresonator with a 28 MHz loaded linewidth and a 100 GHz free spectral range. The input is encoded at 50 MSa/s using an arbitrary waveform generator. The optical spectrum of the soliton comb is shown in Fig 2(a). The intensities of comb modes are measured using a waveshaper and photodetectors as shown in Fig. 2(b) when a chaotic series input is applied. Each comb mode acts as a reservoir node, where they are used for optimizing output weights using ridge regression. Depending on the task,

our RC can be used for chaotic time series prediction or nonlinear channel equalization (NLEQ). For the NLEQ task, numerical simulation is also performed.

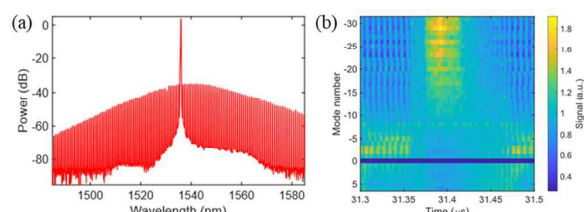


Figure 1: (a) Optical spectrum of an experimentally generated single soliton comb. (b) Photo-detected comb mode responses in the Santa Fe experiment.

For the Santa Fe chaotic time series task, 3000 points are used for training and 1000 points are used for testing. In Fig 3(a), we show the prediction of the time series data, achieving a normalized mean square error (NMSE) of 0.061. Compared to our numerical results of 0.029, we find that noise degrades the performance of our RC. For the NLEQ task, 4000 points are used for training and 4000 points are used for testing. The numerical results and experimental results for NLEQ are shown in Fig 3(b). We also show an experimental symbol error rate (SER) of 6.5×10^{-2} for the NLEQ task at an SNR of 40.

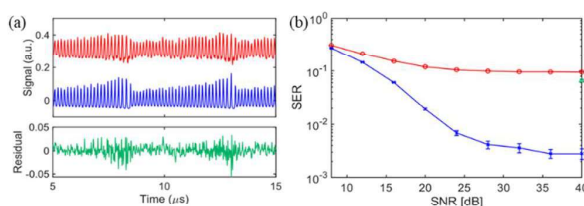


Figure 3: (a) Predicted (red) Santa Fe data, target (blue) Santa Fe data, and residual from difference between predicted and target Santa Fe data (green). (b) NLEQ numerical simulation without optical processing (red), optical processing with no noise (blue), and experimental result (green).

References

- [1] D. J. Gauthier et al., Nat Commun 12, 5564 (2021).
- [2] D. Brunner et al., Nat Commun 4, 1364 (2013).
- [3] S. Sunada, and A. Uchida, Optica 8, 1388-1396 (2021).
- [4] L. Butschek et al., Opt. Lett. 47, 782-785 (2022).

波長可変・繰り返し周波数固定型ファイバ光パラメトリック発振器の ファイバ共振器化

Fiber cavity implementation of a wavelength-tunable,
repetition-rate-fixed fiber optical parametric oscillator

東大院工¹, 東大先端研², ○(D)宋 清澄¹, 高橋 俊¹, 小関 泰之^{1,2}

EEIS, UTokyo¹, RCAST, UTokyo², ○(D)Qingcheng Song¹, Shun Takahashi¹, Yasuyuki Ozeki^{1,2}

E-mail: songqingcheng@g.ecc.u-tokyo.ac.jp

Stimulated Raman scattering (SRS) microscopy is a label-free and molecular-vibration-sensitive biological imaging method [1]. It employs synchronized two-color pulses—known as pump and Stokes beams—whose frequency difference determines the specific molecular bonds that are probed [2]. In our previous work, we developed a wavelength-tunable fiber optical parametric oscillator (FOPO) with a fixed repetition rate, enabling synchronization with a Ti:sapphire laser [3]. However, this system used a free-space cavity, which required frequent alignment. In this study, we demonstrate a fiber cavity implementation of a wavelength-tunable FOPO with a fixed repetition rate, offering a stable and tunable source for SRS imaging.

Figure 1(a) illustrates the schematic of FOPO cavity, where a photonics crystal fiber (PCF) serves as the nonlinear medium. The FOPO converts the pump light at ~ 1040 nm into a signal output centered around 850 nm via the four-wave mixing process. Wavelength tunability and spectral filtering are achieved by adjusting the angle of an intracavity diffraction grating, while the position of the fiber collimator (COLL4) is simultaneously changed to compensate for cavity length variations and maintain a constant repetition rate during tuning.

The FOPO delivers a maximum output power of ~ 10 mW and offers a tunable wavelength range from 840 nm to 865 nm (Fig. 1(b)-(c)). Its spectral bandwidth of ~ 1 nm meets the requirements for high spectral resolution in SRS microscopy (Fig. 1(d)). The PCF-based cavity configuration demonstrates potential for realizing an all-fiber FOPO that is alignment-free and enables rapid wavelength tuning, making it a highly promising light source for future biomedical imaging applications.

Acknowledgement. This work was supported by JST SPRING GX, and JST-CREST JPMJSP2108.

References. [1] C. W. Freudiger *et al.*, *Science* **322**, 1857 (2008). [2] C. Xu *et al.*, *Nat. Photon.* **7**, 875 (2013). [3] S. Takahashi *et al.*, *Biomed. Opt. Express* **5**, 3191 (2024).

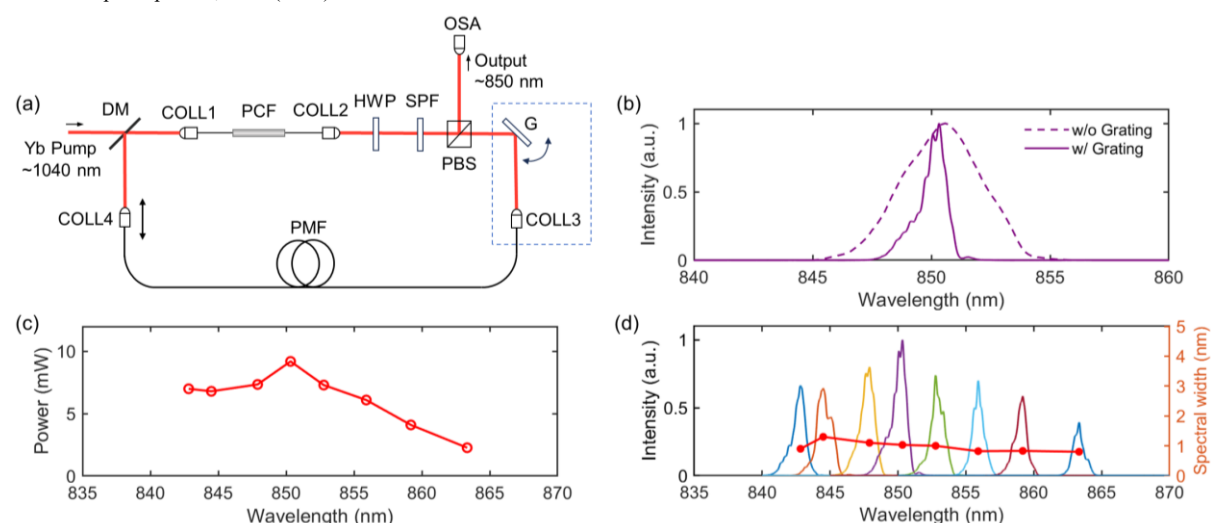


Fig. 1. (a) Schematic of FOPO. DM: dichroic mirror. COLL: collimator. PCF: photonic crystal fiber. HWP: half-wave plate. SPF: short-pass filter. PBS: polarizing beam splitter. G: diffraction grating. PMF: polarization-maintaining fiber. (b) Normalized spectrum of the FOPO without grating and with grating. (c)-(d) Output power, spectrum and spectral width of FOPO.

4 JSAP-Optica Joint Symposia 2025 | 一般セッション(口頭講演) : 4.3 Laser sources and Laser applications

[9p-N203-1~9] 4.3 Laser sources and Laser applications

[9p-N203-1]

[Optica Special Lecture] A History of Commercial Mode-locked Lasers and Application to Multi-Photon Microscopy

○James Kafka^{1,2} (1.Optica President, 2.Spectra-Physics / MKS)

[9p-N203-2]

Investigation of Radiation Tolerance of Mode-Locked Lasers with Radiation-Hardened Erbium Doped Fibers

○Nozomu Takagi¹, Yuichi Takeuchi¹, So Aiba¹, Ren Kondo¹, Yushi Tanaka¹, Mitsuru Musha¹ (1.ILS/UEC)

[9p-N203-3]

Chirp-Managed Yb Fiber Laser Delivering 14 nJ, 1.1 ps Pulses

○Yifan Ma^{1,2}, Maolin Dai^{1,2}, Yuanjun Zhu^{1,2}, Sze Set^{1,2}, Shinji Yamashita^{1,2} (1.Tokyo Univ., 2.RCAST, Tokyo Univ.)

[9p-N203-4]

Femtosecond Mode-Locked Oscillator Based on a Double-Clad Tm:ZBLAN Fiber

○(D)Nur Atikah Binti Azali¹, Takao Fuji¹ (1.Toyota Tech. Inst.)

[9p-N203-5]

[JSAP-Optica Joint Symposia Invited Talk] Development of ultrafast lasers based on broadband mid-infrared gain materials

○Daiki Okazaki¹, Yuri Kirita¹, Yasuhara Ryo², Shigeki Tokita¹ (1.ICR, Kyoto Univ., 2.NIFS)

[9p-N203-6]

Development of a Yb-based Thin-disk laser for a high average power regenerative amplifier.

○(P)Ahmed Ramadan Ibrahim¹, Natsuki Kanda¹, Yasuo Nabekawa¹, Eiji. J. Takahashi¹ (1.RAP, RIKEN)

[9p-N203-7]

Effect of structured laser light in multilayered absorbing media for bio-imaging applications- A simulation study

○(P)Maria Merin Antony¹, Murukeshan Vadakke Matham¹ (1.Nanyang Techn. Univ.)

[9p-N203-8]

Exploring Laser Envelope Effects of Subcycle Pulses on Photoelectron Momentum Distributions

○(P)Rambabu Rajpoot¹, Eiji J. Takahashi¹ (1.RIKEN)

[9p-N203-9]

[JSAP-Optica Joint Symposia Invited Talk] Mid-IR Ring Laser Oscillator for Intra-Cavity Dual-Frequency-Comb Spectroscopy

○Reza Amani¹, Kaoru Yamanouchi² (1.CALS Tokyo Univ, 2.iALFA Tokyo Univ)

A History of Commercial Mode-locked Lasers and Application to Multi-Photon Microscopy

James D. Kafka, *Spectra-Physics / MKS*

Abstract: I will review the history of commercial mode-locked lasers from mode-locked Argon ion lasers and Nd:YAG lasers to synchronously pumped dye lasers and the revolution brought on first by Ti:sapphire and then Yb doped lasers. I will conclude with the application of these lasers to the field of multi-photon microscopy. © 2025 Jim Kafka

1. Mode-locked gas lasers

The record of mode-locked lasers developed at commercial companies likely begins with an ingenious publication [1], and patent [2], describing mode-locking of a Helium Neon laser in 1968. The author, George Huggett, detected and amplified the beat note generated by the longitudinal modes of the laser and used the signal to drive a KD*P phase modulator. The system produced 50 mW of mode-locked pulses but was likely never offered for sale. The commercial Argon Ion Laser was developed in the late 1960s, and the first report of a mode-locked version from 1971 offered “preliminary specifications” of 250 mW of average power with 150 ps pulses at 140 MHz repetition rate [3]. This performance was obtained with a *small frame* ion laser. By 1978, a mode-locked version of the *large frame* ion laser was offered for sale. This produced picosecond pulses and was offered with a synchronously pumped dye laser. The *typical* dye laser output, using Rhodamine 6G dye was reported as 100 mW with 2-3 ps pulses at 82 MHz repetition rate and thus 1.2 nJ of energy. A cavity dumped version of this laser was offered that produced 15 ps pulses with 35 nJ of energy.

2. Mode-locked solid-state lasers and dye lasers

In the early 1980s, mode-locked lamp pumped Nd:YAG lasers were brought to the market, first by Quantronix followed by Spectra-Physics in 1983 and then Coherent. These were actively mode-locked lasers using an acousto-optic modulator to produce typically 80 ps pulses and were often frequency doubled using a nonlinear crystal to generate green light for synchronously pumping dye lasers. Accessories to these lasers included fiber/grating pulse compressors for the YAG laser which allowed pulse durations as short as 200 fs to be produced by the dye lasers at a range of wavelengths, as well as harmonic generation modules. Colliding pulse mode-locked (CPM) lasers were also brought to market by Clark MXR. These lasers produced shorter pulses (sub-100 fs) at a fixed wavelength and were pumped by cw lasers.

3. Ti:sapphire lasers

After the Ti:sapphire gain medium was developed in the 1980s [4], there were multiple publications exploring different mode-locking methods. The world of commercial mode-locked lasers changed drastically when mode-locked Ti:sapphire products were offered by Spectra-Physics and Coherent. Simultaneously, a break through in mode-locking methods that made use of the nonlinearity in the gain crystal was reported by workers in St. Andrews University [5], with the excitement evident during a standing room only postdeadline paper session at CLEO 1990. Today there are thousands of mode-locked Ti:sapphire lasers in laboratories across the world. Commercial variations include sub-10 fs pulse lasers from multiple vendors, synchronously pumped OPOs and even a green diode-pumped version.

4. Ytterbium doped lasers

Enabled in part by phenomenal increases in diode power and brightness, Yb doped lasers in bulk and fiber and thin disk format, became attractive sources in the early 2000s. These mode-locked lasers were both higher power and less expensive but at the cost of longer pulse durations and lack of tunability. This combination of attributes enabled new industrial markets with record average powers being offered to the market by Trumpf. To address the scientific need for tunability and shorter pulses, synchronously pumped OPOs were developed with the Spectra-Physics InSight® being introduced in 2010.

5. Fiber lasers, mid-IR lasers and the future

In the last decade many new vendors entered the commercial market for mode-locked lasers. Mode-locked fiber lasers doped with Yb, Nd and particularly Er have demonstrated impressive performance in a compact package. Multiple vendors have pushed to longer wavelengths with Tm and Ho doped fibers and Cr doped ZnS and ZnSe bulk crystals. This talk will review the evolution of commercial mode-locked lasers as they progressed from gas lasers and dye lasers to solid-state lasers and OPOs and finally to directly diode-pumped lasers. Much of the early work is dependent on unpublished internal documents and as such is focused on the author’s employer. There are currently dozens of excellent commercial suppliers of mode-locked lasers, and the interested reader is encouraged to search for them, as the current state of these offerings is beyond the scope of this paper. The options available today cover an enormous range of performance parameters and the prospect for future offerings is enticing.

6. Application of mode-locked lasers to multi-photon microscopy

I will describe the origins of two photon microscopy, with the pioneering work occurring more than 30 years ago [6] and highlight the differences between 2-photon microscopy and the 1-photon confocal configuration. The development of the mode-locked Ti:sapphire laser was perfectly timed to accelerate the adoption of the 2-photon technique. I will detail both the physics and engineering involved in the design of the Ti:sapphire lasers and emphasize the modifications we made to optimize these sources for this application.

Longer wavelengths sources were desired to provide deeper penetration into biological samples, so we developed an entirely new mode-locked platform with longer wavelengths and greater tunability. These sources also provided multiple outputs at different wavelengths and enabled new microscopy techniques such as femtosecond Coherent anti-Stokes Raman Scattering or CARS. Label free techniques using second harmonic generation and third harmonic generation were also employed. Multiple methods were then applied to a single sample in a technique known as multimodal imaging. Finally, I will describe the unique advantages and challenges of 3-photon excitation. In the future, we can look forward to new experimental techniques that will drive laser source development and new laser technologies that will accelerate existing applications and enable new ones as well.

References: [1] G. R. Huggett, “Mode-locking of cw lasers by regenerative RF feedback,” Appl. Phys. Lett. 13, 186–187 (1968). [2] U.S. Patent # 3,594,660. [3] Internal Spectra-Physics document somehow saved by Alan Petersen. [4] P. F. Moulton, “Spectroscopic and laser characteristics of Ti:Al₂O₃,” J. Opt. Soc. Am. B 3, 125–133 (1986) and references therein. [5] D. E. Spence, P. N. Kean, and W. Sibbett, “60-fsec pulse generation from a self-mode-locked Ti:sapphire laser,” Opt. Lett. 16, 42 (1991). [6] W. Denk, J. H. Strickler and W. Webb, “Two-Photon Laser Scanning Fluorescence Microscopy,” Science 248, 73 (1990)

Investigation of Radiation Tolerance of Mode-Locked Lasers with Radiation-Hardened Erbium Doped Fibers

Nozomu Takagi, Yuichi Takeuchi, So Aiba, Ren Kondo, Yushi Tanaka, Mitsuru Musha

Institute for Laser Science, University of Electro-Communications

E-mail: n_takagi@ils.uec.ac.jp

Currently, highly-stable spaceborne microwave generation system with $\delta f/f \sim 10^{-15}$ level has been developed which consists of iodine-stabilized lasers [1] and optical frequency combs [2]. Our optical frequency combs are based on erbium doped figure-8 NALM (Nonlinear Amplifying Loop Mirror) fiber mode-locked laser ($f_{\text{rep}} = 51.15$ MHz) which has two types erbium-doped fibers (80 dB/m and 7 dB/m) and realize low phase noise, self-start oscillation and long-term stable operation (fig.1(a)). This mode-locked laser oscillates in the stretched pulse mode-locking regime. As a spaceborne laser, mode-locked laser should have highly tolerance against radiation exposure at more than 100 krad. In our preliminary radiation tests, our mode-locked lasers with normal erbium-doped fibers (EDF) terminated its mode-locking operation at total dose of 35 krad mainly due to radiation-induced absorption (RIA) in the EDFs (fig.1 (b)). Since high doped radiation-hardened EDF is not commercially available, we asked Exail company to develop specially-costumed high doped radiation-hardened EDF and they succeed in making 80-dB/m high concentrated EDF whose dispersion is optimized for our mode-locked lasers. By using these specially-costumed fibers, we develop radiation-hardened mode-locked laser with the same configuration as shown in fig.1 (a) and in this summer, we planned to apply them to the radiation test. In the presentation, the optical characteristics of the radiation-hardened fibers and the results of radiation test of mode-locked lasers using the radiation-hardened fibers will be presented.

The present study has been promoted in collaboration with JAXA and NICT, and is financially supported by Stardust program by Ministry of education, culture, science and technology (MEXT).

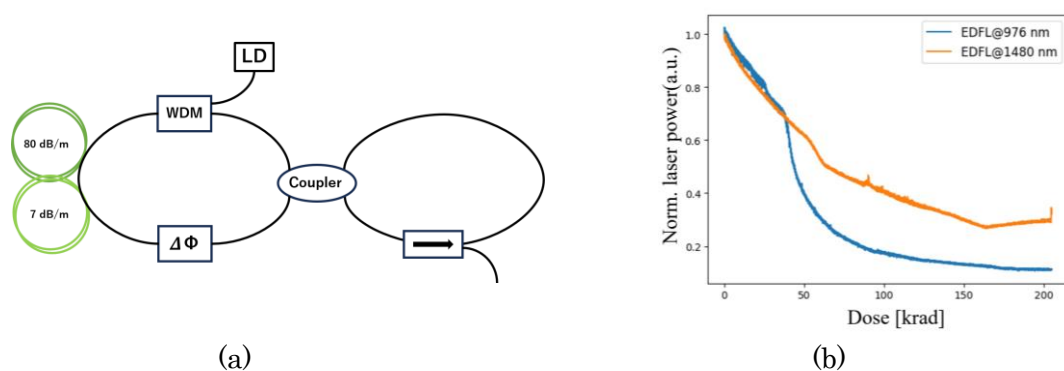


Fig.1 (a)figure-8 cavity of mode-locked lasers, (b)Output power of EDFL is decreasing as total dose increasing due to RIA

References

- [1] Aru Suemasa, et al (2023), "Development of Laser-Optical Clocks for Future QZSS and Experimental Evaluation of a Seven-Satellite Constellation", Proceedings of the 54th Annual Precise Time and Time Interval Systems and Applications Meeting
- [2] Yuichi Takeuchi et al (2024), "SPACEBORNE OPTICAL FREQUENCY COMB BY USING FIGURE-8 MODE-LOCKED FIBER LASER FOR HIGHLY-STABLE MICROWAVE GENERATION", ICSO 2024

チャープ制御型 Yb ファイバレーザによる 14 nJ
エネルギーおよびピコ秒パルスの生成

Chirp-Managed Yb Fiber Laser Delivering 14 nJ, 1.1 ps Pulses

東大工¹, 東大先端研², [○]麻 一凡^{1,2}, 戴 茂林^{1,2}, 朱元 軍^{1,2}, セット ジイヨン^{1,2}, 山下 真司^{1,2}
Tokyo Univ.¹, RCAST, Tokyo Univ.¹, [○] Yifan Ma¹, Maolin Dai^{1,2},
Yuanjun Zhu^{1,2}, Sze Y. Set^{1,2} and Shinji Yamashita^{1,2}
E-mail: mavifan@g.ecc.u-tokyo.ac.jp

Mode-locked fiber lasers operating in the 1 μm region have attracted significant attention for applications in micromachining, biomedical imaging, and nonlinear optics. Their performance is strongly influenced by the dispersion regime of the cavity. In anomalous dispersion regimes, conventional soliton lasers typically generate transform-limited femtosecond pulses but suffer from strict energy scaling limits (often <1 nJ) due to soliton area constraints [1]. In contrast, normal dispersion (all-normal or net-normal) cavities support high-energy dissipative solitons with pulse energies exceeding 10 nJ, but usually at the cost of long pulse durations (~ 50 ps) and strong linear chirp, requiring external compression for practical use [2].

In this work, we demonstrate a chirp-managed Yb-doped fiber laser that operates in a net-positive dispersion regime using a long segment of single-mode fiber (SMF) and weak grating-based dispersion compensation. Despite the simple architecture, the laser generates 1.1 ps sech² pulses with 14 nJ pulse energy at 78 MHz, resulting in 1.1 W average output power. The system shows excellent temporal coherence and low time-bandwidth product without any external pulse compressor. These features position this laser as a practical and scalable ultrafast source, combining high energy, high efficiency, and short pulse duration in a compact design.

To provide sufficient nonlinear phase accumulation for pulse shaping, the cavity includes approximately 1.8 meters of standard single-mode fiber (SMF) spliced to the Yb-doped gain fiber. Due to the long total fiber length, the cavity exhibits substantial net normal (positive) dispersion. To balance this, we incorporate a grating pair (GP, LightSmyth, T-1000-1040) with collimators in the free-space section. The grating pair serves a dual purpose: it provides negative dispersion compensation and acts as a spectral filter, helping to reshape and stabilize the pulse. One of the diffraction gratings is mounted on a translation stage, enabling fine-tuning of the dispersion to reach the optimal pulse duration and spectral phase.

Through iterative adjustment and optimization of both the total fiber length and the grating pair separation, we were able to realize a balance between nonlinear phase accumulation and dispersion compensation, achieving stable mode-locking with maximized output power and minimized pulse duration. Notably, the laser is pumped with up to 2.1 W of 976 nm light, yielding an optical-to-optical efficiency of 52%. Stable self-starting operation was consistently achieved when the output power reached approximately 530 mW, corresponding to a pump power of about 1.0 W.

Long-term stability was also verified through a continuous 6-hour monitoring, during which the output power remained consistent without evidence of multi-pulsing or state changing.

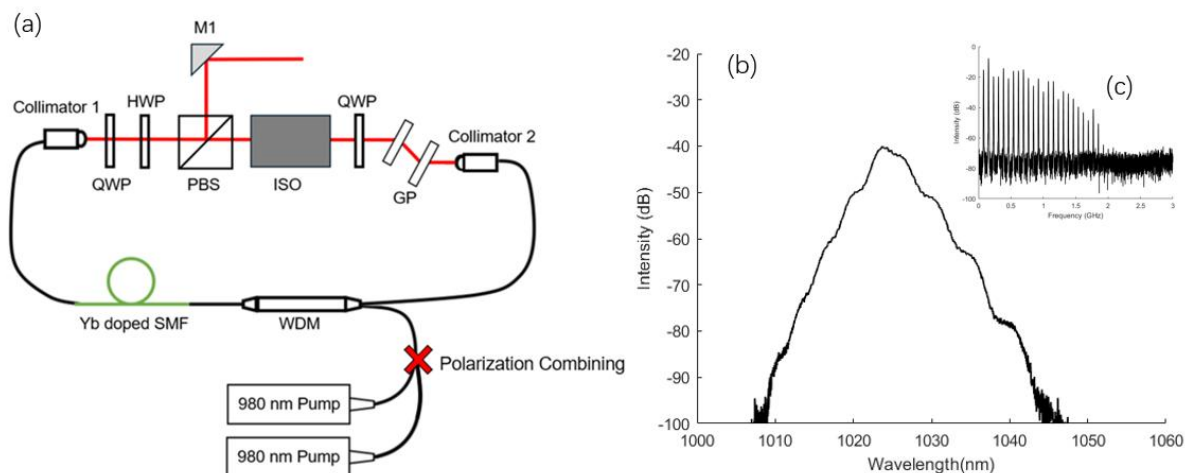


Figure 1 (a) System Layout. (b) Optical spectrum. (c) RF spectrum

- [1] Grelu, P., (2012). Dissipative solitons for mode-locked lasers. *Nature photonics*, 6(2), 84-92.
- [2] Chong, A., Renninger, W. H., & Wise, F. W. (2007). All-normal-dispersion femtosecond fiber laser with pulse energy above 20 nJ. *Optics letters*, 32(16), 2408-2410.

Femtosecond Mode-Locked Oscillator Based on a Double-Clad Tm:ZBLAN Fiber

Nur Atikah Azali¹ and Takao Fuji¹

¹ Laser Science Laboratory, Toyota Technological Institute, 2-12-1 Hisakata, Tempaku-ku, Nagoya, 468-8511, Japan

E-mail: sd24601@toyota-ti.ac.jp

1. Introduction

The generation of ultrashort optical pulses in the 2 μm region is an extensively expanding field due to its advantages in various fields such as in medical applications, mid-infrared generation, and high field physics. Thulium-doped fibers are an ideal gain medium for generating ultrashort 2 μm pulses as they possess a broad emission spectrum from 1.7 μm to 2.1 μm . ZBLAN fibers are an interesting host material to generate ultrashort pulses since ZBLAN fibers have a low anomalous dispersion. In our previous work, we have developed an oscillator based on a Tm:ZBLAN fiber with precise intracavity dispersion control with a grating stretcher. The oscillator produced 2 μm pulses with a duration of 45 fs, which is one of the shortest in 2 μm oscillators [1].

In this contribution, we present the performance of a mode-locked oscillator based on double-clad Tm:ZBLAN fiber. There is no grating stretcher in the cavity, thus a more compact design is possible and the loss inside the cavity will be small. The output power of the oscillator was 402 mW, which is more than ten times higher than that of our previous oscillators [2,3].

2. Experimental Setup

The laser is constructed in a ring cavity configuration as shown in Figure 1. The gain medium is a 1.78 m thulium-doped double clad ZBLAN fiber (Tm:ZBLAN) with a core diameter of 8.7 μm . The oscillator is mode-locked with nonlinear polarization evolution (NPE). A half-wave plate (HWP) and two quarter wave-plates (QWP) are used to adjust the polarization state in the cavity to be mode-locked. An isolator is used to ensure a unidirectional operation in the cavity. A polarizing beam splitter is used as a rejection port for the NPE.

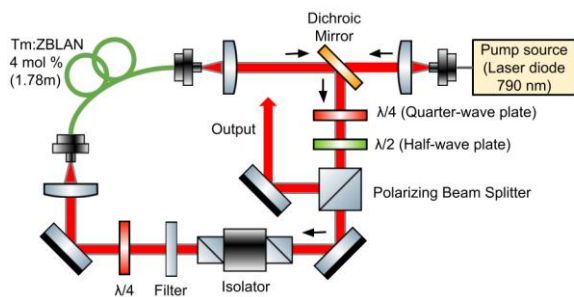


Figure 1: Schematic diagram of the Tm:ZBLAN mode-locked fiber laser

3. Results

The behaviour of the laser is observed by adjusting the pump power and the polarization state of HWP and QWP. The laser was mode-locked when the pump power reached ~ 2000 mW. After decreasing the pump power to ~ 1866 mW, a single-pulse regime is observed with the output power of 345 mW. A broad spectrum spread from 1880 nm to 2005 nm is shown in Figure 2 (a) with a resolution of 0.1 nm. The maximum output power at the mode-locked operation was 402 mW at pump power of 2259 mW with slope efficiency of 14.6%.

The duration of the output pulses was measured using a home-built second-harmonic generation (SHG) frequency-resolved optical gating (FROG) device. The output pulses were compressed using a 20 cm single mode silica fiber and 10 pieces UV fused silica plates ($t=12$ mm). Figure 2 shows the typical FROG analysis of the compressed pulses. The pulse duration is 142 fs. The retrieved spectrum looks almost similar to the spectrum in Figure 2(a), which also confirms the validity of the FROG measurement.

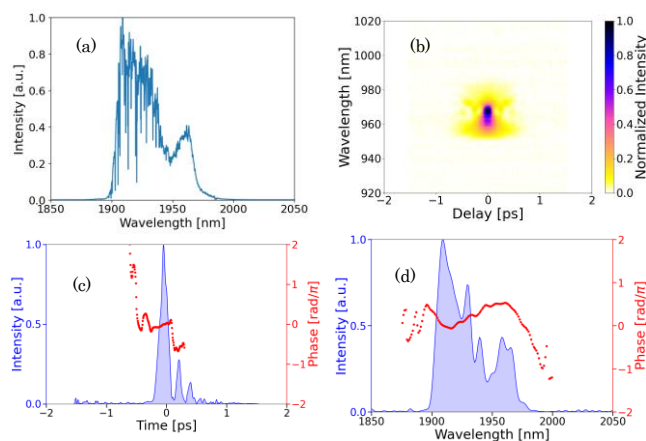


Figure 2: (a) Spectrum of the oscillator output. (b) Measured FROG trace. (c) Time dependence of the power (blue line) and the phase (red dots). (d) Power spectrum (blue line) and the spectral phase (red dots).

References

- [1] Yutaka Nomura and Takao Fuji: Opt. Express **22** 12461 (2014).
- [2] Yutaka Nomura, Masatoshi Nishio, Sakae Kawato, and Takao Fuji: IEEE J. Sel. Top. Quantum Electron. **21** 0900107 (2015).
- [3] Hiroki Kawase, Junya Takano, Riko Noguchi, and T Fuji: Opt. Express **32** 38960 (2024).

Development of ultrafast lasers based on broadband mid-infrared gain materials

○Daiki Okazaki¹, Yuri Kirita¹, Ryo Yasuhara², Shigeki Tokita¹

1. Institute for Chemical Research, Kyoto University, Gokasho, Uji, Kyoto 611-0011

2. National Institute for Fusion Science, National Institutes of Natural Sciences, 322-6 Oroshi-cho, Toki, Gifu 509-5202

E-mail: okazaki@laser.kuicr.kyoto-u.ac.jp

The mid-infrared region has long been recognized as a key spectral domain, primarily due to the resonance of molecular vibrational modes, which facilitates exceptionally sensitive molecular detection and chemical identification. In recent years, this region has drawn increasing attention as a driver for high-harmonic generation, enabling compact, coherent X-ray sources and attosecond pulse generation¹. Moreover, mid-infrared light sources are well-suited to probing sub-cycle electron dynamics while avoiding material damage, which is fundamental for advancing light-wave-driven electronics².

Within the last decade, significant progress has been made in nonlinear frequency down-conversion schemes such as optical parametric chirped pulse amplification based on Ti:Sapphire regenerative amplifiers and Yb-based disk laser amplifiers. However, these approaches face inherent challenges in power scalability and repetition-rate enhancement, primarily due to thermal issues in amplifiers, limited conversion efficiency, and optical damage to nonlinear crystals.

Advances in crystal growth methods and the development of high-average-power continuous-wave and Q-switched laser systems, especially at telecom wavelengths and at 2.9 μm for medical purposes, have recently facilitated the emergence of broadband laser gain media that directly support mid-infrared emission, as represented in Figure 1. In particular, Cr^{2+} - and Fe^{2+} -ion-doped ZnS and ZnSe offer broad emission bandwidths spanning 2–3 μm (shown in Figure 2) and 3–5 μm , respectively, enabling sub-100-fs pulse durations³. Cr:ZnS and Cr:ZnSe, often called the “Ti:Sapphire of the mid-infrared,” demonstrate excellent performance, including the latest phase-stable single-cycle pulse operation⁴, single-cycle mid-infrared waveform control via cascading down-conversion⁵, and terawatt-level amplification⁶ toward extreme nonlinear laser physics.

This presentation will highlight our latest development of ultrafast laser systems based on Cr:ZnS and Fe:ZnSe. We will introduce Cr:ZnS femtosecond oscillators incorporating diameter-controlled single-walled carbon nanotube saturable absorbers, which support 30-fs operation in a self-starting manner^{7,8}. We will also mention their applications in generating multi-octave terahertz pulses^{9,10}. Regarding the amplifiers, we will show carrier-envelope-stable Fe:ZnSe chirped-pulse multi-pass amplifiers¹¹ reaching sub-millijoule levels, including the development of a 3-micron Er-based Q-switched pump

source.

These ultrafast laser sources, based on broadband mid-infrared gain, promise to overcome the limitations in energy and power scalability and pave the way for fascinating applications such as electron or plasma motion control using synthesized infrared-to-terahertz electric fields.

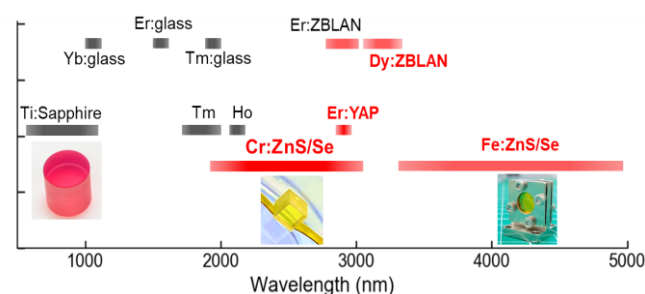


Figure 1 Broadband laser gain medias and their pictures. The horizontal bar indicates their emission wavelength.

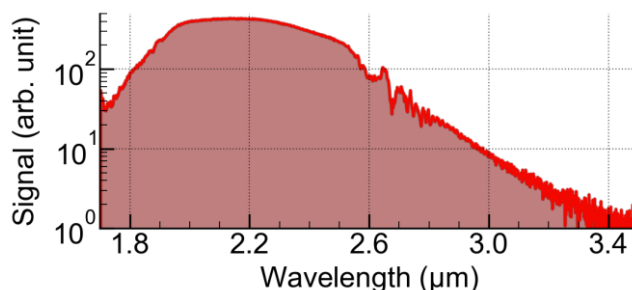


Figure 2 Emission spectrum of polycrystalline Cr:ZnS (DIENTECH) under excitation by a 1.7 μm laser diode.

Reference

- [1] T. Popmintchev *et al.*, *Science*, **336** 1287 (2012).
- [2] M. Borsch *et al.*, *Nat. Rev. Mater.*, **8** 668 (2023).
- [3] S. Mirov *et al.*, *IEEE J. SEL TOP QUANT.*, **24** 5 (2018).
- [4] M. Kowalczyk *et al.*, *Optica*, **10** 6 (2023).
- [5] P. Steinleitner *et al.*, *Nat. Photon.*, **16** 512 (2022).
- [6] X. Lu *et al.*, *Optica*, **10** 11 (2023).
- [7] D. Okazaki, S. Ashihara *et al.*, *Opt. Lett.*, **44** 7 (2019).
- [8] T. Kugel, D. Okazaki, Ko Arai, S. Ashihara, *Applied Optics*, **61** 4 (2022).
- [9] D. Okazaki, A. Weigel, *et al.*, *CLEO®/Europe-EQEC 2025, CF-12.2*.
- [10] M. Aghakasiri, D. Okazaki, A. Weigel, *et al.*, *CLEO®/Europe-EQEC 2025, CC-3.4*.
- [11] D. Okazaki, S. Tokita *et al.*, *11th EPS-QEOD Europhoton Conference, FR-2.1* 2024.

Development of a Yb-based Thin-disk laser for a high average power regenerative amplifier

Ahmed R. Ibrahim, Natsuki Kanda, Yasuo Nabekawa, and Eiji. J. Takahashi

RIKEN Center for Advanced Photonics, RIKEN
E-mail: ahmed.ibrahim@riken.jp

1. Introduction

Thin-disk (TD) laser technology is promising for high pulse energy and high repetition rate owing to its efficient cooling configuration and good scalability [1,2]. Ytterbium-doped yttrium aluminum garnet (Yb:YAG) TD stands out as a gain medium due to its superior crystal quality, high damage threshold, high thermal conductivity, and broad absorption band compatible with high-power laser diodes operating around 930–970 nm [3]. Given the suitability of Yb:YAG with TD technology for developing ultrafast lasers, several works have reported systems such as high-power mode-locked oscillators [4] and regenerative amplifiers (RA) [5].

We are developing a high-average-power Yb:YAG TD RA to serve as a pump source for a few-cycle mid-infrared optical parametric amplification, aimed at high repetition rate and high photon flux attosecond pulse generation.

For this purpose, an RA laser cavity with single-mode beam profile and high optical efficiency is required. Here, we carefully designed the cavity to satisfy those demands by optimizing mode matching between the pump and the cavity mode at TD and consider the effective thermal lens (TL) caused by the TD deformation thus, the cavity is designed to satisfy large stability parameters in a wide range of TL. The schematic of the setup is shown on Fig. 1.

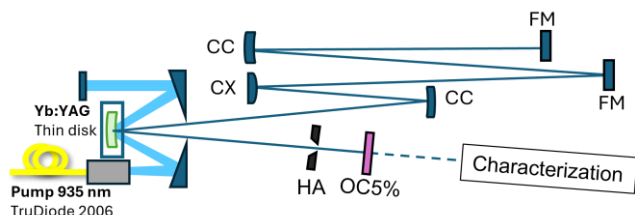


Figure 1: Schematic layout of developed system, CC: concave mirror, CX: convex mirror, FM: flat mirror, HA: hard aperture.

2. Experiments

We employed a Yb:YAG TD crystal with 100 μm thickness, and 10 at. % doping concentration. The crystal was mounted in a TD module providing 36 pump passes and was attached to a diamond heat sink with water cooling. The system was pumped by a laser diode (LD) source (TruDiode 2006), delivering up to 1.2 kW at ~ 935 nm. The cavity was characterized by using output coupler (OC) with transmission of 5%. We examined the cavity in continuous-wave (CW) lasing condition, with maximum pump

power of 200 W, as shown in Fig. 2. We obtained optical efficiency of 48% and a slope efficiency of 58% with near-diffraction-limited beam quality ($M^2=1.08$), which are the highest efficiencies to the best of our knowledge in single-mode TD lasers pumped around 935 nm. Since the optical efficiency didn't reach the saturation regime, we expect an enhancement by using higher pump power. Moreover, further improvement is expected if zero-phonon line pumping (~ 969 nm) is used.

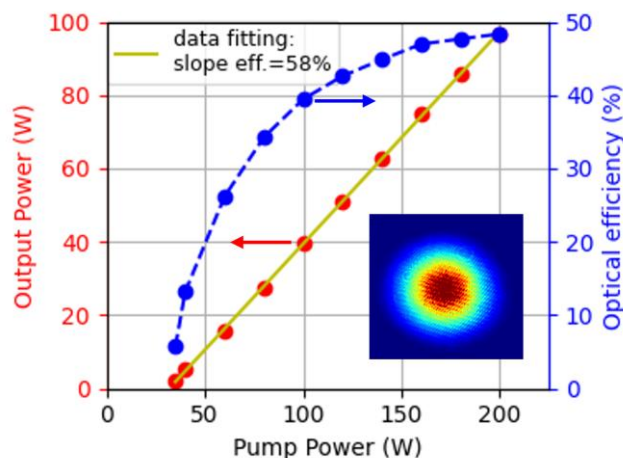


Figure 2: Pump power dependence of the output power in CW lasing. A beam profile is shown in the inset.

3. Conclusions

We are developing a Yb:YAG TD laser towards a high-average-power RA laser. We report a stable CW lasing with a high optical efficiency of 48% and a slope efficiency of 58%, and near diffraction-limited beam quality ($M^2 = 1.08$), by optimizing the cavity design, which will be applied to our development of high-power RA.

Acknowledgements

This research was supported by MEXT Quantum Leap Program (MEXT Q-LEAP) under Grant No. NO118602, JST (K Program) Japan Grant Number (JPMJJP24M1), and JSPS KAKENHI Grant Number JP24K08293.

References

- [1] A. Giesen *et al.*, Applied Physics B, **58** (1994) 365.
- [2] M. Zeyen *et al.*, Opt. Express **32** (2024) 1218.
- [3] J. J. Dong *et al.*, Opt. Soc. Am. B **20** (2003) 1975.
- [4] N. Kanda *et al.*, Light: Sci. Appl. **9** (2020) 168.
- [5] T. Metzger *et al.*, Opt. Lett. **14** (2009) 2123.

Effect of structured laser light in multilayered absorbing media for bio-imaging applications- A simulation study

Maria Merin Antony and Murukeshan Vadakke Matham*

Centre for Optical and Laser Engineering, School of Mechanical and Aerospace Engineering,
Nanyang Technological University, Singapore, *E-mail: mmurukeshan@ntu.edu.sg

1. Introduction

Light transport in multilayered samples is inherently complex at different levels along its depth, influenced by material properties of the sample and optical characteristics of the incident light. Understanding photon transport within these samples is crucial for optimizing optical configurations for imaging various layers in them. One of the widely adapted simulation methods to understand how the scattering and absorption of photons takes place within a medium is Monte Carlo (MC) method for photon transport [1][2]. In this context, this research investigates and compares the effect of structured and unstructured laser light in multilayered absorbing media using MC method for potential bioimaging applications.

2. Methods

To demonstrate the MC based light transport

simulation in layered samples, a software known as ValoMC with MATLAB® interface is used [2]. The sample considered here for the simulation has three layers with absorption (μ_a) and scattering (μ_s) coefficients, as detailed in Fig. 1a. A black layer with high absorption is added as the final layer to absorb all the transmitted photons from the illuminated 10^7 photon packets. Here, the flux distribution along the plane ABCD is investigated and the Gaussian laser beam is structured by sinusoidally modulating the intensity.

3. Results and discussion

When a sinusoidally modulated Gaussian beam is introduced into the sample, interference occurs at the focal plane, leading to an increase in photon intensity and thereby enhancing the overall reflectance

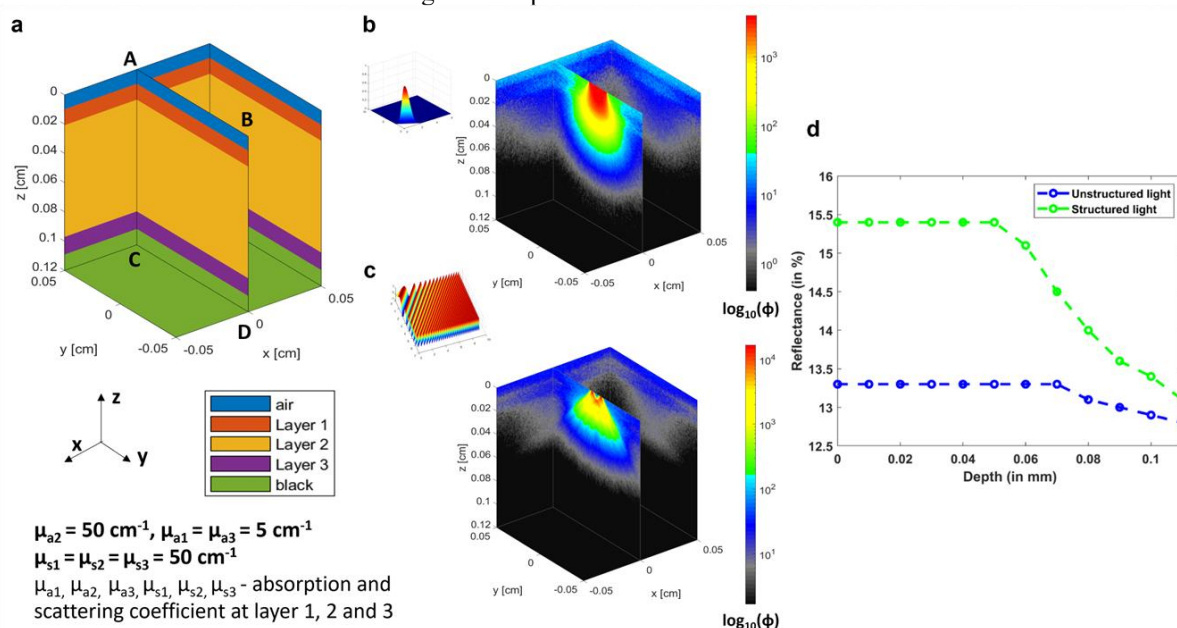


Fig. 1. a. Three layer sample geometry and properties. Flux distribution in the sample when illuminated with b. Gaussian laser beam and c. structured laser light launched at $z = 0 \text{ cm}$, d. Reflectance variation (%) w. r. t depth

It is observed from results in Fig. 1 b and c that the structured laser light can confine the high intensity optical light to a thin plane compared to unstructured light, which can improve the optical sectioning ability of the setup. The use of structured laser light also improves the reflectance by ~3%, from absorbing multilayered samples compared to unstructured laser light as illustrated in Fig. 1. d.

4. Conclusion

The simulation results show that the structured laser light has more potential to improve the optical imaging in multilayered samples compared to unstructured laser light.

Acknowledgements: The authors acknowledge support from COLE-EDB funding and WiEST Development Grant 2025 at NTU, Singapore.

References

- [1] Liu, Y., et al., Biomed Opt Express, 2015. 6(12): p. 4859-70.
- [2] A.A. Leino, A. Pulkkinen and T. Tarvainen, OSA Continuum 2, 957-972 (2019)

Exploring Laser Envelope Effects of Subcycle Pulses on Photoelectron Momentum Distributions

Rambabu Rajpoot, Eiji J. Takahashi

RIKEN Center for Advanced Photonics, RIKEN-Wako, Saitama, Japan

E-mail: rambabu.rajpoot@riken.jp

Over the past few decades, significant progress has been made in understanding the interaction between strong laser fields and atomic or molecular targets. When an intense laser pulse ionizes an atom or molecule, the released electron is accelerated by the field and may be driven back to rescatter off the ionic core. This rescattering process encodes both structural and dynamical information about the target, which can be extracted from the analysis of above-threshold ionization (ATI) spectra and photoelectron momentum distributions (PMDs).

Recent advances in laser technology have enabled the generation of ultrashort pulses with full-width at half-maximum (FWHM) durations shorter than an optical cycle [1–2]. In such sub-cycle regimes, the shape of the pulse envelope plays a much more critical role than in few-cycle pulses. In this work, we investigate how the envelope function of sub-cycle driving fields affects the resulting ATI spectra and PMDs. The electric field profile of a linearly polarized laser pulse with arbitrary envelope and duration is expressed as [3]:

$$E(t) = \text{Re} \left\{ \frac{A_d(t')}{|A_d(0)|} f(t') E_0 \exp(i\omega_0 t' + i\phi_0) \right\}, \quad (1)$$

where $t' = t - t_0 - z/c$ is the retarded time, $f(t')$ is the analytical envelope function, and ϕ_0 represents the carrier-envelope phase (CEP). We consider three envelope functions: Gaussian, hyperbolic secant (sech), and Lorentzian. Figures 1(a) and 1(b) show the half-cycle waveforms of these envelopes for CEPs of 0° and 90° , respectively. The temporal confinement of ultrashort pulses introduces intrinsic chirp, resulting in a blueshift of the central frequency, whose extent depends on the envelope shape—as evident from the variation in field amplitudes near the peaks.

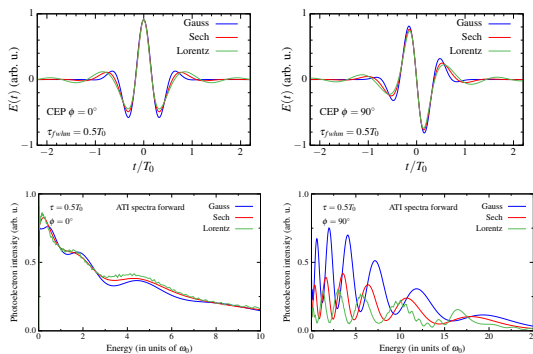


Figure 1: (a,b) Half-cycle laser waveforms for different envelope functions and (c,d) corresponding ATI spectra.

Figures 1(c) and 1(d) present the corresponding ATI spectra for a helium atom driven by the three pulses for CEPs of 0° and 90° . Among the three, the Lorentzian envelope yields the largest blueshift in central frequency. For cosine-like pulses ($\phi_0 = 0^\circ$), the ATI spectra are nearly identical across envelope types since the dominant contribution arises from the central peak, which has comparable intensity in all cases. In contrast, for sine-like pulses ($\phi_0 = 90^\circ$), the intracycle interference peaks shift to lower energies when moving from Gaussian to Lorentzian envelopes. This shift correlates with the decreasing field strength near the peak of the respective pulse shapes.

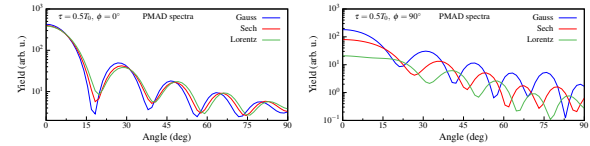


Figure 2: PMADs for CEPs (a) 0° and (b) 90° in the radial momentum range $0.4 < p < 0.5$ a.u.

We also examine the photoelectron momentum angular distributions (PMADs) by integrating the PMDs over the radial momentum range $0.4 < p < 0.5$ a.u., shown in Fig. 2. For both CEP values, the angular peaks are most pronounced for the Gaussian envelope and progressively diminish for the sech and Lorentzian cases. In Fig. 2(a), the PMADs exhibit the “spider-leg” structure associated with forward scattering interference. Furthermore, the modulation depth between peaks—indicative of the relative strength of scattering versus direct ionization pathways—is highest for the Gaussian envelope and decreases successively for the sech and Lorentzian envelopes.

In conclusion, our study highlights the significant influence of the envelope function in sub-cycle laser pulses on the ATI spectra and photoelectron angular distributions. Both the intracycle interference structures in the ATI spectra and the angular features in the PMADs are highly sensitive to the envelope shape, emphasizing the need for precise control over pulse forms in ultrafast strong-field experiments.

References

- [1] H. Liang et al, Nat. Commun. **8**, 141 (2017).
- [2] L. Xu et al, Nat. Photon. **18**, 99-106 (2024).
- [3] Q. Lin et al, Phys.Rev. Lett. **97**, 253902 (2006).

Mid-IR Ring Laser Oscillator for Intra-Cavity Dual-Frequency-Comb Spectroscopy

A. Amani Eilanlou¹ and Kaoru Yamanouchi²

¹ CALS, School of Science, The University of Tokyo, ² iALFA, The University of Tokyo

E-mail: amani@chem.s.u-tokyo.ac.jp

1. Introduction

Dual-frequency-comb spectroscopy is a powerful technique to study spectroscopic properties of atoms and molecules with high resolution in a wide wavelength range with no dispersive optics [1]. Using the repetition rate difference (Δf_{rep}) between the two laser beams created by a bidirectional ring laser oscillator, one can simplify the experimental setup and avoid using sophisticated electronics [2]. In our previous study [3], we were not able to determine Δf_{rep} in a bidirectional Yb:KGW ring laser oscillator (216 MHz, 312 fs) pumped by a multimode laser diode (LD), but it is possible to determine Δf_{rep} if a single-mode pump laser is adopted because a much higher intra-cavity intensity can be achieved using Kerr lens mode-locking (KLM) at a tighter focus.

Once Cr-doped laser materials are adopted in our laser system, the central wavelength can be extended to 2300 nm, so that a wider range of chemical species can be investigated. Moreover, by placing a sample in the ring laser oscillator, the sensitivity of spectroscopic measurements can be raised significantly. In this study, we develop a 500-MHz-class Kerr lens mode-locked Cr:ZnS ring laser oscillator and discuss its applicability to intra-cavity dual-frequency-comb spectroscopy. We also show that high-average-power polarized erbium-ytterbium (EY) all-fiber pump laser sources raise the stability of KLM.

2. Experimental results

The ring laser cavity consists of a 5% output coupling mirror, a plane mirror, and a pair of $R=100$ mm concave mirrors with a total cavity length of ~ 540 mm, which ensures an operation at a high repetition rate beyond 500 MHz. The Cr:ZnS laser crystal is placed between the concave mirror pair and is pumped by a home-built EY-doped fiber laser (1560 nm, 15 W) with a random polarization. All the dielectric mirrors have a broadband reflectance, low loss, and low high-order dispersion in the spectral range of 2200–2400 nm. The polycrystalline Cr:ZnS laser medium (Dien Tech) with a thickness of 3.2 mm, having a doping concentration of $\sim 6 \times 10^{18} \text{ cm}^{-3}$, is placed at the Brewster's angle. As a result, it absorbs $\sim 52\%$ of the pump laser and strongly reflects the σ -polarized component yielding a unidirectional continuous wave (CW) output power of 950 mW at an absorbed pump power of 2.9 W. The intra-cavity high-order dispersion and self-phase modulation are compensated using a sapphire plate ($t=5$ mm) providing a GDD of -1045 fs^2 .

To start mode-locking, we have to first increase the absorbed pump power and then decrease it to 1.6 W, so that KLM starts by a current spike in the LD driver of the pump

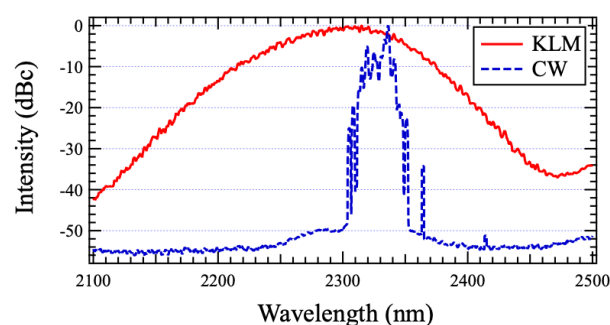


Fig. 1: A broadband spectrum obtained after KLM start-up (solid curve) and the CW spectrum (dashed curve).

fiber laser. The obtained broadband spectrum measured by an optical spectrum analyzer (Yokogawa, AQ6375E) is shown in Fig. 1, in which the resultant broadband spectrum after KLM start-up is compared to the CW spectrum. The obtained bandwidth of 84.5 nm corresponds to a Fourier-limit pulse duration of 89 fs. The output power of 135 mW is equally achieved in each arm of the ring cavity. We plan to resolve the pulse trains using two-photon absorption in a GHz-class InGaAs photodiode, in the near future. The stability of mode-locking is a function of the polarization of the pump fiber laser. Because of the gradual rotation of the polarization of the pump fiber laser, we find that KLM becomes unstable, and the ring cavity gets back to CW oscillation after a few minutes. To improve the stability of KLM, we are currently developing high-average-power polarized EY-doped all-fiber lasers.

3. Conclusion

We have developed a 500-MHz-class Cr:ZnS ring laser oscillator with a bidirectional output power of 135 mW and broadband spectrum supporting sub-100-fs pulse generation near a central wavelength of 2300 nm. Development of high-average-power polarized all-fiber pump lasers is expected to raise the KLM stability.

Acknowledgements

This project is funded by JSPS KAKENHI (24K01373); MEXT (Q-LEAP JPMXS0118068681); Amada Zaidan (AF-2023215-B3); We are grateful to Yokogawa for their support.

References

- [1] V. Schuster et al., *Opt. Express* **29**, 21859–21875 (2021).
- [2] T. Ideguchi et al., *Optica* **3**, 748–753 (2016).
- [3] A. Amani Eilanlou et al., *Appl. Phys. B* **130**, 119 (2024).

[9a-N204-1~8] 4.6 Terahertz Photonics

[9a-N204-1]

Measurement of Terahertz Wave Intensity Inside a LiNbO₃ Crystal for a Terahertz Parametric Generator Using Probe Beam Incident from the Z-surface

○Akitoshi Niidome¹, Sota Mine^{1,2}, Kodo Kawase¹, Kosuke Murate¹ (1.Nagoya Univ., 2.RIKEN)

[9a-N204-2]

Generation of tunable high-order terahertz vortices by soft-aperture DFG

○Mizuki Adachi¹, Yuzuru Sakai¹, Hayato Fujishiro¹, Katsuhiko Miyamoto^{1,2} (1.Chiba Univ., 2.Chiba Univ. MCRC)

[9a-N204-3]

Design of a Silicon-based THz Quarter-wave plate for a Spectral Drill Cavity

○(M1)Victor Isao Iwanaga¹, H. Shirasaka¹, S. Hayashi², K. Miyamoto³, Y. Urata⁴, K. Nawata⁵, J. Shikata⁶, N. Sekine², S. Ohno¹ (1.Tohoku Univ., 2.NICT, 3.Chiba Univ., 4.PHLUXI Inc., 5.Tohoku Inst. of Tech., 6.Nihon Univ.)

[9a-N204-4]

Terahertz optical skyrmions generation by DAST-DFG

○(M2)Rina Ito¹, Shusaku Mikami¹, Aoi Yamashita¹, Rihito Tamura¹, Kaito Sato¹, Wataru Senzaki¹, Yuto Yoneda¹, Katsuhiko Miyamoto^{1,2} (1.Grad Sch of Eng, Chiba Univ, 2.MCRC)

[9a-N204-5]

Two-Color Laser-Induced Microplasma THz Radiation at MHz Repetition Rate

○Tatsunosuke Hanano¹, Takumi Fukuda¹, David Bacon¹, Etienne Cardi², Stefan Skupin³, Luc Berge⁴, Sukhdeep Dhillon², Juliette Mangeney², Jerome Tignon², Julien Madeo¹, Keshav Dani¹ (1.OIST, 2.ENS, 3.Lyon 1 Univ, 4.Bordeaux Univ)

[9a-N204-6]

Integrated Terahertz Beam-steering Based on Injection-locked Resonant Tunneling Diodes and Silicon Waveguide Platform

○(P)Weijie Gao¹, Nguyen Ngo¹, Daiki Ichikawa¹, Yuta Inose¹, Shuichi Murakami², Yoshiharu Yamada², Hidemasa Yamane², Yosuke Nishida³, Safumi Suzuki⁴, Masayuki Fujita¹ (1.Osaka Univ., 2.ORIST, 3.ROHM. Co. Ltd, 4.Inst. Sci. Tokyo)

[9a-N204-7]

High-Efficiency Terahertz Harmonic Generation from Two-Dimensional MoS₂

○(D)Youwei Wang¹, Kosaku Kato¹, Thanh Nhat Khoa Phan¹, Verdad C. Agulto¹, Mikihiko Nishitani¹, Goro Isoyama², Makoto Nakajima¹ (1.ILE, the Univ. of Osaka, 2.SANKEN, the Univ. of Osaka)

[9a-N204-8]

Power Combination of Resonant Tunneling Diodes Using Terahertz Photonic-Crystal Y-branch Circuit

○(P)Ngo Hoai Nguyen¹, Yuta Inose¹, Yuki Morita¹, Yosuke Nishida², Yoshiharu Yamada³, Hidemasa Yamane³, Shuichi Murakami³, Masayuki Fujita¹ (1.The Univ. of Osaka, 2.ROHM, 3.ORIST)

Measurement of Terahertz Wave Intensity Inside a LiNbO₃ Crystal for a Terahertz Parametric Generator Using Probe Beam Incident from the Z-surface

Akitoshi Niidome¹, Sota Mine^{1,2}, Kodo Kawase¹, Kosuke Murate¹

¹ Nagoya University, ²RIKEN

E-mail: niidome.akitoshi.n7@s.mail.nagoya-u.ac.jp

1. Introduction

The injection-seeded terahertz (THz)-wave parametric generator (is-TPG) is a high-intensity, single-frequency THz-wave source with wide frequency tunability from 0.4 to 5.0 THz [1]. Although previous studies have simulated the generation and intensity distribution of THz-waves inside MgO:LiNbO₃ crystals, detailed observations of the THz-wave amplification process have been rarely reported. Therefore, the mechanisms of THz-wave generation and amplification inside the crystal of the is-TPG are not yet fully understood. In our previous work, we injected a probe beam from the Y-surface of the MgO:LiNbO₃ crystal and observed Stokes beam upconverted from the THz-waves generated within the crystal, allowing us to monitor the amplification of THz-waves along the x-axis, corresponding to the propagation direction of the pump beam [2]. In the present study, to investigate THz-wave propagation not only along the x-axis but also along the y-axis, we attempted to observe the THz-waves by injecting the probe beam from the Z-surface of the crystal.

2. Method & Results

Figure 1(a) shows the experimental setup. Because the detection Stokes beam is very weak to measure, we used an additional MgO:LiNbO₃ crystal as a parametric amplifier prior to observation with a near-infrared (NIR) camera. To observe the THz-wave distribution at different positions within the generation crystal, the probing position was scanned using a stage. For data processing, pixels corresponding to the detection Stokes beam were extracted from the camera images, and a heatmap was generated by arranging the data laterally according to the stage position.

Figure 1(b) shows the result of probing THz parametric fluorescence generated when only the pump beam was incident on the MgO:LiNbO₃ crystal. The horizontal axis represents the distance from the pump beam input surface (the left side of the generation crystal in Fig. 1(a)), while the vertical axis corresponds to the pixel position on the NIR camera. Since the detection Stokes beam is generated under non-collinear phase-matching conditions, the frequency of the THz-wave can, in principle, be estimated from the pixel position on the NIR camera. However, the frequency was not calibrated in this experiment, so only the pixel positions are shown instead. It was observed that the THz parametric fluorescence gradually increased at approximately 40 mm from the input surface of the generation crystal.

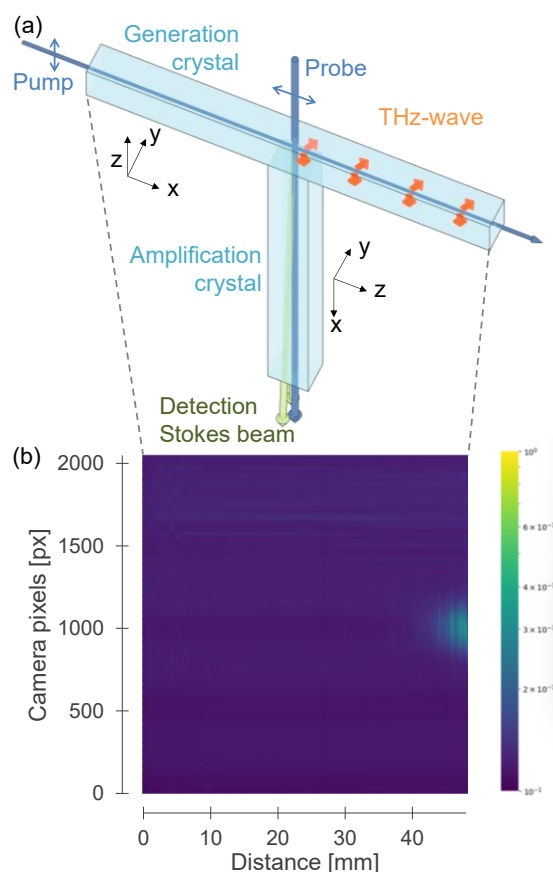


Fig. 1 (a) Experimental setup and data processing. (b) Probing results of THz parametric fluorescence. The left side is front of the crystal.

3. Conclusions

In this study, the probe beam was injected from the Z-surface of the crystal, and THz parametric fluorescence was observed. This result suggests that the spatial distribution of THz-waves in the xy-plane of the crystal can be measured.

Acknowledgements

This work was partially supported by Japan Science and Technology Agency (JST) ASPIRE Program (JPMJAP2340) and FOREST Program (JPMJFR212J), Japan Society for the Promotion of Science KAKENHI (22J20963, 24K00943).

References

- [1] K. Murate, S. Mine, and K. Kawase, IEEE J. Sel. Top. Quantum Electron. **29** (2023) 1.
- [2] A. Niidome, S. Mine, K. Kawase, K. Murate, The 72nd JSAP Meeting Spring **3** (2025) 261.

Generation of tunable high-order terahertz vortices by soft-aperture DFG

Mizuki Adach¹, Yuzuru Sakai¹, Hayato Fujishiro¹, Katsuhiko Miyamoto^{1,2}

¹ Chiba University, ² Molecular Chirality Research Center, Chiba University
E-mail: k-miyamoto@faculty.chiba-u.jp

1. Introduction

Optical vortices have an annular intensity spatial profile and exhibit orbital angular momentum (OAM) determined by a topological charge, ℓ [1]. The utilization of optical vortices in the visible to near-infrared spectrum is extensively researched [2]. Terahertz (THz) vortices possess the potential to offer innovative enhanced spectroscopic capabilities, including the identification of two-dimensional materials with high spatial resolution.

We have previously shown soft aperture difference frequency generation (DFG) with a Gaussian beam and optical vortex as pump beams, successfully producing frequency-tunable THz vortices with topological charge $\ell=1$ [3]. In this presentation proposes an expansion of this technology to produce second-order and higher THz vortices with high purity and tunable frequency.

2. Experiments

Figure 1 illustrates an experimental configuration for producing tunable high-order THz vortices via a soft aperture difference frequency generation (DFG) with a DAST crystal. A 1.5 μm dual-wavelength light source, produced by a custom PPSLT-OPA, is employed to excite the DAST crystals, thereby generating the THz outputs. The wavelength λ_1 was set at 1.56 μm . Its Gaussian mode output was converted into an optical vortex ($\ell = 2$ and 3) using a spiral phase plate (SPP) at the wavelength of 1.56 μm . The output wavelength λ_2 was tunable from 1.51 to 1.64 μm , and within this range, the intensity distribution retained a Gaussian profile. The two beams were subsequently concentrated onto a DAST crystal, producing a high-order THz vortex output. The output power was measured with a cryogenic silicon bolometer and a room temperature detector (Gentec: THZ5B-BL). A THz camera (NEC IRV-T0832) was utilized to evaluate the intensity distribution of THz beams.

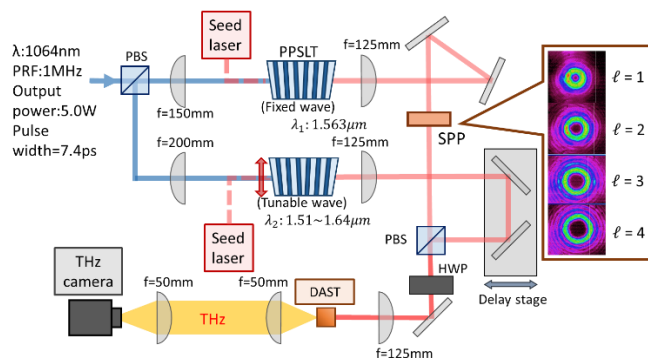


Fig.1 Experimental setup for high-order THz vortex source.

3. Experimental results

The experiment intensity distributions of high-order THz vortex by soft-aperture DFG are summarized in Fig.2 (a) and (b). The DFG outputs at the 4 THz exhibited an annular spatial profile originated from phase singularity. Figure 2 (c) and (d) show also intensity distribution by astigmatic focusing method [4]. It should be noted that the number of dark spots in the figure corresponds to topological charges, which are $\ell = 2$ and 3, respectively. The tuning range of the high-order THz vortices extended from 3 to 6 THz, with maximum output powers of 3.5 and 3.0 μW at 4 THz, respectively.

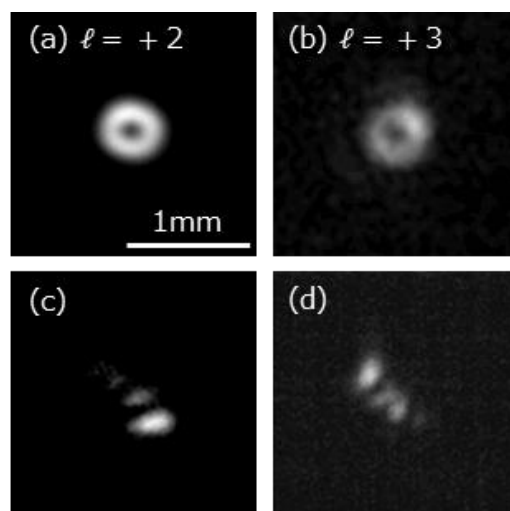


Fig.2 Intensity distributions of the 4 THz ($\ell = 2, 3$) (a), (b)), a conventional lens, and ((c), (d)), a tilted lens

4. Conclusions

Within the frequency range of 3 to 6 THz, we have successfully produced high-order THz vortices. The beam profile demonstrated a distinct ring at all terahertz frequencies that were measured during the experiment. The advanced THz spectroscopy that originates from OAM will be accessible through the use of an OAM- and frequency-versatile THz vortex source.

References

- [1]. L. Allen *et al.*, Phys Rev A **45** (1992) 8185–8189.
- [2]. Y. Shen *et al.*, light: science & applications. **8** (2019) 90.
- [3]. K. Miyamoto *et al.*, Opt. Express **27** (2019) 31840-31849.
- [4]. P. Vaity *et al.*, Physics Letters A, **377** (2013) 1154-1156.

Design of a Silicon-based THz Quarter-wave plate for a Spectral Drill Cavity

Tohoku Univ.¹, NICT², Chiba Univ.³, PHLUXi Inc.⁴, Tohoku Inst. of Tech.⁵, Nihon Univ.⁶

[○]V. I. Iwanaga¹, H. Shirasaka¹, S. Hayashi², K. Miyamoto³, Y. Urata⁴, K. Nawata⁵, J. Shikata⁶,

N. Sekine², S. Ohno¹

E-mail: victor.isao.iwanaga.r8@dc.tohoku.ac.jp

Recently, Landau quantization in photonic systems, similar to the Landau levels of electrons in a uniform magnetic field, has gained significant attention in fundamental physics. These Photonic Landau levels, generally arising from pseudomagnetic fields acting on a photonic system, offer a meaningful analogy between the behaviors of electrons and photons [1]. In this context, a bridge can be drawn between a two-dimensional electron gas and optics by considering the geometric phase experienced by light inside a Fabry–Pérot cavity, induced by a geometric phase shifter [2]. Referred to as a Spectral drill, the rotation of broadband wave plates is required to enable continuous axis mode sweeping, the result of which could potentially reveal phase information about photonic Landau levels by constructing a spectral drill in the THz band.

In this work, we have designed a silicon subwavelength grating that exhibits quarter-wave plate (QWP) behaviour at THz frequencies [3]. Its operating principle is from birefringence, where continuous tuning of the proportionality between the grating period and height determines the QWP operating frequency in a selectable manner. Specifically, FDTD simulations of QWP gratings operating from 1.2 to 0.4 THz are performed using MEEP demonstrating a relative bandwidth of approximately 50% by assuming a 3% tolerance in phase difference between orthogonal polarizations, as depicted in **Fig. 1**. Such broadband qualities are realized by a double-dip shape around the desired center frequency in the phase difference spectrum, as seen in **Fig. 2**. For applications requiring strict QWP behaviour within a 0.5% tolerance, a grating design that produces a disconnected plateau shape in the phase difference spectrum is considered, whose weighted relative bandwidth reaches approximately 40%.

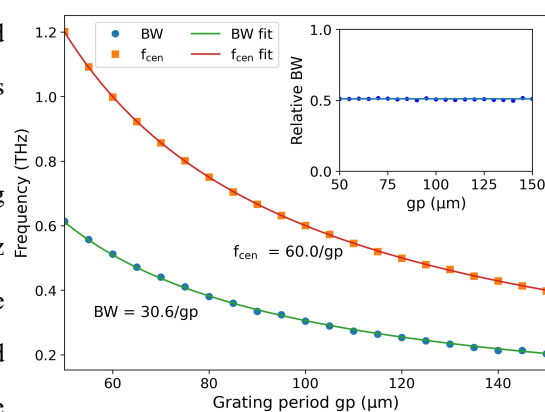


Fig.1: Grating period dependence of center frequency and bandwidth. Inset shows the corresponding relative bandwidth.

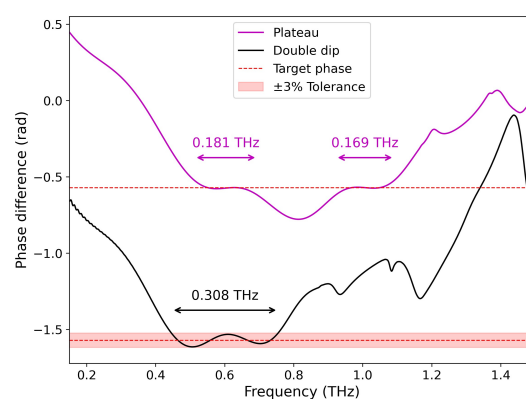


Fig.2: Phase difference spectra. Plateau-shaped spectrum is shifted up 1 rad for clarity.

This work was partially supported by Tohoku University – NICT matching fund.

[1] J. Pan, Z. Wang, Y. Meng, X. Fu, Y. Shen, Q. Liu, *Communications Physics*, vol. 8, pp. 111, 2025.

[2] S. Ohno, *OSA Continuum*, vol. 1, pp. 136-144, 2018.

[3] B. Z. a. Y. Gong, *Opt. Express*, vol. 23, pp. 14897-14902, 2015.

Terahertz optical skyrmions generation by DAST-DFG

Rina Ito¹, Shusaku Mikami¹, Aoi Yamashita¹, Rihito Tamura¹, Kaito Sato¹, Wataru Senzaki¹,
Yuto Yoneda¹, Katsuhiko Miyamoto^{1,2}

¹Graduate School of Engineering, Chiba University,

²Molecular Chirality Research Center, Chiba University

E-mail: k-miyamoto@faculty.chiba-u.jp

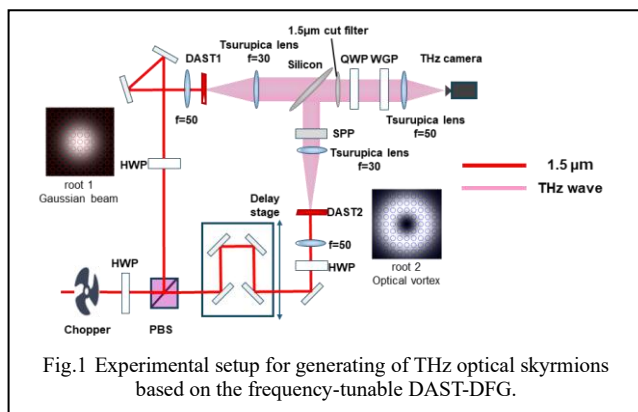
1. Introduction

Optical skyrmions [1], a kind of structured light [2] characterized by topologically stable configurations and unique polarization textures, have garnered significant interest due to their potential in applications such as optical manipulation [3] etc. Interactions between optical skyrmions and magnetic materials are particularly expected to be significant in the terahertz (THz) frequency. However, to date, optical skyrmions have only been realized in the visible and near-infrared spectral ranges. Its generation in the THz frequency range remain difficult, primarily due to technical challenges.

In this presentation, we report on the results of generating optical skyrmions at 4 THz based on the difference frequency generation (DFG) using a 4-N, N-dimethylamino-4'-N'-methylstilbazolium tosylate (DAST) crystal [4].

2. Experiments

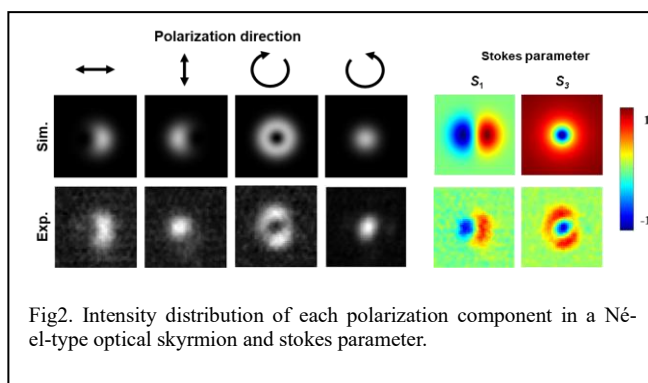
Figure 1 shows the experimental apparatus for generation THz optical skyrmions. A homemade two-wavelength 1.5 μm band pump source based on periodically poled stoichiometric lithium tantalite (PPSLT) optical parametric amplifier (OPA). The THz output from the DAST1 crystal propagates with a Gaussian beam profile, while the THz output from the DAST2 crystal is converted into a first-order optical vortex utilizing a Tsurupica spiral phase plate [5]. The beams from the two paths overlap spatially on the silicon substrate and are also overlapped temporally by the optical delay line. The quarter wave plate (QWP) transforms them into orthogonal circularly polarized beams, so producing the THz optical skyrmions. The intensity distribution of linear polarization for each THz optical skyr-



mion was specifically evaluated utilizing a wire grid polarizer in combination with a THz camera (NEC T0832).

3. Results

Figure 2 summarizes the experimental results of the generated THz optical skyrmion. The orbital angular momentum of the optical vortex is +1, and the frequency is adjusted to 4 THz. The arrows at the top of the image indicate the polarization direction, which corresponds to the direction of the wire grid polarizer (WGP). The intensity distribution rotated in the same direction of rotation as the WGP indicated the presence of Néel-type optical skyrmions. The estimated skyrmion number for this beam is ~ 0.88 (the ideal value is 1), attributable to the low signal-to-noise ratio.



Summary

We have successfully demonstrated the generation of THz optical skyrmions with Néel-type polarization texture at a frequency of 4THz.

References

- [1] Y. Shen, X. Wang, Z. Xie, C. Min, X. Fu, Q. Liu, M. Gong, X. Yuan, *Light: Science & Applications*, **8** (2019) 90.
- [2] A. Forbes, M. de. Oliveira, M. R. Dennis, *Nat. Photonics*, **15** (2021) 253.
- [3] R. Tamura, P. Kumar, A. S. Rao, K. Tsuda, F. Getzlaff, K. Miyamoto, N. M. Litchinitser, T. Omatsu, *APL Photonics*, **9** (2024) 046104.
- [4] K. Miyamoto, K. Sano, T. Miyakawa, H. Niinomi, K. Toyoda, A. Vallés, T. Omatsu, *Opt. Express*, **27** (2019) 31840.
- [5] K. Miyamoto, K. Suizu, T. Akiba, T. Omatsu, *Appl. Phys. Lett.*, **104** (2014) 261104.

Two-Color Laser-Induced Microplasma THz Radiation at MHz Repetition Rate

○(D) T. Hanano¹, T. Fukuda¹, D. R. Bacon¹, E. Cardi², S. Skupin³, L. Bergé⁴, S. Dhillon², J. Mangeney², J. Tignon², J. Madéo¹ and K. M. Dani¹

¹Femtosecond Spectroscopy Unit, Okinawa Institute of Science and Technology Graduate University, Onna, Okinawa, Japan 904-0495, ²Laboratoire de Physique de l'École Normale Supérieure, ENS, Université PSL, CNRS, Sorbonne Université, Université Paris Cité, 75005 Paris, France, ³Université de Lyon 1 - CNRS, Institut Lumière Matière, UMR 5306, 69622 Villeurbanne, ⁴Centre des Lasers Intenses et Applications, Université de Bordeaux, CNRS, CEA, 33405 Talence, France.

E-mail: t.hanano@oist.jp

1. Introduction

In recent years, there has been a growing interest for sources of high-field and broadband THz radiation operating at high repetition rate, which offers high signal-to-noise ratio (SNR) and fast acquisition rates. Among the typical methods for generating THz radiation, two-color laser-induced plasma stands out for its potential scalability with no damage threshold limitations. However, current methods rely on mJ-class systems that either operate at kHz repetitions, providing low SNR [1] or require extremely high average power at higher repetition rate [2], thus limiting the practical use of plasma-based THz sources. Here, we explore the use of microplasmas [3, 4], with micron-scale spot size, enabling the use of μ J- and MHz-class lasers to produce THz radiation. In this talk, we will present the first results of two-color microplasma-based THz radiation at MHz repetition rate.

2. Experiment

We generate THz radiation from the two-color microplasma using a Yb: fiber amplifier operated at 1 MHz with a 250 fs pulse duration and a pulse energy of 27 μ J. We generate second harmonic (515 nm) in a BBO crystal, leading to a pulse energy corresponding to 16% of the fundamental (1030 nm). Both fundamental and second

harmonic beams are tightly focused by a concave mirror with 12 mm focal length. We use electro-optic sampling with a 1 mm ZnTe crystal (110) to measure the THz temporal waveform (Fig.1a) showing a 2 THz bandwidth (Fig.1b), currently limited by the gating beam pulse duration.

3. Conclusion

We demonstrate THz radiation from two-color microplasma, using a μ J-class laser at MHz repetition rate. Future improvements to access the full spectrum bandwidth and optimization towards high-field magnitude and large bandwidth will be discussed.

Acknowledgement

This work was supported by the Femtosecond Spectroscopy Unit of the Okinawa Institute of Science and Technology Graduate University.

References

- [1] T. I. Oh et al., Appl. Phys. Lett. **105**, 041103 (2014).
- [2] J. Buldt et al., Opt. Lett. **46**, 5256 (2021).
- [3] F. Bucccheri and X.-C. Zhang, Optica **2**, 366 (2015).
- [4] I. Thiele et al., Phys. Rev. A **96**, 053814 (2017).

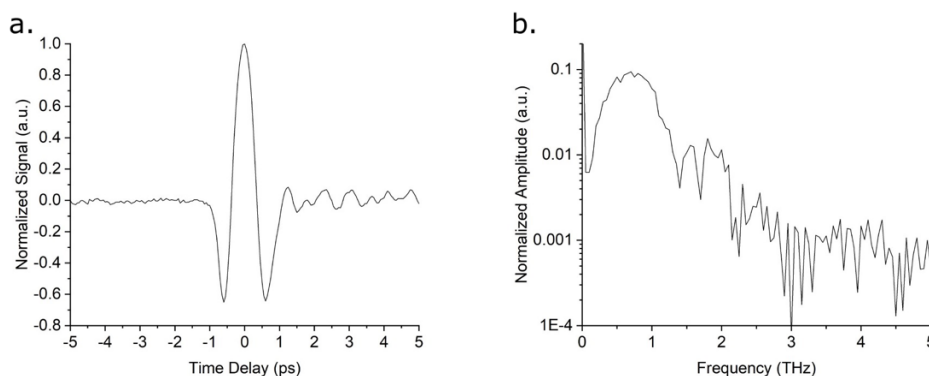


Figure 1. **a.** Normalized THz waveform from two-color microplasma, and **b.** Normalized spectrum.

Integrated Terahertz Beam-steering Based on Injection-locked Resonant Tunneling Diodes and Silicon Waveguide Platform

Osaka Uni¹, ORIST², ROHM. Co. Ltd.³, Inst. Sci. Tokyo⁴, [○]Weijie Gao¹, Nguyen H. Ngo¹,
Daiki Ichikawa¹, Yuta Inose¹, Shuichi Murakami², Yoshiharu Yamada², Hidemasa Yamane²,
Yosuke Nishida³, Safumi Suzuki⁴, and Masayuki Fujita¹

E-mail: gao.weijie.es@osaka-u.ac.jp

Terahertz beamformers are emerging as indispensable components for next-generation wireless systems, promising ultra-high data rates, directional communication, and high-resolution imaging [1]. However, achieving agile and efficient beam steering at terahertz frequencies remains a major challenge due to the lack of compact, low-loss, and electrically tunable components that are compatible with planar integration. Existing solutions such as mechanically reconfigurable lenses, frequency-scanned leaky-wave antennas, or metasurface-based techniques either suffer from limited tuning speed, high insertion loss, or poor integration scalability, leaving a critical gap in realizing high-performance on-chip terahertz beamforming systems.

In this work, we present an electronically beam-steerable antenna operating at the 300-GHz band, enabled by resonant tunneling diodes (RTDs) integrated with a silicon effective-medium waveguide platform [2]. As shown in Fig. 1(a), the proposed architecture consists of two subwavelength-spaced silicon waveguides, each clad with an anisotropic effective medium and terminated by a rod antenna. Each path is driven by an injection-locked RTD oscillator [3] shown in Fig. 1(b), whose output phase is dynamically controlled through bias voltage tuning [4]. An integrated 3-dB power divider and directional couplers ensure coherent signal delivery and synchronized operation between the RTDs. By exploiting the bias-tunable phase response of RTDs, dynamic beam steering is achieved through phased-array principles without relying on bulky or lossy phase shifting components. Both experimental measurements and electromagnetic simulations show a beam-steering range of $\pm 20^\circ$, as illustrated in Fig. 1(c), demonstrating the first realization of active electronic beam steering at terahertz frequencies using RTD-based phased arrays. Compared to CMOS or photonic-based beamforming systems, our RTD-silicon integration offers significant advantages in terms of simpleness, phase control agility, and low insertion loss. Moreover, the planar nature of architecture allows for scalable integration, making it suitable for large-scale phased arrays in future communication and sensing platforms. This work introduces a new class of terahertz integrated beamformers that combine nonlinear electronic oscillators with silicon photonic waveguide engineering. The proposed RTD-based phased-array antenna represents a foundational step toward fully integrated, electronically reconfigurable terahertz frontends, addressing key demands of future 6G and beyond networks, real-time imaging, and broadband radar systems. This work was partly supported by JST CREST (JPMJCR21C4) and KAKENHI (24H00031).

References

- [1]. W. Wang *et al.*, *Nature*, **632**, (2024) 8025.
- [2]. W. Gao *et al.*, *Opt. Express*, **27**, (2019) 26.
- [3]. N. Ngo *et al.*, *APMC* 2023.
- [4]. Y. Suzuki *et al.*, *IEEE Trans. THz Sci. Techno.*, **12**, (2022) 5.

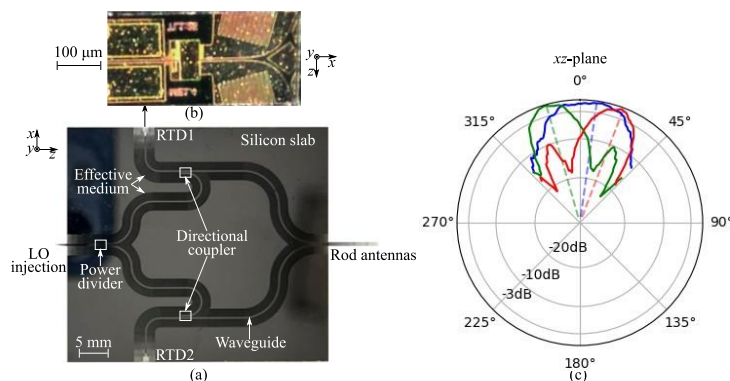


Fig.1. (a) Fabricated terahertz integrated beamformer based on all-silicon effective-medium-clad waveguide platform. (b) Microscope image of RTD chip. (c) Measured radiation patterns with beam angle at -20° , 0° and 20° at 340 GHz.

High-Efficiency Terahertz Harmonic Generation from Two-Dimensional MoS₂

You Wei Wang¹, Kosaku Kato¹, Thanh Nhat Khoa Phan¹, Verdad C. Agulto¹,
Mikihiko Nishitani¹, Goro Isoyama², Makoto Nakajima¹

¹ Institute of Laser Engineering, The University of Osaka, ² SANKEN, The University of Osaka,
E-mail: nakajima.makoto.ile@osaka-u.ac.jp

1. Introduction

In recent years, advancements in the intensity of terahertz (THz) sources like THz free-electron lasers (THz-FELs) have made it possible to conduct research on harmonic generation (HG) in the THz regime [1,2]. HG in the THz regime originates primarily from the nonlinear response of conduction electrons, in contrast to the inter-band-driven mechanisms typical in the optical regime. Graphene, owing to its linear band structure, has demonstrated efficient THz-driven HG [3]. However, its HG efficiency tends to saturate under strong-field excitation due to rapid carrier heating and associated nonlinear conductivity saturation. In contrast, molybdenum disulfide (MoS₂), a two-dimensional (2D) semiconductor, exhibits a stronger nonlinear response than graphene in the optical regime. This improvement is attributed to the trigonal warping of its band structure, which introduces anisotropy near the high-symmetry points and enables enhancing the nonlinear optical response [4]. These features also make 2D-MoS₂ a promising material for efficient HG in the THz regime. Nevertheless, its nonlinear behavior in the THz regime has not yet been reported. In this presentation, we report our recent observations on the characteristics of THz-HG from 2D-MoS₂.

2. Experiment

The 2D-MoS₂ samples were grown on Si/SiO₂ substrates using chemical vapor deposition. Raman scattering measurements identified the MoS₂ film as a trilayer. For the THz-HG experiments, we employed the THz-FEL at the SANKEN, the University of Osaka [5]. The central frequency of the THz-FEL waves was set to 2.9 THz, and harmonic components in the output were removed by transmitting the beam through synthetic quartz.

The fundamental THz wave was focused onto the 2D-MoS₂ sample at an incident angle of 45°, and the generated third harmonic (THG) harmonics radiated in the reflection direction were detected using a DLATGS (JASCO), and fifth harmonics were detected by an MCT detector (Hamamatsu Photonics). The fundamental THz wave was blocked by the window KRS-5, which works as a frequency filter set in front of the detector. The harmonic spectrum was obtained by Fourier transforming the signal recorded using a Michelson interferometer.

3. Results

When a 2.9 THz fundamental wave was incident on the 2D-MoS₂ sample, we observed signals with central fre-

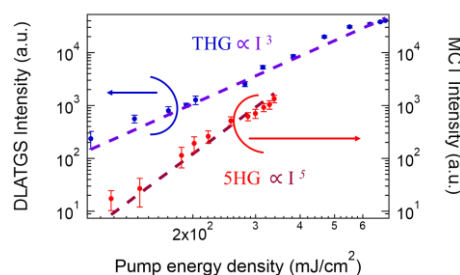


Fig1. The dependence of HG on the pump energy density I .

quencies at 8.6 THz and 14.3 THz, corresponding to the THG and 5HG, respectively. Furthermore, we investigated the dependence of the HG intensity on the intensity of the pump energy density I showing in Fig.1. Over a range of input energy densities from 110 mJ/cm² to 700 mJ/cm² (Maximum electric field strengths 1 MV/cm), the THG intensity was found to scale nearly cubically and with the intensity of the fundamental wave, while the 5HG intensity exhibited a fifth-order dependence. Meanwhile, when the maximum incident fundamental pulse energy at the sample was 1.9 mJ, the THG pulse had an energy of 7.5 nJ, corresponding to an energy conversion efficiency of 4×10^{-6} , which is equivalent to the reported value for graphene [3]. Unlike other materials [1,3], MoS₂ thin films retain nonlinear susceptibility under high excitation intensity, enabling efficient and stable harmonic conversion.

4. Conclusion

We demonstrated THz-HG from 2D-MoS₂ using the THz-FEL. The MoS₂ films exhibited a high HG efficiency comparable to that of graphene, and importantly, maintained high efficiency even under strong excitation, making it a promising candidate for HG wavelength conversion devices.

Acknowledge

This work was supported by JSPS, grant numbers KAKENHI JP20H02206, JP23K17748, JP24H00317, JP24H02232, and JST SPRING, Grant Number JPMJSP2138.

References

- [1] Thanh Nhat Khoa Phan, et al., Opt. Lett. **49** (2024) 1073.
- [2] Thanh Nhat Khoa Phan, et al., Opt. Lett. **49**, (2024) 5039.
- [3] Hassan A. Hafez, et al., Nature **561**, (2018) 507.
- [4] Säynätjoki, A., Karvonen, et al., Nat Commun **8**, (2017) 893.
- [5] Keigo Kawase, et al., Nucl. Instrum. Methods Phys. Res. **960**, (2020) 163582.

Power Combination of Resonant Tunneling Diodes Using Terahertz Photonic-Crystal Y-branch Circuit

Nguyen H. Ngo¹, Yuta Inose¹, Yuki Morita¹, Yosuke Nishida², Yoshiharu Yamada³,
Hidemasa Yamane³, Shuichi Murakami³, Masayuki Fujita¹

¹ The University of Osaka, ² ROHM Co., Ltd., ³ Osaka Research Institute of Industrial Science and Technology
E-mail: ngo.h-nguyen.es@osaka-u.ac.jp

Recently, the development of information communication technologies toward 6G and beyond has accelerated the adoption of silicon-based terahertz integrated circuits [1]. Substrateless silicon waveguides [2], which offer ultralow-loss properties, are well-suited for interconnects [3] with various functional designs. Among terahertz sources, resonant tunneling diodes (RTDs) have emerged as compact, self-oscillating devices capable of emitting terahertz waves up to ~ 2 THz, with various applications in communications, sensing, and imaging [4]. Most conventional RTDs primarily employ backside radiation, achieving milliwatt powers [5], but they are not suitable for integration with the silicon waveguides. To overcome this limitation, in-plane radiating RTDs have been developed [6], although their output power remains limited to a few tens of microwatts.

In this paper, we demonstrate power combining from two in-plane RTD chips using a photonic-crystal Y-branch waveguide. The Y-branch waveguide is based on a silicon photonic-crystal slab structure [7]. To match the RTDs' oscillation frequencies, the air holes are designed with a lattice constant (a) of $216\ \mu\text{m}$, a radius of $0.3a$, and a thickness of $200\ \mu\text{m}$. To achieve high transmittance, the sizes of air holes localized at the Y-junction are optimized [8], yielding operation in the 345–380 GHz range.

The experimental setup for measuring the combined power is shown in Fig. 1. The RTD was fabricated on a $100\text{-}\mu\text{m}$ InP substrate, incorporating an in-plane tapered slot antenna [6]. Each RTD was biased via ground-signal probes, while the output port was connected to a spectrum analyzer through a WR-2.8 hollow waveguide. The RTDs were carefully selected to ensure consistent oscillation frequencies and powers. Separately, the two RTDs in the Y-branch waveguide exhibited oscillation frequencies of 356.0 GHz and 356.9 GHz, with measured powers of -32.0 dBm and -35.3 dBm, respectively. When operated simultaneously, they exhibited an identical oscillation frequency at 357.5 GHz with an output power of -27.4 dBm. This power increase suggests that the RTDs were mutually injection-locked, with phase matching between them leading to constructive interference.

The proposed all-silicon Y-branch waveguide demonstrates the feasibility of power combining from individual RTD oscillators. Further power enhancement can be made by using a larger number of better-matched RTDs and increasing the transmittance of the waveguide system.

This work was supported in part by the JST CREST (JPMJCR21C4) and KAKENHI (24H00031).

References

- [1] M. Fujita, NAFOSTED Conference on Information and Computer Science **8** (2021) 348.
- [2] D. Headland *et al.*, APL Photonics **8** (2023) 091101.
- [3] N. H. Ngo *et al.*, IEEE Photonics Conference (2024).
- [4] S. Suzuki *et al.*, Applied Physics Express **17** (2024) 070101.
- [5] S. Suzuki *et al.*, IEEE International Electron Devices Meeting (2024).
- [6] X. Yu *et al.*, Electronics Letters **55** (2019) 398.
- [7] K. Tsuruda *et al.*, Optics Express **21** (2015) 31977.
- [8] M. Danaie *et al.*, International Journal of Optics and Photonics **12** (2018) 33.

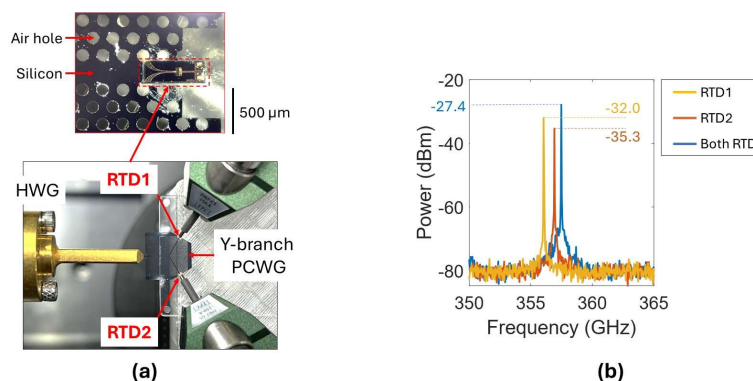


Fig. 1 (a) Experimental setup of the power combiner using two RTDs. (b) Measured power spectra of separate RTDs and both RTDs activated. HWG: hollow waveguide, PCWG: photonic crystal waveguide.

4 JSAP-Optica Joint Symposia 2025 | 一般セッション(口頭講演) : 4.6 Terahertz Photonics

[10a-N203-1~9] 4.6 Terahertz Photonics

[10a-N203-1]

[JSAP-Optica Joint Symposia Invited Talk] Sub-10 nm nano-gaps for terahertz spectroscopy of interfacial water

○Jeeyoon Jeong¹ (1.Kangwon Natl. Univ.)

[10a-N203-2]

Single-Cell Imaging and Spectroscopy Using Scanning Point Terahertz Source Microscopy

○(P)Yaheng Wang¹, Luwei Zheng², Hironaru Murakami³, Masayoshi Tonouchi¹, Takahisa Matsuzaki², Kazunori Serita⁴ (1.Okayama Univ., 2.The Univ. of Osaka, 3.Fukui Univ. of Tech., 4.Waseda Univ.)

[10a-N203-3]

Thickness Dependence Resonance Characteristics of Meta-Atoms Excited by a Point Terahertz Source

○Yixin Zhao¹, Kazunori Serita¹ (1.Waseda Univ.)

[10a-N203-4]

Fundamental Study of a Terahertz Scanner Using Parametric Wavelength Conversion

○Koya Tsubota¹, Sota Mine^{1,2}, Kodo Kawase¹, Kosuke Murate¹ (1.Nagoya Univ., 2.RIKEN)

[10a-N203-5]

Imaging of the catalytic reaction of platinum-thin-films with hydrogen gas using a terahertz chemical microscope

○Takuya Yamanaka¹, Jin Wang¹, Toshihiko Kiwa¹ (1.Okayama Univ.)

[10a-N203-6]

[JSAP-Optica Joint Symposia Invited Talk] Development of Novel Terahertz Light Source Using Resonant Tunneling Diodes

○Takashi Arikawa¹ (1.Univ. of Hyogo)

[10a-N203-7]

Semiquantitative interfacial characterization of $\text{Hf}_x\text{Zr}_{1-x}\text{O}_2/\text{Si}$ heterojunctions via terahertz emission spectroscopy○(D)TIANKAI JIA¹, Haining Li², Manjakavahoaka Razanoelina¹, Takahiro Teramoto³, Takeshi Kijima², Hiroyasu Yamahara², Munetoshi Seki², Hitoshi Tabata², Masayoshi Tonouchi⁴, Iwao Kawayama¹ (1.Kyoto Univ., 2.The Univ. of Tokyo, 3.The Univ. of Kitakyushu, 4.Okayama Univ.)

[10a-N203-8]

Multimode Laser-Driven CW-THz TDS for Ammonia Gas Sensing

○(D)Yuanhao Zeng¹, Keiji Komatsu², Kosaku Kato¹, Verdad C. Agulto¹, Thanh Nhat Khoa Phan¹, Toshiyuki Iwamoto^{1,3}, Makoto Nakajima¹ (1.ILE, The Univ. of Osaka, 2.Dept. of Mat. Sci. & Bioeng., Nagaoka Univ. of Tech., 3.Nippo Precision Co., Ltd.)

[10a-N203-9]

Terahertz characterization of silver nanoparticles with fractal structures in polymethyl methacrylate films

○Sota Itayama¹, Tomoki Kawahara¹, Jin Wang¹, Takeyasu Nobuyuki¹, Kiwa Toshihiko¹
(1.Okayama Univ.)

Sub-10 nm nano-gaps for terahertz spectroscopy of interfacial water**Kangwon National University and Institute of Quantum Convergence Technology¹, °Jeeyoon Jeong¹****E-mail: peterjyy@kangwon.ac.kr**

Understanding the behavior of water confined within nanoscale environments is crucial across numerous scientific disciplines, as it underpins key phenomena such as ion solvation, molecular transport, and interfacial electrochemical processes. A central focus has been the dielectric properties of nanoconfined water, especially the reduced permittivity arising from the restricted dipole reorientation of interfacial water layers. While recent advances have enabled direct measurements of static permittivity using two-dimensional material-based nanocavities and electrostatic force microscopy, insights into the high-frequency (optical) permittivity remain limited. Previous optical studies often relied on systems like nanoporous media or beryl crystals, which lack precise control over water layer thickness below 10 nm. Although ultrathin water films can be prepared under cryogenic and vacuum conditions, these are not representative of biologically relevant environments. Therefore, developing an ambient-compatible platform for systematic optical characterization of nanoconfined water remains an urgent goal for advancing both fundamental science and biomolecular applications. In this talk, we will discuss (1) fabrication of sub-10 nm metallic gaps suitable for enhancing terahertz absorption, (2) means to couple water into such gaps for sensitive terahertz spectroscopy of nanoconfined water, and (3) observation of reduced terahertz permittivity of the nanoconfined water, which is found to arise from confinement effect suppressing the long-range collective motion of water molecules, in addition to the previously well-known interfacial effect.

Single-Cell Imaging and Spectroscopy Using Scanning Point Terahertz Source Microscopy

Yaheng Wang¹, Luwei Zheng², Hironaru Murakami³, Masayoshi Tonouchi¹, Takahisa Matsuzaki⁴,
Kazunori Serita⁵

¹ Research Institute for Interdisciplinary Science, Okayama University, ² Institute of Laser Engineering, The University of Osaka, ³ Department of Electrical, Electronic and Computer Engineering, Fukui University of Technology, ⁴ Department of Applied Physics, The University of Osaka, ⁵ Graduate School of Information, Production, and Systems, Waseda University
E-mail: yahengwang@okayama-u.ac.jp

1. Introduction

Terahertz (THz) technology, with its high sensitivity to water content and biomolecular interactions, along with its non-invasive and label-free nature, offers significant advantages over conventional methods in cancer detection and holds great promise for advancing precision medicine. While current THz biomedical imaging studies focus on tumor or tissue-level analysis [1,2], effective exploration at the single-cell scale remains largely uncharted. In our previous work, we successfully demonstrated THz imaging of 1 mm cancer tissue and cell using the Scanning Point THz Source (SPoTS) microscopy [3,4]. To further extend its application to the microscale, this study successfully achieved THz reflection-mode imaging of approximately 10 μm mouse melanoma cells.

2. SPoTS Microscopy

The configuration of the SPoTS microscopy is illustrated in Fig. 1. A 1.56 μm femtosecond (fs) laser is split into pump and probe beams. The pump beam, modulated by an optical chopper, passes through a galvanoscanner, lenses, and an ITO sheet, and is focused onto a GaAs substrate to generate THz waves via optical rectification. Since the beam diameter of the THz source is limited by the fs laser wavelength, near-field THz measurements of samples with subwavelength resolution can be achieved. The ITO sheet transmits the laser while reflecting THz waves, which are focused onto the THz detector. The probe beam, converted to 780 nm by a PPLN crystal, activates the THz detector. Time-domain THz waveforms are obtained by scanning a delay stage, and the sample coated on the GaAs substrate is scanned using a mechanical XY moving stage.

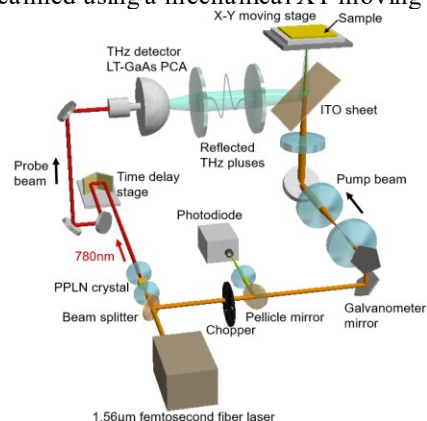


Figure 1. Configuration of SPoTS microscopy.

3. Single-Cell THz Imaging Results

Mouse melanoma cell lines with high and low metastatic potential (B16-F10 and B16-F1) were coated onto a GaAs substrate for THz imaging. The cells, approximately 10 μm in diameter, were imaged in reflection mode by detecting THz waves reflected from the surface of the GaAs substrate. As the cells are in direct contact with the substrate, the reflected THz signals contain structural information, enabling clear visualization of surface features. Fig. 2(a) shows the optical images of the cells, while Fig. 2(b) presents the corresponding THz image. From the imaging results, we successfully captured high-resolution THz images of single cancer cells with an approximate size of 10 μm , and the surrounding cell colonies can also be clearly identified. Near-field THz spectroscopy of these cells revealed differences in their spectral properties, which are discussed in detail.

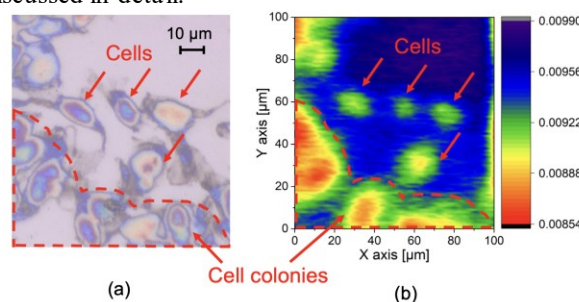


Figure 2. (a) Optical and (b) THz images.

4. Conclusion

This study successfully demonstrated high-resolution THz imaging of individual mouse melanoma cells (~10 μm) using the SPoTS microscopy. The results reveal clear cellular structures and surrounding colonies with THz waves. This highlights the potential of the SPoTS microscopy for advanced biomedical diagnostics and single-cell analysis.

Acknowledgements

This work was partially supported by JST FOREST Program (Grand numbers JPMJFR2029 and JPMJFR205N) and JSPS KAKENHI (JP22H01550, JP23H00184, and JP25K01294).

References

- [1] R. A. Woodward et al., *Phys. Med. Biol.* **47** (2002) 3853.
- [2] J. Y. Park et al., *J. Appl. Phys.* **109** (2011) 063110.
- [3] K. Okada et al., *Opt. Continuum* **1** (2022) 527.
- [4] K. Serita et al., The 12th Asia-Pacific Laser Symposium, EW1-02, Hakodate, Hokkaido (Sep. 4 - 7, 2023).

Thickness Dependence Resonance Characteristics of Meta-Atoms Excited by a Point Terahertz Source

¹ Yixin Zhao, and ¹ Kazunori Serita

¹ Graduate School of Information, Production, and Systems, Waseda University
E-mail: yx-zhao@fuji.waseda.jp

Terahertz (THz) metamaterials have attracted attention for their unique ability to control and manipulate THz waves, enabling the development of novel THz devices [1]. For applications to various fields such as integrated circuits and biochips, compact THz metamaterial sensors with high sensitivity are essential. However, due to the diffraction limit of THz waves, most THz metamaterial sensors require hundreds or thousands of meta-atoms, the elementary unit of metamaterials, to be excited by far-field THz waves. To overcome this limitation, we have developed a point THz source technique [2], in which THz waves are locally generated via optical rectification in a nonlinear optical crystal at the focal spot of a femtosecond pulse laser beam, which is on a sub-wavelength scale. This enables resonance excitation in just a few arrays of meta-atoms while maintaining high sensitivity [3]. To further improve compactness and sensitivity, it is necessary to optimize parameters such as structure, array numbers, and metallic thickness. Among these, metallic thickness is particularly important, as the skin depth effect suggests that resonance becomes significant near a critical sub-skin-depth value under the far-field THz excitation [4]. However, the influence of the metallic thickness on the resonance characteristics under the point THz source excitation has not yet been explored. Therefore, in this study, we investigated the variation in resonance characteristics with respect to metallic thickness.

The inset in Fig. 1(a) shows the meta-atom structure used in the investigation. The diameter of each meta-atom is $84\ \mu\text{m}$, and they are configured in 3×3 arrays with a period of $120\ \mu\text{m}$. The polarization of the generated THz waves, E_{THz} , is perpendicular to the direction of the gap. In the experiment, only the center of the center meta-atom is excited by the point THz source, which has a beam diameter of approximately $10\ \mu\text{m}$. Fig. 1(a) illustrates the measured THz transmittance spectra for two cases: 30 nm and 130 nm thickness. In both cases, remarkable resonance peaks are observed around 0.55 THz, with the amplitude being higher for the 130 nm sample. These results agreed well with the simulated spectra as shown in Fig. 1(b). While the skin depth at 0.5 THz is calculated to be approximately 111 nm, even meta-atoms with thickness below the skin depth exhibit remarkable resonance under the point THz source excitation. This finding contributes to the development of more efficient meta-atom sensors. A detailed analysis of surface current distributions is also presented to provide further insight into optimization strategies under point THz source excitation.

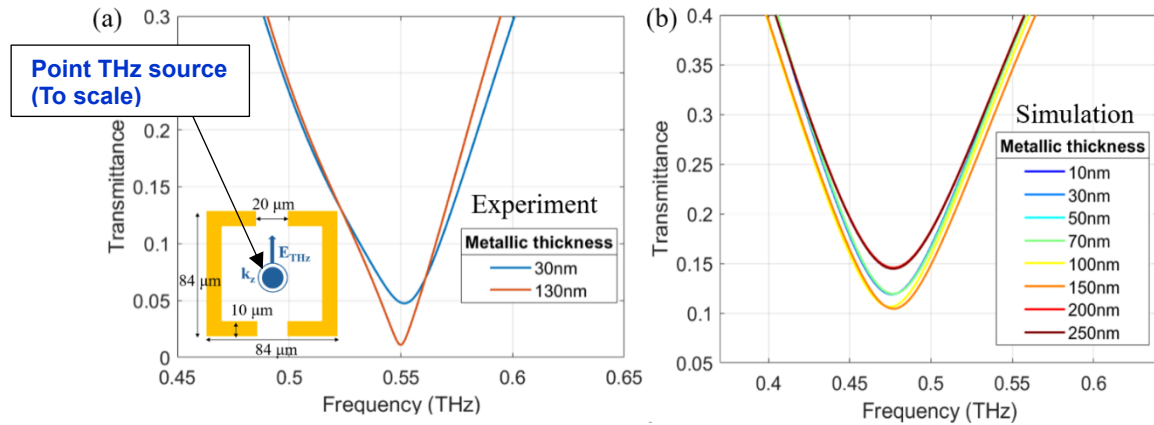


Figure 1. (a) The experimental THz transmittance of double gap 3×3 meta-atom arrays with metallic thickness of 30 nm and 130 nm. Inset shows the schematic diagram of the meta-atom. Only the center of the center meta-atom is excited by the point THz source and the E-field of the terahertz wave is shown as the arrow E_{THz} . (b) The simulated THz transmittance spectra with various metallic thickness.

Acknowledgements

This work was partially supported by JST FOREST Program (JPMJFR2029) and JSPS KAKENHI (JP25K01294).

References

- [1] T. J. Yen et al., *Science* **303**, 1494 (2004).
- [2] K. Serita et al., *Opt. Express* **20**, 12959 (2012).
- [3] K. Serita et al., *APL Photonics* **3**, 051603 (2018).
- [4] R. Singh et al., *Opt. Express* **16**, 6537 (2008).

Fundamental Study of a THz Scanner Using Parametric Wavelength Conversion

Koya Tsubota¹, Sota Mine^{1,2}, Kawase Kodo¹, Kosuke Murate¹

¹ Nagoya University, ²RIKEN
E-mail: tsubota.koya.t5@s.mail.nagoya-u.ac.jp

1. Introduction

An injection-seeded terahertz (THz) wave parametric generator (is-TPG) [1] is a high-power THz-wave source with frequency tunability ranging from 0.4 to 5.0 THz. In addition, THz-wave detection (parametric detection) [2] is possible through a process inverse to generation, making it a promising approach for a variety of imaging applications.

However, THz imaging using is-TPG typically relies on a raster scan method, which results in long measurement times. In this study, we developed a THz scanner utilizing THz parametric detection, aiming to achieve faster imaging.

2. Experimental Setup and Results

Figure 1 shows the experimental setup of the THz scanner system using is-TPG. The THz-wave generated by the is-TPG was shaped into a vertically elongated beam and irradiated onto the sample. The transmitted THz-wave was then directed into an MgO:LiNbO₃ crystal for parametric detection, where it was upconverted into a near-infrared detection Stokes beam. At this stage, the THz-wave was incident such that the THz beam profile at the sample position was imaged onto the surface of the detection crystal, allowing the image of the THz-wave to be transferred to the detection Stokes beam. An imaging optical system was also placed in the path of the detection Stokes beam, projecting the image formed immediately after entering the crystal onto a near-infrared camera sensor. This enabled the acquisition of a one-dimensional THz image from the one-dimensional detection Stokes beam image. The sample was then scanned laterally at fixed intervals using a motorized stage, and the obtained one-dimensional detection Stokes beam images were arranged in two dimensions to reconstruct the full image.

In conventional THz parametric detection, the THz-wave is input into the side (Y-surface) of the crystal via a Si prism to satisfy the noncolinear phase-matching angle: 64 degrees. However, in the present THz scanner system, in order to preserve the spatial information of the THz-wave with high resolution, both the pump beam and the THz-wave were incident on the same face (X-surface) of the crystal. In this configuration, the angle between the pump beam and the THz-wave inside the crystal is approximately 15 degrees, under which parametric detection is generally considered infeasible. Nevertheless, we recently discovered that THz parametric detection exhibits an exceptionally large tolerance for the angle of incidence [3], confirming that detection is

still possible under this condition.

Figure 2 shows the imaging result from a one-dimensional scanning of a metal sample. The sample, with the letters "THZ" printed using silver nanoparticle ink, as shown in Fig. 2(a), was measured at 1.5 THz, and the obtained image is shown in Figure 2(b). Figure 2(c) shows the image after background removal. The metal sample approximately 10mm in size was imaged with millimeter-order resolution, demonstrating the basic feasibility of the approach.

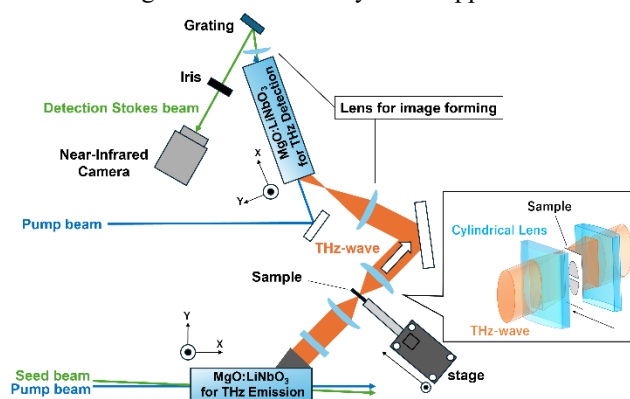


Fig. 1. Experimental setup of the THz scanner system

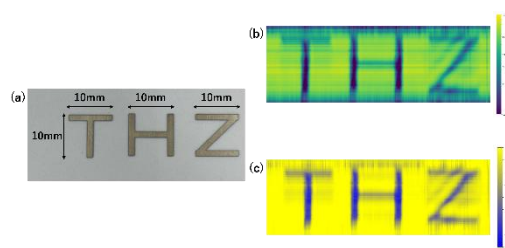


Fig. 2. (a) View of the "THZ" sample; (b) corresponding imaging result; and (c) imaging result after background subtraction.

Funding

JST ASPIRE (JPMJAP2340), FOREST (JPMJFR212J), and JSPS KAKENHI (22J20963, 24K00943).

References

- [1] K. Murate, S. Mine, K. Kawase, IEEE J. Sel. Top. Quantum Electron. 29 (2023) 8500813.
- [2] H. Sakai, K. Kawase, K. Murate, Opt. Lett. 45, (2020) 3905.
- [3] H. Inoue, S. Mine, K. Kawase, K. Murate, Sci. Rep. (2025). in press

Imaging of the catalytic reaction of platinum-thin-films with hydrogen gas using a terahertz chemical microscope

Takuya Yamanaka, Jin Wang, Toshihiko Kiwa

Graduate School of Interdisciplinary Science and Engineering in Health Systems, Okayama University
E-mail: pmpu303j@s.okayama-u.ac.jp

1. Introduction

Hydrogen is recognized as an energy resource with a low environmental impact. Developing highly effective catalysts is essential to realizing an “ecosystem” of hydrogen energy, because catalysts play an important role in every part of the ecosystem, e.g., producing hydrogen from water, storing hydrogen, and generating energy from the hydrogen. Conventionally, the efficiency of catalytic reactions is evaluated by the amount of product after the reaction, which is measured using a mass spectrometer or a gas chromatograph. However, it is difficult to evaluate the catalytic reaction directly and to evaluate reactions of various catalysts simultaneously.

In our group, we have proposed and developed a terahertz chemical microscope (TCM) to visualize electric potentials [1]. The TCM utilizes a sensing plate of SiO₂ film/ Si film on a sapphire substrate. The sensing plate generates and radiates THz by irradiating a femtosecond laser onto the Si films. The intensity of the THz is proportional to the depletion field of the Si film, so the intensity of the THz changes when the electric potentials on the sensing plate change at the laser irradiation area. Thus, the electric potential distribution on the sensing plate can be visualized by scanning the laser across the sensing plate. Here, a catalytic metal film was deposited on the sensing plate, and an electric potential shift was observed due to the catalytic reaction of the platinum (Pt) thin films with hydrogen gas.

2. Experimental

Fig. 1(a) shows the schematic of the sensing plate with the Pt film. The Pt film was deposited by sputtering with a thickness of 50 nm on half of the sensing plate surface. Then, the fabricated plate was mounted in the gas chamber to expose it to hydrogen gas as shown in Fig. 1(b). A hydrogen gas with a concentration of 95% was used to evaluate the catalytic reaction of the Pt film. A femtosecond fiber laser with a pulse width of 100 fs and a center wavelength of approximately 790 nm was used as an optical source. A radiated THz from the sensing plate was detected by a conventional bow-tie-type photoconductive antenna.

3. Results and discussion

Fig. 2 shows the map of the difference in THz amplitudes before and after exposure to hydrogen gas. The distributions of THz amplitudes before and after exposure to hydrogen gas were measured by the TCM, and the difference in the amplitudes was plotted. Since the work function of the Pt thin film, which is proportional to the electric potential of the surface of the sensing plate, increased, the

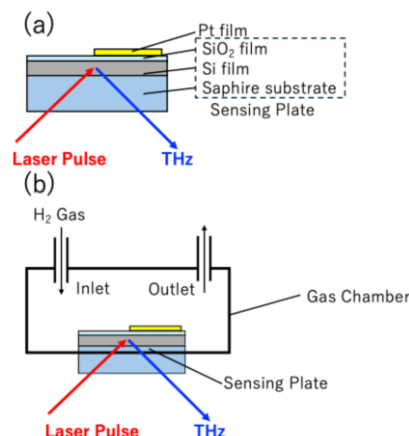


Fig. 1 Schematic of (a) the sensing plate with a platinum film and (b) the gas chamber.

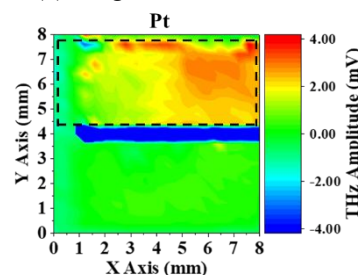


Fig. 2. The difference in THz amplitudes before and after exposure to hydrogen gas. The dashed rectangle indicates the area where the Pt thin film was deposited.

amplitude of the THz increased. Also, Nonuniformity in the amplitude distribution was observed, which could be caused by the nonuniformity in the morphology of the Pt thin films. This result indicates that the TCM could visualize the difference in catalytic reactions on the surface of sensing plates.

4. Summary

We have developed the TCM to visualize the catalytic reactions of Pt thin films. The change in the THz amplitude, which is related to the work function shift of the thin films, could be observed. This result suggests that combinatorial optimization of catalysis will be realized by fabricating various types of catalysis on a single sensing plate.

References

- [1] T. Kiwa, *et al.*, *Opt. Exp.*, **20**, 11637-1164, 2012.

Development of Novel Terahertz Light Source Using Resonant Tunneling Diodes

Univ. of Hyogo, Takashi Arikawa

E-mail: arikawa@eng.u-hyogo.ac.jp

The realization of time-domain spectroscopy in the late 1980s [1] triggered a rapid expansion of research utilizing terahertz (THz) waves. The key to this advancement was the development of mode-locked THz pulse generation using femtosecond lasers. Various generation methods have been developed using photoconductive antennas, nonlinear optical crystals, semiconductor surfaces, and gas plasmas. In all of these methods, identical THz electric field waveforms can be generated repeatedly [2]. This property enables sampling of the electric field in the time domain, making THz time-domain spectroscopy possible. In the frequency domain, the spectrum of such a source forms a frequency comb with zero offset frequency and evenly spaced longitudinal modes located at integer multiples of the repetition frequency [3]. Currently, the generation of such THz frequency comb inevitably relies on photonics technologies employing expensive femtosecond lasers. However, our recent research has revealed a promising path toward realizing equivalent sources based on compact semiconductor electronic devices, specifically resonant tunneling diodes (RTDs) [4,5]. In this talk, I will present recent progress on the development of novel THz RTD oscillators, including mode-locked oscillation [6], frequency comb generation [7,8], broadband generation [9] and time-domain measurement techniques [10,11]. I will also discuss future prospects for this technology.

- [1] P. R. Smith, D. H. Auston, M. C. Nuss, IEEE J. Quantum Electron. **24**, 255 (1988).
- [2] X.-C. Zhang, J. Xu, *Introduction to THz Wave Photonics* (Springer, 2009).
- [3] H. Füsser, M. Bieler, J. Infrared, Millimeter, Terahertz Waves **35**, 585 (2014).
- [4] S. Suzuki, M. Asada, Appl. Phys. Express **17** 070101 (2024).
- [5] K. Tsuruda et al., In Proc. 2020 IEEE International Symposium on Radio-Frequency Integration Technology (RFIT) 193-195 (IEEE, 2020).
- [6] T. Hiraoka, Y. Inose, T. Arikawa, H. Ito, K. Tanaka, Nature Communications **13**, 3740 (2022).
- [7] K. Tabuchi et al., The 72nd JSAP Spring Meeting 2025, 14p-K504-2.
- [8] T. Arikawa, Y. Daikoku, T. Hiraoka, Y. Inose, K. Tanaka, 47th International Conference on Infrared, Millimeter and Terahertz Waves (IRMMW-THz), Delft, Netherlands, 2022, pp. 1-4.
- [9] R. Tsujimura et al., The 85th JSAP Autumn Meeting, 20a-A34-10.
- [10] T. Arikawa, J. Kim, T. Mukai, N. Nishigami, M. Fujita, T. Nagatsuma, K. Tanaka, Nature Communications **15**, 5358 (2024).
- [11] R. Tamaki, K. Takahashi, T. Arikawa, I. Katayama, 49th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz), Perth, Australia, 2024, pp. 1-2.

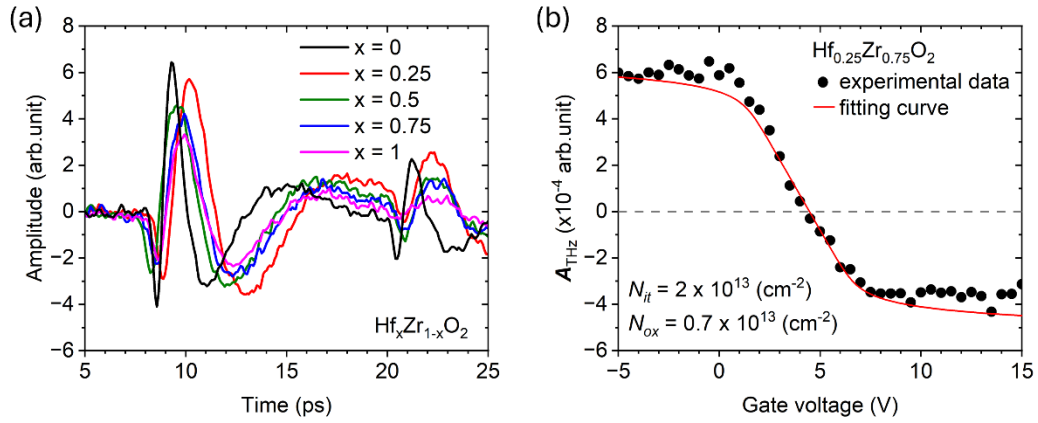


Figure 1. (a) THz waveforms emitted from HZO/*p*-Si samples with different Hf and Zr content; (b) THz peak amplitude vs. gate voltage for Hf_{0.25}Zr_{0.75}O₂/*p*-Si: experimental data (black data) and theoretical fit (red line).

Reference

- [1] S. S. Cheema et al., Nature 604, 65–71 (2022).
- [2] T. Mochizuki et al., Applied Physics Letter, 110, 163502 (2017).
- [3] Y. Taur et al., “Fundamentals of Modern VLSI Devices”, Cambridge University Press, 2009.

Multimode Laser-Driven CW-THz TDS for Ammonia Gas Sensing

Yuanhao Zeng¹, Keiji Komatsu², Kosaku Kato¹, Verdad C. Agulto¹, Thanh Nhat Khoa Phan¹,
Toshiyuki Iwamoto^{1,3}, and Makoto Nakajima¹

¹ Institute of Laser Engineering, The University of Osaka, ² Department of Materials Science and Bioengineering, Nagaoka University of Technology, ³ Nippo Precision Co., Ltd.,
E-mail: nakajima.makoto.ile@osaka-u.ac.jp

1. Introduction

Terahertz time-domain spectroscopy (THz-TDS) systems based on femtosecond (fs) pulsed lasers have shown great potential in nondestructive and non-contact inspection of semiconductor and biomedical materials [1]. Due to their time-domain measurement approach using mechanical delay scanning, THz-TDS systems can retrieve both amplitude and phase information, enabling their use in gas sensing applications [2]. However, the high cost and bulky nature of femtosecond lasers limit their suitability for practical, on-site, or commercial deployment. Therefore, a more cost-effective alternative is provided by continuous-wave multimode laser diode (cw-MLD) based TDS [3-4]. In this work, we demonstrate that a

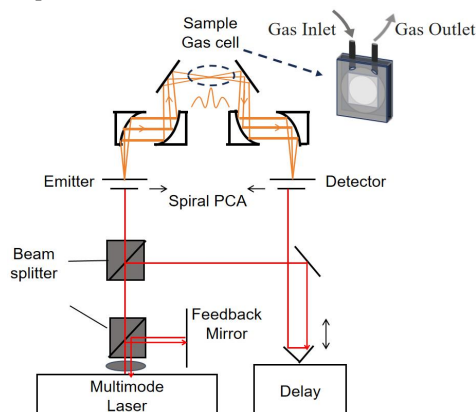


Fig. 1. Schematic diagram of the CW-MLD THz-TDS system and gas cell.

MLD-THz-TDS system can detect phase shifts caused by ammonia gas at parts-per-million (ppm) levels.

2. Experiment and Results

The MLD-THz-TDS system, as illustrated in Figure 1, employs commercially available multimode laser diodes (MLDs) with a center wavelength of approximately 660 nm. One part of the laser beam drives a photoconductive antenna (PCA) emitter to generate THz radiation, while the other part passes through a mechanical delay line and is directed to a PCA detector, where it overlaps with the received THz signal for coherent detection. The experimental system has a stability of approximately 7 fs for the time axis.

A gas cell is placed in the THz beam path, as shown in the setup. The cell is primarily constructed of metal, with both ends sealed using 3-mm thick PTFE windows to ensure low-loss THz transmission. Inside the cell, a piece

of porous glass with 50 nm pores is used which can trap ammonia molecules. During the experiment, a mixture of ammonia and dry air is continuously introduced into the cell. As the porous glass traps the ammonia molecules, the

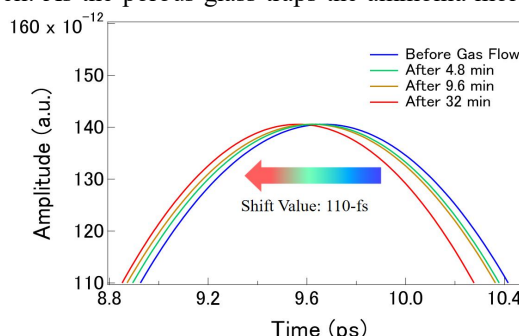


Fig. 2. Magnified view of the THz time-domain waveform peak. As ammonia gas was introduced into the cell at a fixed flow rate of 0.5 L/min (4.3 ppm concentration), the peak exhibited a clear time advancement, reaching a maximum shift of 110 fs.

detected THz time-domain signal begins to shift. By varying the flow rate of the gas, we not only detected the time shift caused by ammonia, but also demonstrated that the magnitude of this shift can be used to estimate the gas concentration.

As shown in Figure 2, controlling the flow of air containing 4.3 ppm ammonia with a flow rate of 0.5 L/min, the observed time shift reaches approximately 110 fs which is well above the system's timing uncertainty of 7 fs, clearly indicating a detectable ammonia-induced time shift.

3. Conclusions

In this study, we successfully demonstrated the use of a compact and cost-effective MLD-based THz-TDS system for gas sensing. Our system was able to detect a time shift of approximately 110-fs under a 4.3 ppm ammonia concentration. These results highlight the high sensitivity and stability of the MLD-TDS, paving the way for its application in real-time, low-cost gas sensing across various environmental and industrial scenarios.

Acknowledgement

This work was supported by JST SPRING, Grant Number JPMJSP2138.

References

- [1] J. Neu et al., J. Appl. Phys., 124 (2018) 231101.
- [2] K. Komatsu, et al., ACS Omega 7 (2022) 30768.
- [3] O. Morikawa et al., Jpn. J. Appl. Phys., **59** (2020) 082003.
- [4] F. Kuwashima et al., Opt. Express, **28** (2020) 24833.

Terahertz characterization of silver nanoparticles with fractal structures in polymethyl methacrylate films

Sota Itayama¹, Tomoki Kawahara², Jin wang¹, Nobuyuki Takeyasu², Toshihiko Kiwa¹

¹ Graduate School of Interdisciplinary Science and Engineering in Health Systems, Okayama university, Japan

² Graduate School of Natural Science and Technology, Okayama university, Japan

E-mail: p2r35xgc@s.okayama-u.ac.jp

1. Introduction

Terahertz (THz) waves are attractive for biosensing because they are non-ionizing and interact with biomolecular vibrations. Conventional detectors still suffer from poor signal reliability and sensitivity. Metamaterial coatings that concentrate THz fields offer a way forward, and silver nanoparticle tree-like fractal structures (AgTFs) are especially promising: they exhibit broadband THz response, can be fabricated rapidly in bulk, and can coat wide areas for wall-scale sensors. Tanaka et al. [1] observed a solvent-dependent THz peak in AgTF powders dried directly on quartz substrates, but the reliability of their spectra was limited by thickness artifacts and by the narrow 0.1–2 THz measurement window of their setup. In this work, we suppress those artifacts by embedding AgTFs in uniform PMMA films and use a 0.5–5 THz time-domain spectrometer to resolve multiple solvent-tuned resonances. AgTFs fabricated in acetone, ethanol, and a 1:1 mixed solvent are compared to assess their suitability for large-area THz biosensing.

2. Method

Three types of solvents were used to fabricate AgTFs: acetone, ethanol, and a 1:1 mixture of both. To reduce variations due to differences in sample thickness, the AgTFs were embedded in film form using polymethyl methacrylate (PMMA) as a matrix. The samples were 13 mm in diameter and approximately 0.1 mm in thickness. THz absorption spectra were measured using a THz-TDS system (TAS7500SU, Advantest Corp.).

3. Result

Figure 1 shows the THz-TDS absorption spectra of the three AgTF films. The acetone sample shows a single resonance at 3.98 THz, whereas the ethanol sample exhibits two resonances at 0.91 THz and 1.62 THz. The mixed-solvent sample (1:1 acetone/ethanol) presents resonances at 1.48 THz and 4.23 THz. These solvent-dependent peak positions correlate with the viscosity of the fabrication solvent: ethanol suppresses lateral growth and produces finer branches, leading to lower-frequency modes, while acetone yields coarser branches and shifts the resonance to higher frequencies. Controlling solvent viscosity therefore provides a simple means to tune the THz response of AgTFs, underscoring their potential for

large-area THz biosensing applications.

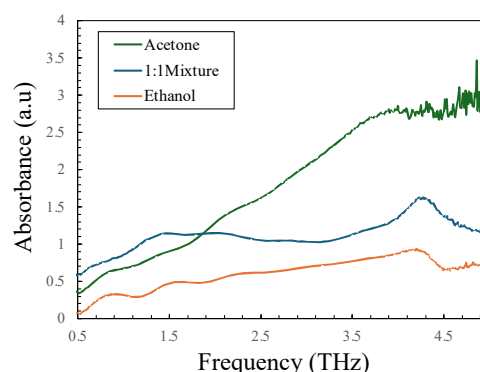


Fig. 1. Absorption spectra of AgTFs prepared under acetone solvent, ethanol solvent and mixed solvents in the terahertz region

4. Conclusion

In this study, we fabricated silver nanoparticle tree-like fractal structures (AgTFs) in acetone, ethanol, and a 1:1 mixed solvent and showed that their THz resonance peaks shift with solvent choice, demonstrating solvent-tunable THz responses suitable for large-area biosensing. Future work will refine growth conditions for more uniform, reproducible AgTFs and develop surface functionalization methods for selective biomolecule detection.

This work was partially supported by JSPS KAKENHI grant no. 23K26574.

References

- [1] H. Tanaka, S. Itayama, N. Takeyasu, J. Wang, and T. Kiwa, "Terahertz spectroscopic characterization of fractal silver nanoparticle structures," in Proc. Asia-Pacific Conf. Appl. Electromagn. (APACE), Kuala Lumpur, Malaysia, Nov. 2024.
- [2] K. Nogami et al., "Self-growth of silver tree-like fractal structures with different geometries" Applied Physics A, vol 128, no 10, pp.860, Sep.2022

4 JSAP-Optica Joint Symposia 2025 | 一般セッション(口頭講演) : 4.6 Terahertz Photonics

[10p-N203-1~10] 4.6 Terahertz Photonics

[10p-N203-1]

[JSAP-Optica Joint Symposia Invited Talk] Development of a High-Power Laser-Integrated Backward Terahertz-wave Parametric Oscillator

○Yuma Takida¹, Hiroaki Minamide¹ (1.RIKEN RAP)

[10p-N203-2]

Terahertz-Wave Detection by Omnidirectional Phonon-Polariton Coupling and Amplification

○(D)Yuto Yoneda^{1,2}, Yuma Takida², Joselito E. Muldera², Alexander De Los Reyes², Yuehong Xu², Kunio Ishida³, Hiroaki Minamide^{1,2} (1.Chiba Univ., 2.RIKEN, 3.Utsunomiya Univ.)

[10p-N203-3]

Terahertz Time-Domain Ellipsometry of Liquids Without a Liquid Cell

○Atsuki Kamio¹, Verdad C. Agulto¹, Zixi Zhou¹, Kosaku Kato¹, Thanh Nhat Khoa Phan¹, Toshiyuki Iwamoto^{1,2}, Makoto Nakajima¹ (1.ILE, Univ. of Osaka, 2.Nippo Precision Co., Ltd)

[10p-N203-4]

Magneto-Optical Terahertz Time-Domain Ellipsometry of the Narrow-Gap Semiconductor InSb with Varying Carrier Densities

○(D)Zixi Zhao¹, Verdad C. Agulto¹, Atsuki Kamio¹, Kosaku Kato¹, Thanh Nhat Khoa Phan¹, Toshiyuki Iwamoto^{1,2}, Toshihiko Shimizu¹, Nobuhiko Sarukura¹, Makoto Nakajima¹ (1.ILE, Univ. of Osaka, 2.PNP)

[10p-N203-5]

Efficient THz Absorber based on Polymer-Hexaferrite Composite Films

○Justin LLANDRO^{1,2}, Zhehong LIU^{2,3}, Yoshito MURATA⁴, Yoshihiro OKAMURA^{3,4}, Yasujiro TAGUCHI^{2,3}, Youtarou TAKAHASHI^{3,4}, Yoshinori TOKURA^{3,4,5}, Satoshi OKAMOTO^{1,2} (1.Sumitomo Chemical, 2.RIKEN BZP, 3.RIKEN CEMS, 4.Univ. Tokyo, 5.Tokyo College)

[10p-N203-6]

Three-Dimensional Evaluation of the Cochlea Using Terahertz Near-Field Imaging

○(D)LUWEI ZHENG¹, Takeshi Fujita², Akinobu Kakigi², Hironaru Murakami³, Masayoshi Tonouchi⁴, Niu Zhengya⁵, Kazunori Serita⁵ (1.The Univ. of Osaka, 2.Kobe Univ., 3.Fukui Univ. of Tech., 4.Okayama Univ., 5.Waseda Univ.)

[10p-N203-7]

Investigation of the Physical Properties of Colloidal Indium Tin Oxide Nanocrystals Using Terahertz Spectroscopy

○(P)Daichi Eguchi¹, Kosaku Kato¹, Verdad C. Agulto¹, Makoto Nakajima¹ (1.The Univ. of Osaka)

[10p-N203-8]

Anisotropic Temperature Dependence of Carrier Transport in Beta-Gallium Oxide Epilayer Evaluated by Terahertz Time-Domain Spectroscopy

○Shuang Liu¹, Verdad C. Agulto¹, Kosaku Kato¹, Toshiyuki Iwamoto^{1,2}, Thanh Nhat Khoa Phan¹, Hisashi Murakami³, Yoshinao Kumagai³, Makoto Nakajima¹ (1.UOsaka ILE, 2.Nippo Prec., 3.TAT Appli. Chem.)

[10p-N203-9]

Measurement of the Complex Anisotropy Ratio of the Nonlinear Optical Susceptibility in the Third Harmonic Generation by Terahertz Free-Electron Laser

○(P)KHOA PHAN¹, You Wei Wang¹, Kosaku Kato¹, Verdad C. Agulto¹, Goro Isoyama², Makoto Nakajima¹ (1.UOsaka, ILE, 2.UOsaka, SANKEN)

[10p-N203-10]

Label-Free Detection of Glucose and Lactate Using Terahertz Chemical Microscope with Aptamer-Functionalized Sensing Plates

○Yuta Mitsuda¹, Ryotaro Kubo¹, Hikaru Nakagawa¹, Toshihiko Kiwa¹, Jin Wang¹ (1.Graduate school of Okayama Univ.)

Development of a High-Power Laser-Integrated Backward Terahertz-wave Parametric Oscillator

Yuma Takida, Hiroaki Minamide

RIKEN Center for Advanced Photonics, RIKEN
E-mail: yuma.takida@riken.jp

1. Introduction

Non-destructive sensing using sub-terahertz (sub-THz) waves offers promising applications for industrial fields, thanks to their attractive properties, such as higher spatial resolution than millimeter waves. To realize a practical sensing system, a compact, robust, and high-output-power sub-THz-wave source is essential. As a strong candidate to meet these requirements, we recently demonstrated laser-driven backward THz-wave parametric oscillators (BW-TPOs) by using a slant-stripe-type periodically poled lithium niobate (PPLN) crystal [1–4]. The primary advantage of the BW-TPO is the mirrorless configuration owing to the counter-propagating interaction, where a pump photon is down-converted to backward-propagating THz-wave and forward-propagating idler photons without an optical cavity. This makes turn-key and alignment-free robust operation possible.

In this work, we have developed a compact all-in-one module of an injection seeded BW-TPO with a footprint size of 13.9 cm by 5.5 cm, as shown in Fig. 1.

2. Experiment

In this BW-TPO module, the driving pump source of a passively Q-switched Nd:YAG microchip laser, BW-TPO gain medium of a slant-stripe-type PPLN crystal mounted on a motorized rotation stage, and all the optical components including a simple layout for injection seeding to the idler wavelength were assembled in a palm-sized package. From this compact module, the monochromatic backward-propagating THz-wave output was obtained with a maximum peak power of 15 W at 0.33 THz. Furthermore, by tuning the quasi-collinear phase-matching condition in the PPLN crystal, mode-hop-free frequency tunability from 0.29 to 0.35 THz was demonstrated.

Using the developed BW-TPO module, THz-wave imaging in reflection geometry was performed. The BW-TPO module and whole optical setup for reflection imaging were assembled on the optical breadboard that was mounted on a 2-axis motorized translation stage, while the position of the sample to be imaged was fixed. Fig. 2 shows the result of 0.3-THz reflection imaging with an area size of 150 mm by 200 mm with a 1-mm step without signal averaging. This result demonstrates the robust operation of the developed BW-TPO module.

3. Conclusions

We have developed a palm-sized compact all-in-one

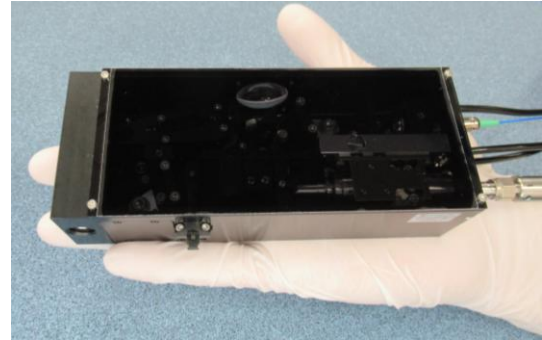


Fig. 1. Photograph of the developed palm-sized all-in-one BW-TPO module.

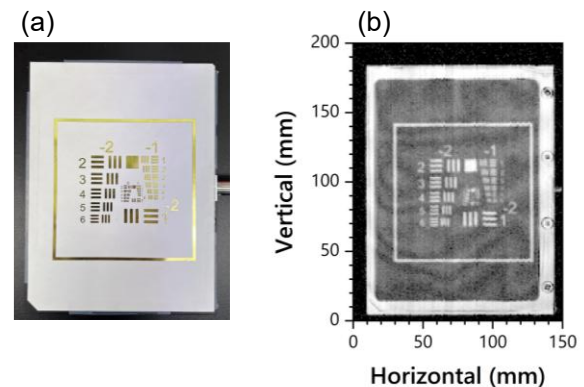


Fig. 2. (a) USAF 1951 test target pattern sample and (b) 0.3-THz reflection imaging result.

BW-TPO module. Such a bright, frequency-tunable, and compact sub-THz-wave source is promising for real-world non-destructive sensing applications.

Acknowledgements

We thank Prof. H. Ito, Prof. M. Kumano, Dr. J. E. Muldera, Dr. D. Yadav, Dr. A. E. De Los Reyes, Dr. Y. Xu, Mr. Y. Yoneda, and Dr. K. Nawata for fruitful discussions. This work was supported in part by Innovative Science and Technology Initiative for Security, Grant Number JPJ004596, ATLA, Japan.

References

- [1] K. Nawata *et al.*, Sci. Rep. **9** (2019) 726.
- [2] Y. Takida *et al.*, APL Photon. **5** (2020) 061301.
- [3] J. Muldera *et al.*, Opt. Express **31** (2023) 23966.
- [4] J. Muldera *et al.*, Opt. Express **33** (2025) 22049.

Terahertz-Wave Detection by Omnidirectional Phonon-Polariton Coupling and Amplification

Chiba Univ.¹, RIKEN², Utsunomiya Univ.³ °Yuto Yoneda^{1,2}, Yuma Takida², Joselito E. Muldera²,

Alexander De Los Reyes², Yuehong Xu², Kunio Ishida³ and Hiroaki Minamide^{1,2}

E-mail: yuto.yoneda@riken.jp

Introduction

Frequency up-conversion detection, a theory proposed by M. Takatsuji in 1966 [1], enables ultra-low-noise detection of terahertz (THz) waves at room temperature. Backward terahertz-wave parametric oscillation (BW-TPO) has recently attracted attention for its potential to achieve low phase noise and high quantum conversion efficiency through narrowband oscillation [2]. However, nonlinear optical conversion requires strict phase matching, limiting the detection configuration—especially in BW-TPO, where THz-wave absorption restricts the interaction length.

In this study, we demonstrate a detection method utilizing phonon-polariton coupling and amplification by BW-TPO, which enables omnidirectional THz-wave detection without relying on conventional phase matching. Phonon-polaritons induced by THz waves generate dipole responses that provide omnidirectional gain in the plane orthogonal to the pump polarization, which are then up-converted and amplified in the phase-matched direction.

This approach lays the foundation for THz System on a Chip (T-SoC) platforms using meta surfaces, with potential applications in atmospheric monitoring, space debris detection, and remote sensing.

Experimental setup

Figure 1 shows the schematic of the experimental setup. BW-TPO was implemented using a slanted-stripe periodically poled lithium niobate (PPLN) crystal under quasi-collinear phase matching (QCPM). A pump pulse (0.46 ns, 100 Hz) was used, with 4.02 mJ on the generation side and 2.26 mJ on the detection side, below the oscillation threshold. A 500 mW CW seed laser was injected into the generation side. The generated THz wave was directed into the detection-side PPLN crystal along the direction counter to that of the phase-matching condition.

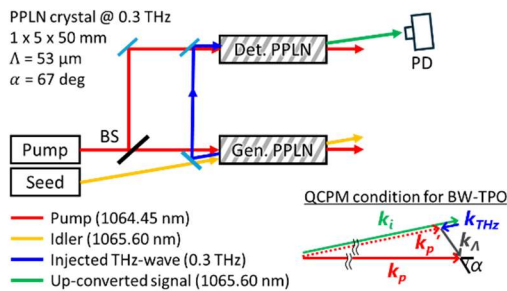


Fig. 1. Experimental setup for coherent THz-wave detection injected by counter direction of the phase-matching condition

Results and Discussion

Figure 2 shows the detection results of the up-converted signal. The red line indicates output with THz-wave injection, and the blue line shows the baseline without it. Similar setups were adapted for two other directions of THz-wave injection, lateral and phase-matched, respectively. In all cases, a high signal-to-noise ratio was observed, demonstrating robust detection regardless of incident direction.

The underlying detection mechanism proceeds in two distinct stages. First, incident THz-waves—regardless of their propagation direction—excite phonon modes that generate dipole oscillations near the threshold of parametric oscillation. These phonon-polariton interactions are inherently omnidirectional in the plane perpendicular to the pump polarization. Second, the dipole-induced modulation enables nonlinear up-conversion along the phase-matched direction, resulting in optical parametric amplification of the signal. This mechanism confirms that directional flexibility in THz-wave detection can be achieved through phonon-polariton coupling and amplification.

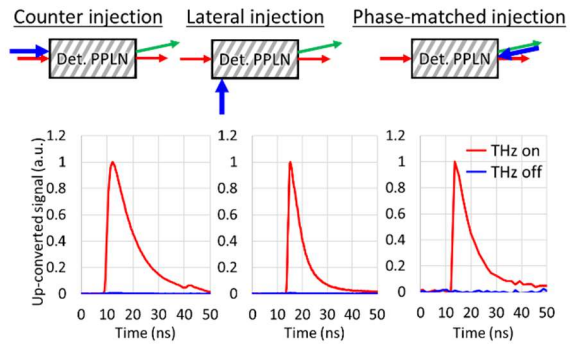


Fig. 2. Experimental result of up-converted signal for different injection direction

Acknowledgment

The authors would like to thank Prof. H. Ito of RIKEN/Tohoku University, Prof. M. Kumano of Tohoku University and Prof. M. Sato of Yamagata University for fruitful discussions. This work was supported by RIKEN Student Researcher Program and JST SPRING, Grant Number JPMJSP2109.

Reference

- [1] M. Takatsuji, "Theory of Far Infrared Detection Using Nonlinear Optical Mixing," *Jpn. J. Appl. Phys.* **5**, 389 (1966)
- [2] K. Nawata, Y. Tokizane, Y. Takida, and H. Minamide, "Tunable Backward Terahertz-wave Parametric Oscillation," *Sci. Rep.* **9**, 726 (2019).

Terahertz Time-Domain Ellipsometry of Liquids Without a Liquid Cell

Atsuki Kamio¹, Verdad C. Agulto¹, Zixi Zhao¹, Kosaku Kato¹, Thanh Nhat Khoa Phan¹,
Toshiyuki Iwamoto,^{1,2} and Makoto Nakajima¹

¹ Institute of Laser Engineering, The University of Osaka, ² Nippo Precision Co., Ltd.
E-mail: nakajima.makoto.ile@osaka-u.ac.jp

1. Introduction

Terahertz time-domain spectroscopy (THz-TDS) has become widely used as a non-contact technique capable of evaluating the dielectric and conductive properties of materials through the analysis of both amplitude and phase of the electric field. However, it remains challenging to measure liquid samples which strongly absorb terahertz radiation. In transmission THz-TDS, highly absorbing liquids require extremely thin liquid cell spacers to allow sufficient signal transmission. This requirement for thin sample layers can lead to measurement errors in the extracted optical constants, making high-precision evaluation difficult. In this study, terahertz time-domain ellipsometry (THz-TDE) was utilized to directly irradiate liquid samples with THz waves without using liquid cells.

2. Results

To demonstrate THz-TDE for liquid measurements, we investigated water which has known optical constants. Distilled water was placed in a 40 mm × 40 mm container and measured using THz-TDE without a window. THz-TDE was performed using Tera Evaluator, developed by Nippo Precision, Co., Ltd., with a spectral range from 1 THz to 3 THz [1-3]. The measurement chamber was purged with dry air to prevent THz absorption by water vapor. In the ellipsometry measurements, the reflected THz wave first passes through a rotating analyzer, which rotates from $\phi_A = 0^\circ$ to 360° in 15° increments, before being recorded by the detector. The p- and s-polarized components were then extracted via nonlinear regression analysis based on the analyzer angle dependence of the detected signal. The detailed analysis method is discussed in [1]. This approach enables more accurate retrieval of the p and s polarization components compared to direct measurements of each component.

Fig. 1a shows the time-domain waveform magnified around the peak of the s-polarized terahertz wave reflected from the surface of water. As time progresses, the waveform exhibits a delay and a decrease in amplitude, which is attributed to a lowering of the water surface level caused by evaporation. These effects generate errors in the optical constants acquired from ellipsometry measurements. We developed a frequency-domain correction method to eliminate the effect of time-dependent changes in surface height. Specifically, the reflected waveform was Fourier-transformed, and the resulting amplitude and phase spectra were corrected to compensate for surface-level variation over time.

Fig. 1b presents the absorption spectra of water,

calculated from the complex amplitude ratio (ellipsometric parameters) between p- and s-polarized components. It is evident that the absorption coefficient increases with frequency. In transmission THz-TDS, it is generally difficult to maintain a sufficient signal-to-noise ratio across a broad frequency range such as several terahertz due to the strong absorption by water. In contrast, with THz-TDE, both refractive index and absorption coefficient were successfully evaluated up to 3 THz. Moreover, the corrected measurement results were found to be consistent with previously reported data [4], confirming the validity of our correction approach.

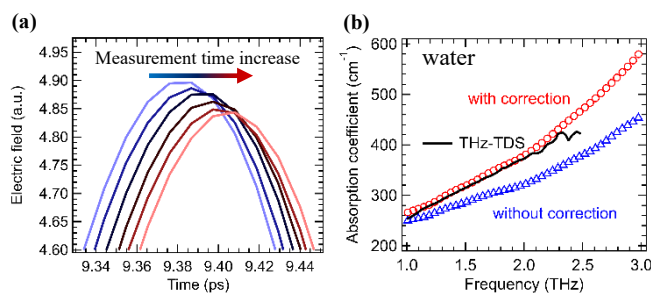


Fig. 1. (a) Time-domain waveforms of s-polarized THz pulses reflected from water surface, measured sequentially over time. The blue curve (leftmost) represents the earliest measurement, while the red curve (rightmost) corresponds to the latest. A gradual temporal delay and amplitude reduction are observed, indicating a decrease in the water surface level due to evaporation. **(b)** Absorption coefficient spectrum of water.

3. Conclusions

We demonstrated that our THz-TDE method, combined with the new analysis approach developed in this study for liquid samples, enables accurate characterization of volatile liquids without the use of a liquid cell. This result highlights the potential of THz-TDE as a robust technique for liquid analysis, especially for samples where conventional containment methods are impractical.

Acknowledgements

This work was supported by JSPS KAKENHI Grant Numbers JP24H00317, JP24H02232, and partially supported by JKA and its promotion funds from AUTORACE.

References

- [1] V. C. Agulto et al., Sci. Rep. 11 (2021) 18129.
- [2] V. C. Agulto et al., Opt. Lett., 50 (2025) 948-951.
- [3] J. Wang et al., Nature, 631 (2024) 67-72.
- [4] K. Jeong et al., J. Biomed. Opt., 18 (2013) 107008.

Magneto-Optical Terahertz Time-Domain Ellipsometry of the Narrow-Gap Semiconductor InSb with Varying Carrier Densities

Zixi Zhao¹, Verdad C. Agulto¹, Atsuki Kamio¹, Kosaku Kato¹, Thanh Nhat Khoa Phan¹, Toshiyuki Iwamoto^{1,2}, Toshihiko Shimizu¹, Nobuhiko Sarukura¹, and Makoto Nakajima¹

¹ Institute of Laser Engineering, The University of Osaka, ² Nippo Precision Co., Ltd.
E-mail: nakajima.makoto.ile@osaka-u.ac.jp

1. Introduction

Terahertz time-domain ellipsometry (THz-TDE) is an emerging terahertz (THz) technique that characterizes semiconductors by analyzing polarization changes of THz waves reflected from the sample. It combines the non-contact advantages of THz techniques with the high phase accuracy of ellipsometry, while also overcoming the limitations of terahertz time-domain spectroscopy (THz-TDS) related to sample thickness and carrier absorption. Additionally, THz-TDE can evaluate not only optical properties, but also carrier transport properties through Drude model fitting [1-4]. However, such analysis of carrier transport properties requires assumptions about parameters like effective mass, which is unfavorable for evaluating low-doped and narrow-gap semiconductors because effective mass depends on carrier density. To address this problem, the magneto-optical Kerr effect (MOKE) is incorporated into THz-TDE [5]. In a magnetic field, electrons undergo cyclotron motion, and the resonance frequency ω_c depends on the applied magnetic field and the electron effective mass. Therefore, electronic transport properties such as the effective mass can be effectively extracted without any assumptions.

2. Experiment

MO-THz-TDE measurements were performed using Tera Evaluator, developed by Nippo Precision, Co., Ltd., with a spectral range of 1-3 THz. An external magnetic field of 0.4 T perpendicular to the sample surface was applied by placing a permanent magnet beneath the sample. The THz wave was incident at an angle of 70°. By rotating the polarizer placed in front of the THz emitter, the incident polarization was modulated between $p = s$ incidence and p -polarized incidence, allowing for the measurement of the complex reflection coefficient r_p without a magnetic field, as well as r_{sp} and r_{pp} under a magnetic field (where the first subscript represents the reflected polarization component and the second represents the incident polarization component).

In this study, undoped and n -type doped InSb (Indium Antimonide) wafers were evaluated. Both samples were cut along the [100] plane and single-side polished. The thicknesses of both samples are about 500 μm , and both samples are opaque to terahertz due to their high carrier absorption.

3. Results

The applied magnetic field induces asymmetric carrier motion via the Lorentz force, leading to the MOKE. As a result, the dielectric response of the sample is described by both the diagonal (ϵ_{xx} , ϵ_{zz}) and the off-diagonal (ϵ_{xy}) components of the dielectric tensor. The ϵ_{zz} represents the dielectric response along the direction parallel to the magnetic

field. Thus, ϵ_{zz} for both samples remains consistent with their zero-field dielectric constants, as carriers are unaffected by the Lorentz force. The ϵ_{xx} and ϵ_{xy} of both samples, obtained from the complex reflection coefficients, are shown in Fig. 1. Doped InSb exhibits a stronger dielectric response in all directions. The real part of ϵ_{xx} for undoped InSb changes sign around 2.2 THz due to the low carrier density, which results in a low plasma frequency falling within the measurement range. In addition, ϵ_{xx} and ϵ_{xy} of the undoped InSb show oscillations near 2.8 THz, attributed to the magneto plasmon–phonon coupling effect. From the Drude model fitting, we obtained a plasma frequency of 5.5 THz, an effective mass of 0.020 m_0 ($m_0 = 9.109 \times 10^{-31}$ kg), and a carrier density of $1.13 \times 10^{17} \text{ cm}^{-3}$ for the doped InSb. For the undoped InSb, the plasma frequency was 2.2 THz, the effective mass was 0.018 m_0 , and the carrier density was $1.67 \times 10^{16} \text{ cm}^{-3}$.

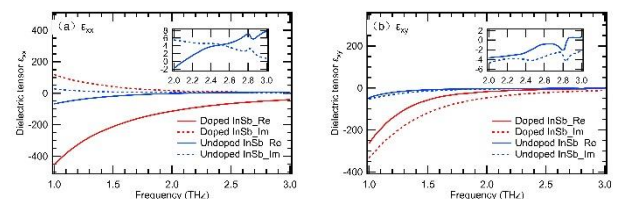


Fig. 1. Experimental spectra of (a) diagonal component ϵ_{xx} and (b) off-diagonal component ϵ_{xy} of dielectric tensor for doped and undoped InSb.

4. Conclusions

Doped and undoped InSb wafers were characterized using MO-THz-TDE. The dielectric tensors of both samples were successfully obtained and thus the electron effective mass is evaluated through the Drude model. These results demonstrate the ability of MO-THz-TDE to evaluate the optical and electron transport properties of narrow-gap semiconductors without any assumptions, making it a potential tool for investigating anisotropy of electron transport properties.

Acknowledgements

This work was supported by JSPS KAKENHI Grant Numbers JP24H00317, JP24H02232, JST SPRING Grant Number JPMJSP2138, and partially supported by JKA and its promotion funds from AUTORACE.

References

- [1] V. C. Agulto, et al., Sci. Reports, **11** (2021) 18129.
- [2] J. Wang, et al., Nature, **631** (2024) 67–72.
- [3] Z. Zhao et al., Opt. Mater. X, **24** (2024) 100352.
- [4] V. C. Agulto, et al., Opt. Lett. **50** (2025) 948-951.
- [5] K. Yatsugi, et al., Appl. Phys. Lett. **98** (2011) 212108.

Efficient THz Absorber based on Polymer-Hexaferrite Composite Films

Sumitomo Chemical Co., Ltd.¹, RIKEN BZP², RIKEN CEMS³, University of Tokyo⁴, Tokyo College⁵,

Justin Llandro^{1,2}, Zhehong Liu^{2,3}, Yoshito Murata⁴, Yoshihiro Okamura^{3,4}, Yasujiro Taguchi^{2,3},

Youtarou Takahashi^{3,4}, Yoshinori Tokura^{3,4,5}, Satoshi Okamoto^{1,2}

E-mail: llandroj@sc.sumitomo-chem.co.jp

Terahertz radiation, particularly the frequency band 0.1~1 THz, is attracting strong interest as a contact-free probe of material properties in security scanning, quality inspection and non-invasive biosensing. However, the penetrating nature of THz radiation and its increasing use in communications also leads to high background noise in THz spectroscopy, making efficient THz absorbers vital. Existing approaches to large-area absorbers have focused on quasi-2D metasurfaces and 3D metamaterials based on nanotubes, microcoils, etc. where dimensions are tailored to THz resonances, and polymer composites which use highly conductive fillers to provide THz absorption. Such materials have been reported to exhibit high absorption but over a relatively narrow frequency range and/or above 1 THz [1].

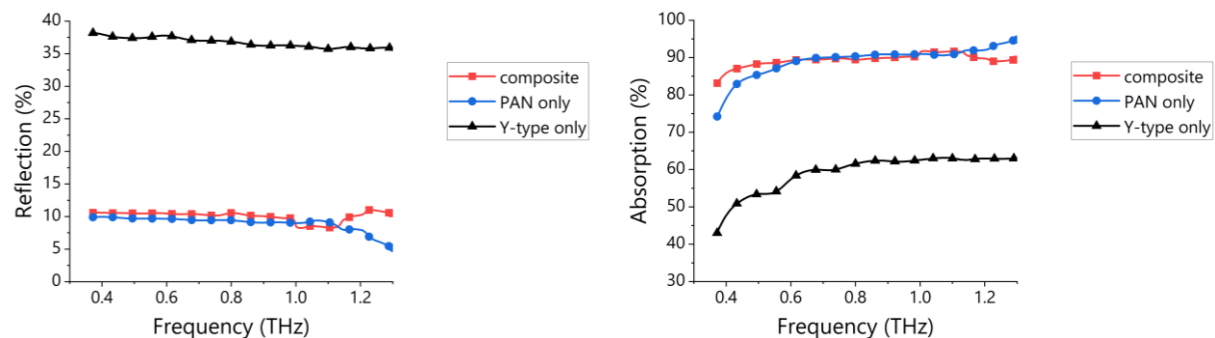


Figure 1: Reflection and absorption of polyacrylonitrile (PAN)/Y-type hexaferrite composite (1mm thick).

Here, we present an alternative approach to realizing a high-performance wide-band THz absorber, based on composites where both matrix and filler act as THz absorbers. Figure 1 shows initial results on a 1mm thick composite with a polar polymer matrix (polyacrylonitrile (PAN)) and a filler of micron-sized particles of multiferroic Y-type hexaferrite $\text{Ba}_{2-y}\text{Sr}_y\text{Co}_{2-x}\text{Fe}_{11+x}\text{AlO}_{22}$, which absorbs THz radiation by electromagnon generation via its strong magneto-electric coupling [2]. Although PAN and single-crystal Y-type hexaferrite absorb most strongly at 0.7~0.8 THz, the frequency at which the composite reaches maximum absorption shifts down to 0.5 THz even with only 4% vol. of the hexaferrite. Work is ongoing to evaluate the effect of increased hexaferrite content and to compare the performance of PAN to other polymers [3].

[1] A.C. Ezika *et al.*, Polymer-Plastics Technology and Materials 64(11), 1633–1652 (2025).

[2] H. Shishikura *et al.*, Phys. Rev. Appl. **9**, 044033 (2018).

[3] T. Takahashi *et al.*, IEEE J. Trans. FM **127**(10), 593–598 (2007).

Three-Dimensional Evaluation of the Cochlea Using Terahertz Near-Field Imaging

Luwei Zheng¹, Takeshi Fujita², Akinobu Kakigi², Hironaru Murakami^{1,3}, Masayoshi Tonouchi⁴, Niu Zhengya⁵, and Kazunori Serita⁵

¹ Institute of Laser Engineering, The University of Osaka, ² Department of Otolaryngology-Head and Neck Surgery, Graduate School of Medicine, Kobe University, ³ Department of Electrical, Electronic and Computer Engineering, Fukui University of Technology, ⁴ Research Institute for Interdisciplinary Science, Okayama University, ⁵ Graduate School of Information, Production, and Systems, Waseda University
E-mail: k_serita@aoni.waseda.jp

1. Introduction

Hearing impairment and loss are widespread conditions that impact a significant portion of the global population, greatly diminishing both communication abilities and overall quality of life [1]. These auditory issues are most commonly associated dysfunctions within the cochlea of the inner ear [2-4]. Achieving non-destructive imaging of the cochlea's internal structure with adequate spatial resolution remains a significant challenge. To address this, we successfully conducted the first non-destructive terahertz (THz) imaging of a mouse cochlea using a THz near-field point source microscope capable of micro-scale resolution [5,6]. High-accuracy three-dimensional (3D) THz time-of-flight (ToF) imaging and reconstruction were also demonstrated. This advancement lays the groundwork for future medical diagnostic applications, particularly in the early detection and evaluation of hearing-related disorders.

2. Method

The methodology employed in this study for 3D terahertz (THz) imaging and structural reconstruction of the cochlea involves three main stages: (1) two-dimensional (2D) data acquisition, (2) structural information extraction, and (3) 3D reconstruction. First, 2D time-domain THz images were obtained at various delay time points using a scanning point-source THz imaging system combined with the time-of-flight (ToF) technique. Second, an unsupervised machine learning algorithm—*k*-means clustering—was applied to classify the 2D THz images into distinct subgroups, enabling the separation of structural and non-structural regions. Finally, using the extracted structural data, a 3D point cloud was generated, and a 3D surface mesh was reconstructed through the Poisson surface reconstruction method. This approach demonstrates high reliability and flexibility, making it applicable to 3D reconstruction of a wide range of biological tissues.

3. Results

Fig. 1 shows the reconstructed 3D results, including 3D point cloud and surface mesh data. Fig. 1(a) and 1(b) show the 3D point cloud and surface mesh results, respectively. Fig. 1(c) shows a cross-sectional view of the 3D surface results shown in Fig. 1(b). The internal structure of the cochlea was easily and clearly observable, as indicated by the arrows in Figs. 1(b) and 1(c). Fig. 1(d) shows the bottom view of the reconstructed 3D surface mesh cochlea. The results demonstrate that the interior and exterior fea-

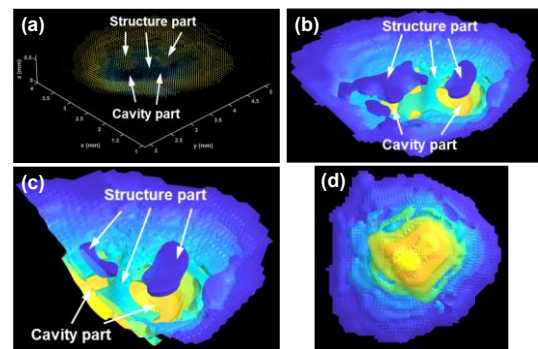


Figure 1 3D point cloud and surface mesh reconstruction.

tures of the cochlea can be successfully and clearly visualized.

4. Conclusions

In this study, we successfully visualized the internal structure of a mouse cochlea using terahertz (THz) near-field imaging with a micrometer-scale point source generated by laser irradiation ($\sim 20 \mu\text{m}$ spot size). The cochlea was placed on a GaAs substrate for effective imaging. 2D THz time-domain images were captured at various delay times, providing depth-resolved structural information. By applying the time-of-flight (ToF) principle, temporal data were converted into depth profiles. Structural features were extracted using *k*-means clustering, enabling 3D reconstruction through point cloud generation and Poisson surface meshing. This approach marks the first 3D THz imaging of cochlear structures and shows great potential for high-resolution imaging of biological tissues and early diagnosis of related diseases. Image analysis for achieving higher resolution and more detailed measurement results are presented.

Acknowledgements

This work is partially supported by the Japan Science and Technology Agency FOREST program (JPMJFR2029 and JPMJFR215F), the Japan Society for the Promotion of Science KAKENHI (JP23K22820, JP23H00184, and JP25K01294), and the China Scholarship Council (Grant No. 202206170007).

References

- [1] S. G. Kujawa and M. C. Hear. *Res.* **330** (2015) 191–199.
- [2] L. F. Corns *et al.*, *Nat. Commun.* **9** (2018) 4015
- [3] Z. Wu *et al.*, *Nat. Neurosci.* **20** (2017) 24–33.
- [4] P. Delmas *et al.*, *Cell* **155** (2013) 278–284.
- [5] K. Serita *et al.*, *Opt. Express* **20** (2012) 12959–12965.
- [6] L. Zheng *et al.*, *Optica* **12** (2025) 437–445.

Investigation of the Physical Properties of Colloidal Indium Tin Oxide Nanocrystals Using Terahertz Spectroscopy

Daichi Eguchi, Kosaku Kato, Verdad C. Agulto, Makoto Nakajima

ILE, The University of Osaka
E-mail: eguchi.daichi.ile@osaka-u.ac.jp

1. Introduction

Colloidal inorganic nanocrystals (NCs) consist of an inorganic core and organic ligands, which contribute to their physical properties and colloidal stability, respectively. Indium tin oxide (ITO) NCs exhibit a localized surface plasmon resonance (LSPR) band in the near-infrared (NIR) region, and the position of this band can be tuned by adjusting the ratio of indium to tin. Due to these properties, ITO NCs have attracted considerable attention for applications in photoenergy conversion materials [1]. The terahertz (THz) region is generally defined as the frequency range between approximately 0.1-10 THz. Although the terahertz region has lower photon energy compared to the visible range (1 THz = ~ 4.1 meV), it enables the measurement of physical phenomena—such as free electron behavior—that are not accessible with visible light. While the physical properties of bulk ITO have been investigated using terahertz spectroscopy [2], those of colloidal ITO NCs remain largely unexplored. In this study, we synthesized a series of ITO NCs with varying indium-to-tin ratios and different surface ligands, and investigated their physical properties using terahertz time-domain spectroscopy (THz-TDS).

2. Methods

The NCs were synthesized according to reported procedure [3]. Indium acetate and 2-ethylhexanoate tin were used as the indium and tin precursors, respectively. The indium-to-tin ratio was controlled by adjusting the molar ratio of the precursors. Ligand exchange from long alkyl chain ligands to inorganic ligands was carried out using BF_4^- (BF_4^- -ITO NCs) [4]. The obtained NCs were characterized by transmission electron microscopy, powder X-ray diffraction measurements, Fourier transform infrared spectroscopy, and steady-state absorption spectroscopy. The samples were prepared as pellets embedded in a matrix, and THz-TDS measurements were conducted in transmission mode using a femtosecond laser and a photoconductive antenna setup (TOPTICA, TeraFlash pro).

3. Results and discussion

The ITO NCs exhibited an LSPR band in the NIR region. After ligand exchange, the BF_4^- -treated ITO NCs showed colloidal stability in polar solvents. This result indicates that the ligand exchange was successful, as the long alkyl chain ligands were non-polar and thus insoluble in polar solvents. Figure 1 presents the THz-TDS results. The amplitude of untreated ITO NCs was nearly identical to that of the matrix alone, while the BF_4^- -ITO NCs showed a re-

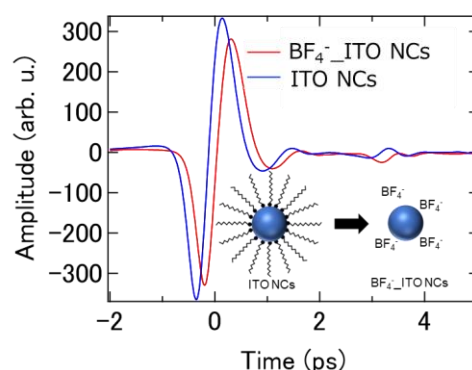


Figure 1. Time-domain waveforms for the BF_4^- -ITO NCs (red) and ITO NCs (Blue).

duced amplitude. This trend was not observed in control experiments using undoped In_2O_3 NCs. These results suggest that both tin doping and inorganic ligands contribute to changes in the terahertz time-domain waveform. From the time-domain data, the real and imaginary parts of the refractive index were calculated. In the BF_4^- -ITO NCs, the imaginary part increased at lower frequencies, whereas this trend was not observed in samples before ligand exchange or in undoped In_2O_3 NCs. These observations suggest that free electrons are delocalized due to the close interparticle distances.

4. Conclusions

In summary, we synthesized ITO NCs with varying indium-to-tin ratios and ligands, and investigated their free electron behavior via terahertz spectroscopy. Our findings indicate that the presence of free carriers and the interparticle distance are important factors in terahertz spectroscopy of nanomaterials. This work may serve as a guideline for applying terahertz spectroscopy to other colloidal NC systems.

Acknowledgements

This work was supported by JSPS KAKENHI under Grant number 24H00317 and 25K17902 and The Hattori Hokokai Foundation.

References

- [1] M. Sakamoto *et al.*, Nat. Commun. **10**, (2019) 406.
- [2] T. Wang *et al.*, Opt. Mater. Express **5**, (2015) 566-575.
- [3] M. Kanehara *et al.*, J. Am. Chem. Soc. (2009) **131**, 17736-17737.
- [4] A. Dong *et al.*, J. Am. Chem. Soc. (2011) **133**, 998-1006.

Anisotropic Temperature Dependence of Carrier Transport in Beta-Gallium Oxide Epilayer Evaluated by Terahertz Time-Domain Spectroscopy

Shuang Liu¹, Verdad C. Agulto¹, Toshiyuki Iwamoto^{1,2}, Kosaku Kato¹, Thanh Nhat Khoa Phan¹, Yoshinao Kumagai³, Hisashi Murakami³, and Makoto Nakajima¹

¹Institute of Laser Engineering, The University of Osaka

²Nippo Precision Co., Ltd.

³Department of Applied Chemistry, Tokyo University of Agriculture and Technology

E-mail: nakajima.makoto.ile@osaka-u.ac.jp

1. Introduction

Gallium oxide (Ga_2O_3), an emerging ultra-wide bandgap semiconductor (~ 4.9 eV), holds great promise for power electronics and deep-ultraviolet optoelectronic devices due to its high breakdown field and Baliga's figure of merit. Among its polymorphs, $\beta\text{-Ga}_2\text{O}_3$ is the most stable and exhibits strong anisotropy owing to its monoclinic structure. Terahertz time-domain spectroscopy (THz-TDS) offers a non-contact approach to probe anisotropic charge transport and phonon modes. While prior studies focused on room-temperature behavior [1-3], this work investigates anisotropic carrier transport in $\beta\text{-Ga}_2\text{O}_3$ over a wide temperature range, providing insights critical for device optimization.

In this study, we investigate the anisotropic terahertz response of $\beta\text{-Ga}_2\text{O}_3$ epitaxial layers along the a-axis [100] and b-axis [010] directions using THz-TDS. The measurements were conducted over a frequency range of 0.2-3 THz and a temperature range of 90-400 K. By fitting the experimental spectra with the Drude-Lorentz model, we quantitatively extracted key anisotropic transport parameters. These results offer fundamental insights into the direction-dependent carrier dynamics of $\beta\text{-Ga}_2\text{O}_3$ and provide valuable theoretical guidance for its integration into high-frequency electronic and optoelectronic devices.

2. Results

A 4.5 μm -thick Si-doped n-type $\beta\text{-Ga}_2\text{O}_3$ homoepitaxial layer was grown on a 647 μm -thick Fe-doped semi-insulating (001)-oriented $\beta\text{-Ga}_2\text{O}_3$ substrate. The highly doped epilayer have a carrier density of $\sim 5 \times 10^{17} \text{cm}^{-3}$ at room temperature measured by Hall method. THz-TDS measurements were conducted using a commercial system (Tera Prospector, Nippo Precision Co., Ltd.) equipped with photoconductive antennas for both THz pulse generation and detection. The sample was mounted in a liquid-nitrogen-cooled cryostat with precise temperature control from 90 to 400 K, housed in a dry-air-purged enclosure to minimize atmospheric water vapor absorption. The transmitted THz time-domain waveforms were recorded and subsequently Fourier-transformed to obtain the complex refractive index spectra.

The frequency-dependent complex refractive index of $\beta\text{-Ga}_2\text{O}_3$ was derived via Fourier transform and Fresnel transmission analysis. By fitting the spectra to Drude-Lorentz model considering only the effect of the first phonon mode of $\beta\text{-Ga}_2\text{O}_3$ on its terahertz response, we obtained the

temperature-dependent parameters of carriers.

Figure 1 presents the temperature dependence of the DC conductivity, derived from the extracted plasma frequency and scattering time via the Drude-Lorentz model. At lower temperatures, the conductivity increases with the thermal activation of dopants, while at higher temperatures it decreases due to enhanced carrier scattering by lattice vibrations. The temperature dependence reveals clear anisotropy in carrier transport between the a- and b-axis directions. The observed anisotropic conductivity may come from slight differences in the electron effective mass, which become less pronounced at elevated temperatures. As temperature rises, DC conductivity anisotropy diminishes, consistent with electron mobility being increasingly limited by optical phonon scattering.

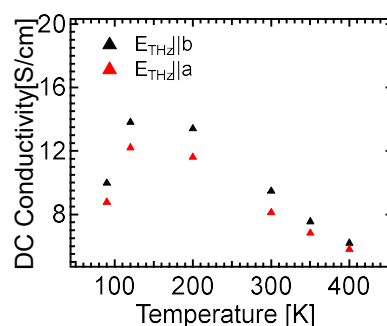


Fig. 1. The temperature dependence of DC conductivity along a- and b-axis.

3. Conclusions

We examined the anisotropic carrier transport in a Si-doped $\beta\text{-Ga}_2\text{O}_3$ epilayer along the [100] and [010] directions using THz-TDS over 90–400 K. The temperature-dependent anisotropy and its underlying mechanisms were discussed.

Acknowledgements

The authors are grateful to Dr. K. Goto for his support in sample fabrication. This work was supported by JSPS KAKENHI Grant Numbers JP24H00317, JP24H02232, and partially supported by JKA and its promotion funds from AUTORACE. This work was supported by JST SPRING, Grant Number JPMJSP2138.

References

- [1] V. C. Agulto et al., *Appl. Phys. Lett.* **118** (2021) 042101.
- [2] V. C. Agulto et al., *Sci Rep* **11**, 18129 (2021).
- [3] J. Wang et al., *Nature* **631**, 67–72 (2024).

Measurement of the Complex Anisotropy Ratio of the Nonlinear Optical Susceptibility in the Third Harmonic Generation by Terahertz Free-Electron Laser

Thanh Nhat Khoa Phan¹, You Wei Wang¹, Kosaku Kato¹, Verdad C. Agulto¹, Goro Isoyama², Makoto Nakajima¹

¹ Institute of Laser Engineering, The University of Osaka, ² SANKEN, The University of Osaka,
E-mail: nakajima.makoto.ile@osaka-u.ac.jp

1. Introduction

The efficient nonlinear optical effect due to free carrier in the infrared region and terahertz (THz) region has been studied in narrow band gap semiconductor. The widely accepted mechanism has been attributed to the momentum-dependent effective mass of the free carrier [1]. This mechanism leads to a real value of the nonlinear susceptibility. Later, several authors extended the calculation and showed that the nonlinear susceptibility is a complex number [2,3], in which the momentum-dependent scattering time contributes to the imaginary part.

By utilizing an intense 4 THz beam from a THz free electron laser (FEL), we observed the angular anisotropy of the third harmonic generation (THG) from indium antimonide (InSb) [4], which revealed the contribution of the imaginary part of the nonlinear susceptibility originating from the momentum-scattering time relation.

2. Experiment

The FEL at the Research Laboratory for Quantum Beam Science at SANKEN, the University of Osaka [5], was used to excite the InSb samples. The FEL emits 5 macro-pulses per second, each containing around one hundred micro-pulses with picosecond duration. The output frequency of the laser was tuned to 4 THz. Radiation with frequency higher than 5 THz were filtered out by a low pass filter. Two wire-grid polarizers were used to set the laser beam polarization. The samples were rotated around their surface normal to change the angle ϕ (the azimuthal angle) between the crystal (010) axis and the polarization of the pumping beam. Then, a third wire-grid polarizer was inserted after the sample and rotated to selectively measured the intensity of the two orthogonal components $I_{\parallel}$ and $I_{\perp}$ of the THG beam, which correspond to the THG electric fields polarized parallel and perpendicular to that of the pumping beam. A DLaTGS (JASCO Corp.) detector was used to measure the signal intensity. A high pass filter was set before the detector to reject the residual 4-THz pumping beam.

3. Results

We observed THG signals with a peak frequency of 12 THz. Fig.1 shows the experiment result of the dependence of the two components $I_{\parallel}$ (diamonds) and perpendicular $I_{\perp}$ (circles) on the sample azimuthal angle. $I_{\parallel}$ was modulated mainly with the angular cycle 90° , corresponding to the $\cos 4\phi$. However, the dips around 45° and 135° had a small

local maximum around each center. This deviation from the $\cos 4\phi$ -like shape is considered to reflect the $\cos 8\phi$ term.

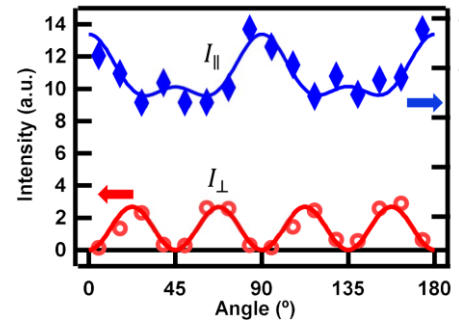


Fig.1. The dependence of THG intensity component $I_{\parallel}$ and $I_{\perp}$ on the sample azimuthal angle.

Meanwhile, $I_{\perp}$ had an oscillation with the angular cycle 45° in agreement with the $\cos 8\phi$ term. We evaluate the value of anisotropy ratio of the nonlinear susceptibility $\chi_R = \chi_2/\chi_1$ by fitting these results with theory equation [6]. The fitted curves were shown by the solid curves in Fig.1. From the fit, the absolute value and complex phase of χ_R were estimated to be $|\chi_R| = 0.38 \pm 0.02$ and $\theta_R = 58^\circ \pm 4^\circ$, respectively. The θ_R is far from zero and thus the imaginary part of the χ_R is considerably large. This result means that either or both of the nonlinear susceptibility tensor components χ_1 and χ_2 has a complex value.

4. Conclusion

The anisotropy ratios χ_R was extracted from the THz THG experimental data and was found to be complex values, the reason of which is proposed to be the non-negligible contribution of momentum dependence of the scattering time to the imaginary part of the nonlinear susceptibility.

Acknowledgements

This work was supported by Japan Society for the Promotion of Science (JSPS), grant numbers KAKENHI JP20H02206, JP23K17748, JP24H00317, JP24H02232.

References

- [1] C. K. N. Patel *et al.*, Phys. Rev. Lett. **17** (1966) 1011.
- [2] A. Mayer *et al.*, Phys. Rev. B **33** (1986) 6962.
- [3] Charles C. Wang *et al.*, Phys. Rev. **188** (1969) 1291.
- [4] Thanh Nhat Khoa Phan *et al.*, Opt. Lett. **49** (2024) 1073.
- [5] Keigo Kawase *et al.*, Nucl. Instruments Methods Phys. Res. Sect. A **960** (2020) 163582.
- [6] Thanh Nhat Khoa Phan *et al.*, Opt. Lett. **49**, (2024) 5039.

Label-Free Detection of Glucose and Lactate Using Terahertz Chemical Microscope with Aptamer-Functionalized Sensing Plates

Yuta Mitsuda¹, Ryotaro Kubo¹, Hikaru Nakagawa¹, Toshihiko Kiwa¹, Jin Wang¹

¹ Graduate School of Interdisciplinary Science and Engineering in Health Systems,
Okayama University

E-mail: p07k4tj7@s.okayama-u.ac.jp

1. Introduction

Glucose and lactate are key biomarkers for conditions such as diabetes and lactic acidosis, necessitating rapid and highly sensitive detection methods. Conventional approaches often rely on labels or enzymes, which involve complex procedures and limited sensitivity.

In this study, we employed a Terahertz Chemical Microscope (TCM) combined with aptamer-functionalized sensing plates to enable label-free and real-time detection of glucose and lactate. By utilizing dielectric changes at the sensing surface, this method offers a promising approach for advanced biosensing applications in the medical field.

2. Method

To detect glucose and lactate with high sensitivity, we employed a Terahertz Chemical Microscope (TCM) equipped with aptamer-functionalized Silicon-on-Sapphire (SOS) sensing plates. Each aptamer was immobilized onto the surface of the SiO₂ layer using a BS3-based crosslinking protocol following surface modification with NaOH and APTES [1].

After aptamer immobilization, target molecules (glucose or lactate) at various concentrations were introduced to the wells containing the sensing plates. Terahertz amplitude was measured before and after molecular binding. The spatial mapping of the THz amplitude was performed using an X-Y stage controlled via LabVIEW, and detection was carried out using photoconductive antenna sensors under femtosecond laser excitation.

3. Result

The terahertz amplitude changed significantly in response to the binding of glucose or lactate to their respective aptamers. This change correlated with concentration in both cases. As shown in Figures 1 and 2, the terahertz amplitude varied systematically with glucose and lactate concentrations, respectively.

For glucose, a monotonic increase in amplitude was observed with increasing concentration, demonstrating the feasibility of quantitative detection. For lactate, distinct amplitude shifts were confirmed across a wide dynamic range, from 0.1 mM to 100 mM.

The results confirmed that TCM enables highly sensitive, real-time, and label-free detection of small biomolecules. Reproducibility was verified through repeated measurements, and amplitude stability was maintained over the course of experiments.

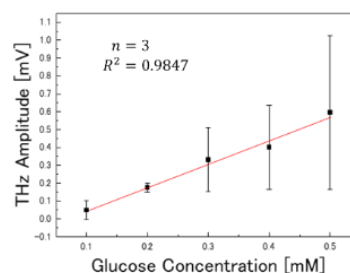


Fig.1 Correlation Between Glucose Concentration and Terahertz Amplitude

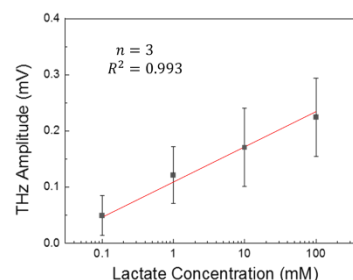


Fig.2 Correlation Between Lactate Concentration and Terahertz Amplitude

4. Conclusion

In this study, we investigated a detection method combining aptamer-functionalized sensors with terahertz chemical microscopy for identifying medically important small molecules such as glucose and lactate. The proposed approach is non-invasive and label-free, demonstrating its potential applicability to diabetes management and lactic acidosis monitoring.

References

- [1]. Jin Wang, et al. Applied Physics Express, 16 (5), 052002, 2023.
- [2]. T. Kiwa, A. Tenma, S. Takahashi, K. Sakai, and K. Tsukada, "Label free immune assay using terahertz chemical microscope," Sensors and Actuators B, 187, pp.8-11, 2013.
- [3]. Kosei Morita, Yuta Mitsuda, Sota Yoshida, Toshihiko Kiwa, Jin Wang, "Mapping Surface Potential in DNA Aptamer-Neurochemical and Membrane-Ion Interactions on the SOS Substrate Using Terahertz Microscopy," Biosensors, 15(1), pp.46 2025.

4 JSAP-Optica Joint Symposia 2025 | 一般セッション(口頭講演) : 4.7 Quantum Optics, Nonlinear Optics and Structured Optics

[7a-N204-1~9] 4.7 Quantum Optics, Nonlinear Optics and Structured Optics

[7a-N204-1]

[JSAP-Optica Joint Symposia Invited Talk] Nanostructured electric field momentum and spin densities in the near-field of plasmonic multimer nanoantennas

○Christophe Pin¹, Sile Nic Chormaic¹, Keiji Sasaki² (1.OIST Graduate Univ., 2.RIES, Hokkaido Univ.)

[7a-N204-2]

Real-time observation of optical vortex-induced surface relief formation in azo-polymers

○Takayuki Umakoshi¹, Kota Kojimoto¹, Rihito Tamura², Feng-Yueh Chan³, Takayuki Uchihashi^{3,4}, Prabhat Verma¹, Takashige Omatsu² (1.Osaka Univ., 2.Chiba Univ., 3.Nagoya Univ., 4.ExCELLS)

[7a-N204-3]

Optical vortex lattices induced light-matter interaction

○(PC)Soki Hirayama¹, Yohei Kawano^{1,2}, A. Srinivasa Rao¹, Takashige Omatsu¹ (1.MCRC, Chiba Univ., 2.HSG K.K.)

[7a-N204-4]

Ultrafast vortex beams for chiral selectivity

○Yuchieh Lin¹, Katsumi Midorikawa¹, Yasuo Nabekawa¹ (1.RIKEN)

[7a-N204-5]

512-Fold Super Resolved Rotation Sensing via Four-Photon High Dimensional Structured Light

○(D)Guy Tshuva¹, Ofir Yesharim¹, Hagai Eisenberg², Ady Arie¹ (1.Tel Aviv Univ., 2.Hebrew Univ.)

[7a-N204-6]

Sub- μ J driven high harmonic generation with a micrometer scale focal spot diameter

○Maria Carla Lupu¹, Filchito Renee Bagsican¹, Tatsunosuke Hanano¹, Michael Man¹, Julien Madeo¹, Keshav Dani¹ (1.OIST)

[7a-N204-7]

[JSAP-Optica Joint Symposia Invited Talk] High-Power Diamond Laser: Generation and Beam Control Techniques

○Zhenxu Bai¹ (1.Hebei Univ. of Tech.)

[7a-N204-8]

Watt-level optical skyrmion beams from a dual mode output coupling laser system

○(PC)Srinivasa Rao Allam¹, Jingni Geng¹, Quan Sheng², Takashige Omatsu^{1,2} (1.Chiba Univ., 2.Tianjin Univ.)

[7a-N204-9]

Numerical Simulation for Modeling Beam Dynamics in Structured Optical Systems

○(D)Naina Sharma¹, Sachin Sharma¹ (1.Netaji Subhas Univ. of Tech.)

Nanostructured electric field momentum and spin densities in the near-field of plasmonic multimer nanoantennas

Christophe Pin¹, Síle Nic Chormaic¹, Keiji Sasaki²

¹ OIST Graduate University, ² RIES, Hokkaido University
E-mail: christophe.pin@oist.jp

1. Introduction

In optics, photonics, and in other fields as well, the topological properties of structured waves have emerged as key ingredients in the development of more advanced metrology, sensing, and information technologies [1]. In recent years, the generation and control of skyrmions, hopfions, and other topological quasiparticles that may be formed in electromagnetic waves have gained substantial attention as they offer multiplexed degrees of freedom for encoding, storing, and transferring information [2,3]. However, efficiently interfacing such light topological quasiparticles with other material (quasi-)particles remains challenging because of the diffraction limit.

2. Results & discussion

In this work, we show that plasmonic multimer nanoantennas can be used to create nanoscale textures with non-trivial topology in the phase, polarization, and spin angular momentum density distributions of the electric field. Plasmonic trimer nanoantennas have been used to confine circularly polarized electric field in a nanogap, allowing for nanoscale rotation of nanoparticles and enantioselective crystallization of chiral crystal structures [4,5]. Moreover, plasmonic multimer nanoantennas may be used to focus optical vortex beams provided that the number of monomer structures is large enough [6].

Optical nanovortex generation may be also achieved under plane wave excitation condition by tuning the phase response of the monomer structures. To this aim, we investigate several strategies. The first one relies on multimer nanoantennas composed of plasmonic dipole resonators with alternate blue- and red-shifted resonances. When excited at an intermediate wavelength, the spectral detuning introduces a phase difference close to π between the optical responses of the two kinds of resonators. We show that, in the case of a hexamer nanoantenna, a quadrupole-like charge distribution is formed and rotates around the nanogap of the nanoantenna upon circularly polarized plane wave irradiation. The second nanoantenna design consists of alternate plasmonic dipole and longitudinal quadrupole resonators. The dipole modes act as bright modes that can excite the dark longitudinal quadrupole modes via near-field coupling. As in the previous case, a π phase difference can be obtained between the optical responses of the two kinds of resonators, leading to the formation of an optical nanovortex (i.e. a phase singularity) in the nanogap of the nanoantenna.

Based on the analysis of the electric field locally excited by the oscillating charges around plasmonic nanogaps, we also investigate the role of the phase delay between the oscillating charges in the emergence of transverse spin angular momentum. We demonstrate that electric field spin skyrmions with deep-subwavelength sizes can be formed in the vicinity of plasmonic multimer nanoantennas.

3. Conclusions

By controlling the phase response of each plasmonic resonator composing a multimer nanoantenna, it becomes possible to control the topological properties of the electric field and its spin angular momentum density on a deep-subwavelength scale. This work demonstrates that nanoscale optical vortices, optical skyrmions, and electric field spin skyrmions can be formed near plasmonic nanogaps. The ability to structure light fields confined near plasmonic nanogaps paves the way for new applications in optical sensing and quantum photonics.

Acknowledgements

This work was supported by JSPS KAKENHI (JP22H01923, JP23K23191, JP18H05205, JP21H04657, JP23H04571, JP23H05464, JP25K01643, JP25K01643). This work was partly supported by “Advanced Research Infrastructure for Materials and Nanotechnology in Japan (ARIM)” of the Ministry of Education, Culture, Sports, Science and Technology (MEXT). Grant Number JPMXP1224HK0142 (Hokkaido University). We are also grateful for the help and support provided by the engineering section of Core Facilities at Okinawa Institute of Science and Technology Graduate University.

References

- [1] Andrew Forbes *et al.*, Nat. Photonics **15** (2021) 253.
- [2] Yijie Shen *et al.*, Nat. Photonics **18** (2024) 15.
- [3] Srinivasa Rao Allam *et al.*, arXiv preprint arXiv:2501.10760 (2025).
- [4] Hideki Fujiwara *et al.*, Nano Lett. **21** (2021) 6268.
- [5] An-Chieh Cheng *et al.*, Small **20** (2024) 2312174.
- [6] Yuji Sunaba *et al.*, Nanophotonics **12** (2023) 2499.

Real-time observation of optical vortex-induced surface relief formation in azo-polymers

Takayuki Umakoshi^{1,2}, Kota Kojimoto¹, Rihito Tamura³, Feng-Yueh Chan⁴, Takayuki Uchihashi^{4,5}, Prabhat Verma¹, Takashige Omatsu^{3,6}

¹Dept. of Applied Physics, Osaka Univ., ²Inst. Adv. Co-creation Studies, Osaka Univ., ³Molecular Chirality Research Center, Chiba Univ., ⁴Dept. of Physics, Nagoya Univ., ⁵ExCELLS, ⁶MCRC, Chiba Univ.,
E-mail : umakoshi@ap.eng.osaka-u.ac.jp

1. Introduction

Azo-polymers exhibit unique mass-transport through photoisomerization reactions under light irradiation, thereby forming surface relief, and thus, it is promising for various applications, such as rewritable optical memory. In recent years, optical vortex, possessing orbital angular momentum (OAM) associated with its helical wavefront, enables the twist of the azo-polymers to form chiral surface structures [1]. However, such chiral surface relief formation has not been fully understood yet. High-speed atomic force microscopy (HS-AFM), which operates at high temporal (<10 frames/s) and spatial (~1nm) resolutions, has the potential to capture nano-scale mass transport of azo-polymers in real-time [2]. In this study, we demonstrate the first real-time observation of optical vortex induced surface relief formation with HS-AFM, as illustrated in Fig. 1.

2. Results and Discussion

An azo-polymers (POT-1) film used in this experiment was spin-coated, and its thickness was measured to be ~1 μm . A continuous-wave green laser was used as a pump source, and its output was converted into a vortex beam with a topological charge ℓ of 1~4 by employing a spiral phase plate (SPP). Note that the helicity of optical vortex can be inverted simply by reversing the SPP. The optical vortex was focused to be *** μm spot on the film by using an inverted optical microscope. Also, a tip-scan HS-AFM was installed on the microscope, so as to observe directly the laser induced deformation in azo-polymers [2].

Figure 2(a) shows the time-laps of chiral surface relief formation observed by HS-AFM. Note that the topological charge ℓ was then fixed to be 4. Interestingly, by inverting the sign of topological charge, the chirality of the surface relief was also reversed (Fig. 2(b)). Further investigation of the surface relief formation including spin-orbital angular momentum coupling effects.

3. Conclusions

We have successfully demonstrated the *in-situ* real-time observation of optical vortex induced chiral surface relief formation of azo-polymers with HS-AFM.

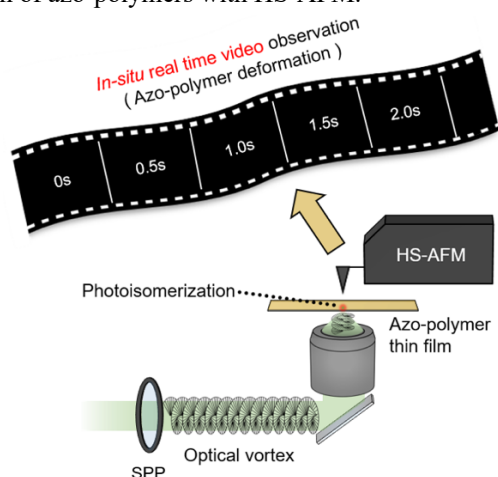


Figure 1 Schematic diagram of HS-AFM and optical vortex combined system.

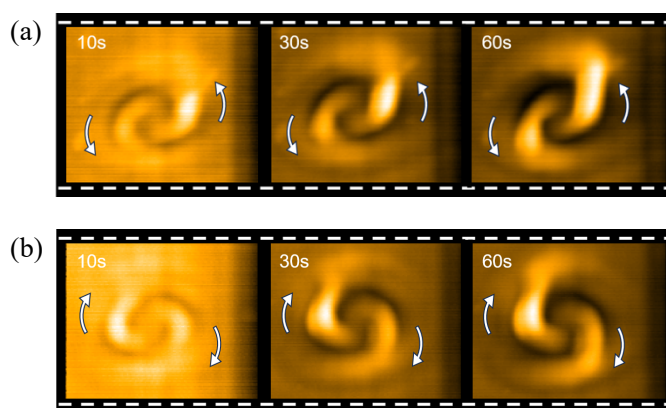


Figure 2 (a), (b) HS-AFM images of azo-polymer surface deformation induced by optical vortex irradiation with reversed total angular momentum.

References

- [1] M. Watabe, et al., *Sci. Rep.*, **4**, 4218, (2014)
- [2] K. Yang, et al., *Nano Lett.*, **24**, 9, 2805, (2024)



Optical vortex lattices induced light-matter interaction

MCRC, Chiba Univ.¹, HSG K.K.²

°(PC)Soki Hirayama¹, Yohei Kawano^{1,2}, A. Srinivasa Rao¹, Takashige Omatsu¹

E-mail: skhrym@chiba-u.jp

Laguerre–Gaussian (LG) modes carry an orbital angular momentum (OAM, characterized by an index ℓ). Also, circularly polarized light possesses spin angular momentum (SAM, characterized by an index $s = \pm 1$). Optical vortex lattices are formed of the coherent superposition of two LG modes with different OAM indices. In particular, circularly polarized optical vortex lattices exhibit unique wavefront and polarization structures (multiple vortices structures) via spin–orbit angular momentum couplings, thereby yielding exotic light–matter interactions. In fact, vortex lattices have been observed in condensed matters, including super-fluids and superconductors, and they have been intensely studied to understand fundamental phenomena. However, there are few reports detailing optical vortex lattices induced light–matter interaction.

In this study, we report on the first demonstration of optical vortex lattices induced light–matter interaction in a photosensitive functional material (azo-polymer with a photo-induced mass transport).

A continuous-wave green laser (wavelength: 532 nm) was used, and its output was converted into optical vortex lattices, formed of LG modes with different OAM states ($\ell = +1, \ell' = +7$ and $\ell = -1, \ell' = -7$), with hexagonal close-packed vortices by employing a spatial light modulator (SLM) and a quarter wave plate. Note that the generated optical vortex lattices were then right-handed circularly polarized (SAM ($s = -1$)). The generated optical vortex lattice was focused to be a $15\ \mu\text{m}$ spot onto an azo-polymer film, so as to form a surface relief structure. The laser power and laser exposure time were then fixed to be $375\ \mu\text{W}$ and 20 seconds, respectively.

Figure 1 shows atomic force microscope (AFM) images of the surface relief structures formed on the azo-polymer film under illumination of optical vortex lattices.

Hexagonal close-packed protrusions were formed at the dark spots (vortices) of the illuminated optical vortex lattices, arising from the photo-induced mass transport. When OAM and SAM had the same sign, the protrusions with relatively low height ($\sim 100\ \text{nm}$) appeared to be interconnected (Fig. 1(a)). In contrast,

when OAM had the opposite sign of SAM, the tall protrusions were formed independently (Fig. 1(b)).

These results manifest the constructive/destructive coupling effects of the OAM and SAM of optical vortex lattices.

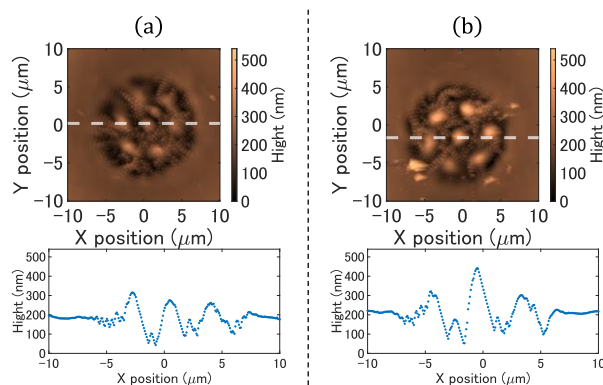


Fig. 1. AFM images of the surface relief structures formed on the azo-polymer under illumination with optical vortex lattice (a) in case that OAM and SAM had the same sign and (b) in case that OAM had the opposite sign of SAM. The line profiles were measured along the path indicated by the white line in the images.

Ultrafast vortex beams for chiral selectivity

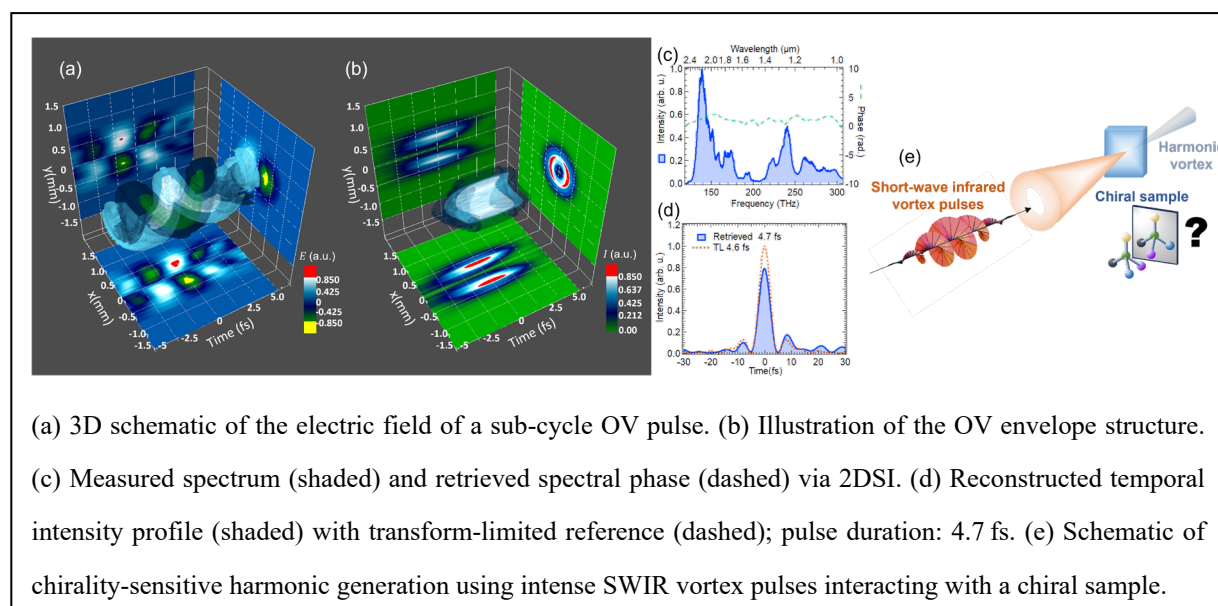
○Yu-Chieh Lin, Katsumi Midorikawa, Yasuo Nabekawa

Ultrafast Coherent Soft X-ray Photonics Research Team, RIKEN Center for Advanced Photonics,

E-mail: yu-chieh.lin@riken.jp

Intense few-cycle optical vortex (OV) pulses with helical wavefronts are powerful tools for strong-field phenomena such as high-order harmonic generation (HHG), filamentation, and supercontinuum generation. When compressed to the sub-cycle regime, precise control over the spatiotemporal electric field becomes critical, especially for interactions governed by the instantaneous field rather than the envelope. We report a carrier-envelope phase (CEP)-controllable OV source in the short-wave infrared (SWIR) regime with over-octave bandwidth (0.9–2.4 μm), delivering 4.7 fs pulses—corresponding to 0.9 optical cycles at a center wavelength of 1.54 μm [1–3]. This intense, CEP-controllable source enables advanced strong-field and chirality-sensitive light–matter interactions.

The OV pulses are generated by converting sub-cycle Gaussian pulses from a SWIR optical parametric amplifier [1] into vortex beams using an achromatic Sagnac interferometer, with topological charge $\ell = 1$ confirmed by spiral interference patterns. Full field reconstruction via two-dimensional shearing interferometry (2DSI) shows close agreement with the transform-limited duration. Notably, CEP tuning allows control over the azimuthal phase of the electric field, enabling active manipulation of the spiral wavefront. This source opens new avenues in enantioselective spectroscopy and chiral discrimination. In this presentation, we will also report recent experimental applications of this SWIR OV source in probing and distinguishing chiral samples.



References

- [1] Y.-C. Lin, Y. Nabekawa, and K. Midorikawa, Nat. Commun. **11**(1), 3413 (2020).
- [2] Y.-C. Lin, K. Midorikawa, Y. Nabekawa, Opt. Express, **30**, 10818-10832 (2022).
- [3] Y.-C. Lin, K. Midorikawa, Y. Nabekawa, Light Sci. Appl. **12**, 279 (2023).

512-Fold Super-Resolved Rotation Sensing via Four-Photon High-Dimensional Structured Light

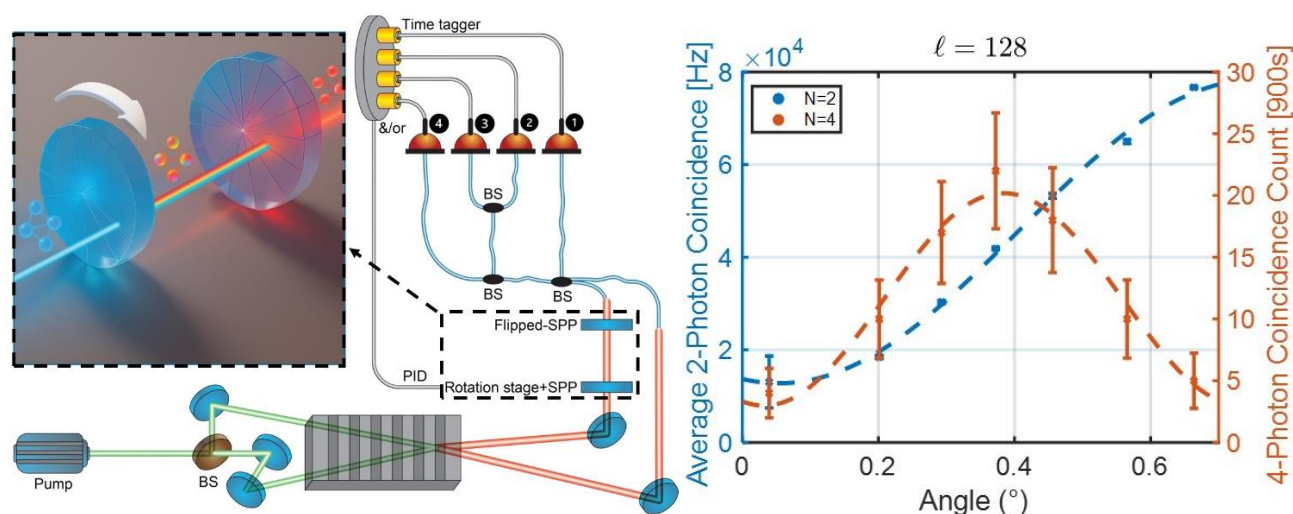
Guy Tshuva^{1*}, Ofir Yesharim^{1*}, Hagai S. Eisenberg², Ady Arie^{1*} **Equal contribution*

1. School of Electrical Engineering, Fleischman Faculty of Engineering, Tel Aviv University, Tel Aviv 69978, Israel

2. Racah Institute of Physics, Hebrew University of Jerusalem, Jerusalem 91904, Israel

Quantum-enhanced sensors that exploit N -photon entanglement surpass the shot-noise limit by $\sqrt{N}$ and achieve N -fold resolution gains [1, 2]. Structured light can further boost sensitivity [3]. However, shaping entanglement beyond two photons remains difficult because of inefficient optical setups and the low generation probability of multi-photon states. Consequently, demonstrations with high-order structured light have so far been restricted to $N \leq 2$ [1], and larger- N interferometers lacked large spatial structure, limiting improvement to N -fold resolution. Our work unifies these capabilities.

We demonstrate, for the first time, four-photon entanglement combined with very high-dimensional structured light ($\ell = 128$). By boosting four-photon production, employing an efficient shaping scheme [3], and adding photon-statistics-based feedback, we attain a 512-fold enhancement in rotation-sensing resolution. A 90 kHz stream of two-photon NOON coincidences serves as the PID error signal, producing a unique entanglement-based lock that preserves phase coherence and enables detection of four-photon fringes up to $\ell = 128$.



Left: experimental setup with a photonic-gear Mach-Zehnder interferometer ($\pm\ell$ spiral plates).

Right: rotation fringes for $\ell = 128$ using four entangled photons, showing 512 $\times$ super-resolution.

Fig.1. shows super-resolution for four-photon and two-photon cases. Blue scattered data are average coincidence counts over 900 seconds. Orange scattered data are four-photon counts for 900s with Poissonian errors. Note that to cover the 4-photon (2-photon) full cycle (half cycle), the rotation angle should change by only $360/512 \approx 0.7^\circ$. As can be seen, the four-photon signal oscillates twice over the same phase range, showing four-photon entanglement.

The simplicity and scalability of our scheme opens the door for quantum sensing of different physical quantities, with increased resolution and sensitivity due to both multi-photon interaction and very high-order modes, essentially breaking the trade-off between the two. Any physical parameter that can be mapped to an optical phase stands to benefit from the simultaneous leverage of multi-photon interference and very high-order spatial modes.

1. A. Forbes, M. de Oliveira, and M. R. Dennis, "Structured light," Nat. Photonics 15, 253–262 (2021).
2. R. Demkowicz, I. Fuentes, and F. Sciarrino, "Quantum metrology," AVS Quantum Sci. 4, 014701 (2022).
3. O. Yesharim, G. Tshuva, and A. Arie, "Quantum-enhanced mechanical rotation sensing using wavefront photonic gears," APL Photonics 9, 106116 (2024).

Sub- μJ driven high harmonic generation with a micrometer scale focal spot diameter

Femtosecond Spectroscopy Unit, Okinawa Institute of Science and Technology, 1919-1 Tancha, Onna son, Okinawa, Japan, 904-0495: Maria Carla Lupu, Filchito Renee Bagsican, Tatsunosuke Hanano, Michael K.

L. Man, Julien Madéo and Keshav M. Dani

E-mail: kmdani@oist.jp

High-order harmonic generation (HHG) is a nonlinear optical process with critical applications in ultrafast science, including attosecond pulse generation [1], coherent XUV imaging [2], and time-resolved photoemission spectroscopy [3]. Conventionally, HHG is driven by femtosecond laser pulses with mJ-level energies at kHz repetition rates, where the beam is focused to spot sizes on the order of hundreds of micrometers. Recent advancements have enabled scaling of the focusing geometry to tens of micrometers, allowing HHG with pulse energies in the tens of μJ [4]. However, efficient HHG using a μm -scale spot size has never been demonstrated. In this work, we demonstrate efficient HHG using a focal spot diameter down to $2\ \mu\text{m}$. By employing a noncollinear optical parametric amplifier (NOPA) operating at a 2 MHz repetition rate, we drive the HHG process with sub- μJ pulse energies. We achieve a photon flux of $\sim 10^{13}$ photons/s at 34 eV, with the harmonic spectrum extending up to 93 eV. In Figure 1-(a) we show the HHG spectrum obtained with a $4\ \mu\text{m}$ spot and 770 nm driving wavelength, where the photon flux at 34 eV is of $\sim 10^{13}$ photons/s. Figure 1-(b) presents the HHG spectrum obtained with a $\sim 2\ \mu\text{m}$ spot and 900 nm driving wavelength, in Ar gas and Al filter, while in Figure 1-(c) there is the HHG spectrum generated in Ne gas, with Zr filter. These results represent a significant step toward compact, high-repetition-rate HHG sources for next-generation ultrafast experiments.

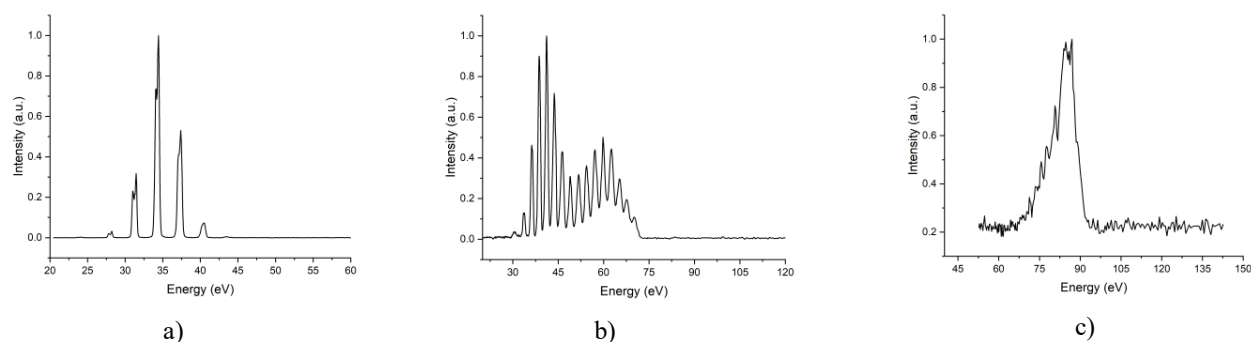


Figure 1. a) HHG spectrum in Ar gas, with a $4\ \mu\text{m}$ spot and 770 nm driving wavelength, b) HHG spectrum with a $2\ \mu\text{m}$ and 900 nm driving wavelength in Ar gas, and c) HHG spectrum with a $2\ \mu\text{m}$ and 900 nm driving wavelength in Ne gas

References

- [1] Li, J., Lu, J., Chew, A. et al, Nat Commun 11, 2748 (2020).
- [2] D. Gardner, et al., Nature Photon 11, 259–263 (2017).
- [3] J. Madéo, et al., Science 370, 1199-1204 (2020).
- [4] Klas, R., Kirsche, A., Gebhardt, M. et al, Photonix 2, 4 (2021)

High-Power Diamond Laser: Generation and Beam Control Techniques

Hebei Univ. of Tech.¹, °Zhenxu Bai¹

E-mail: baizhenxu@hotmail.com

High-power laser sources are indispensable for the advancement of cutting-edge technologies in national defense, aerospace, remote sensing, and precision manufacturing. These applications increasingly demand laser systems that not only deliver high output power but also exhibit superior temporal and spatial coherence, as well as flexible wavelength tunability. However, achieving a synergistic optimization of these parameters remains a long-standing challenge in laser science and engineering, particularly under high-power and high-repetition-rate operating conditions.

Diamond has recently gained significant attention as a next-generation laser material due to its exceptional optical and thermal properties. Its wide transmission window (from the ultraviolet to the far infrared), high nonlinear gain coefficient, ultrahigh thermal conductivity, and outstanding resistance to optical damage collectively position diamond as an ideal platform for the development of high-power and high-coherence laser systems.

In this report, we present recent advances made by our team in the design and implementation of diamond-based high-power laser architectures. We analyze the emerging demands for optical-grade synthetic diamond in photonic and laser applications and examine how its material properties can be fully leveraged through the integration of nonlinear optical processes, such as stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS). By tailoring these effects, we demonstrate the generation of laser outputs with narrow spectral linewidths, high coherence, low phase noise, and wavelength extension beyond conventional gain media limitations. Moreover, we explore various engineering strategies to improve the thermal management, optical stability, and beam quality of diamond laser systems. These include advanced cavity designs, adaptive temporal synchronization techniques, and beam shaping mechanisms, all aimed at overcoming limitations imposed by thermal lensing and gain-induced distortions under high-power operation.

The outcomes of this research not only advance the understanding of diamond as a laser gain and nonlinear medium but also pave the way for the realization of compact, efficient, and high-performance laser sources for future applications in quantum technology, precision metrology, directed energy systems, and beyond.

Watt-level optical skyrmion beams from a dual mode output coupling laser system

Srinivasa Rao Allam^{1,2,3}, Jingni Geng¹, Quan Sheng⁴, and Takashige Omatsu^{1,2,4*}

¹Graduate School of Engineering Chiba University Chiba 263-8522, Japan

²Molecular Chirality Research Centre, Chiba University, Chiba 263-8522, Japan

³Institute for Advanced Academic Research, Chiba University, Chiba, 263-8522, Japan

⁴Institute of Laser and Optoelectronics, School of Precision Instrument and Optoelectronics Engineering, Tianjin University, Tianjin 300072, China

E-mail: *omatsu@faculty.chiba-u.jp

Optical skyrmions possess a non-uniform polarization distribution with a central polarization singularity, and they have currently collected much attention as a 2-dimensional optical quasi-particle, because of their topologically protected properties under space propagation [1,2]. A variety of external mode conversion techniques, based on diffractive optical elements such as spatial light modulators (SLMs) and digital micro-mirror devices (DMDs), have been developed and micro-chip laser cavity reported to experimentally demonstrate the optical skyrmions [3-5], however, they have the limitation of power scalability and mode purity.

To overcome these limitations, we have proposed laser systems with a dual mode output coupling configuration in Pr^{3+} ions doped solid-state and fiber lasers, and we have demonstrated the generation of wavelength-versatile optical skyrmions with high mode purity [6,7]. However, the output powers of the systems were typically limited up to 100 mW owing to low laser gain of Pr^{3+} doped laser materials.

In this work, we report on the generation of watt-level optical skyrmions from a diode pumped neodymium doped yttrium vanadate ($\text{Nd}:\text{YVO}_4$) laser with a dual mode output coupling configuration.

The experimental setup is illustrated in Fig. 1. A 808 nm laser diode was used as a pump source, and its output was focused to be a $\phi 190\ \mu\text{m}$ spot on a a -cut $\text{Nd}:\text{YVO}_4$ crystal (0.3 at.% doping) with an input facet coated for high-reflectivity at 1064 nm and high-transmission at 808 nm. A flat mirror with 10% transmission at 1064 nm was used as an output coupler (OC). The cavity length was then fixed to be 130 mm.

An intracavity wedge plate shearing interferometer (WPSI) (Thorlabs SI100P) (thickness: 2.6 mm) acted as a mode converter to achieve a first order optical vortex output [6]. The generated optical vortex and Gaussian modes were coherently coupled by employing a half-wave plate (HWP) and a polarized beam splitter, so as to produce optical skyrmions and bimerons. The output power and skyrmion number of the skyrmion output were measured to be 1.06 W and ~ 0.9 at the pump power of 5.18 W.

The system will also produce 3 dimensional quasi-particles optical skyrmionic hopfions [8].

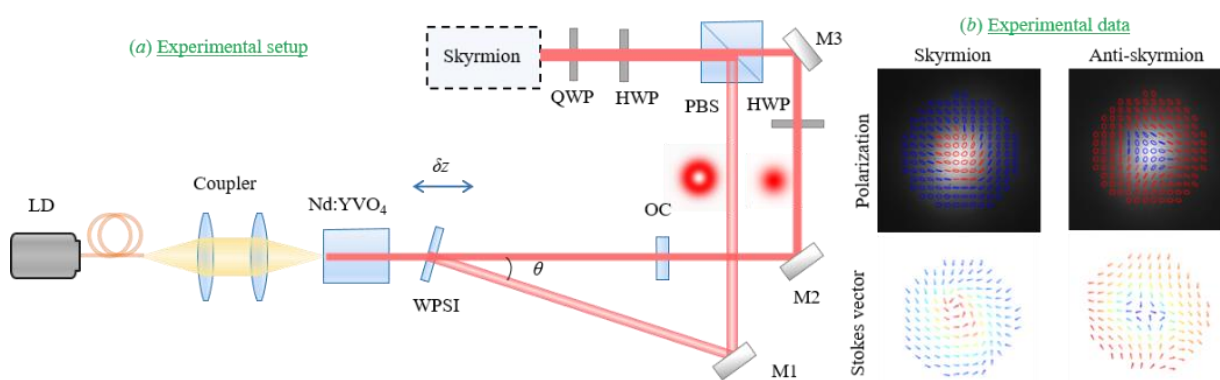


Figure (a) Cavity configuration of $\text{Nd}:\text{YVO}_4$ laser for skyrmions' generation. (b) Experimentally generated optical skyrmions.

References

- [1] S. R. Allam, Y. Yoneda, T. Omatsu, *Optical quasiparticles in paraxial laser beams*, Book Chapter, in *Progress in Optics* **70**, 281-338 (2025).
- [2] Y. Shen, H. Wang, and S. Fan, *Adv. Opt. Photonics* **17**(2), 295-374 (2025).
- [3] R. Tamura, P. Kumar, A. S. Rao, K. Tsuda, F. Getzlaff, K. Miyamoto, N. M. Litchinitser, and T. Omatsu, *APL Photonics* **9**, 046104 (2024).
- [4] A. McWilliam, C. M. Cisowski, Z. Ye, F. C. Speirits, J. B. Götte, S. M. Barnett, and S. Franke-Arnold, *Laser Photonics Rev.* **17**(9), 2300155 (2023).
- [5] W. Lin, Y. Ota, Y. Arakawa, and S. Iwamoto, *Optica* **11**(11), 1588-1594 (2024).
- [6] W. R. Kerridge-Johns, A. S. Rao, and T. Omatsu, *Optica* **11**(6), 769-775 (2024).
- [7] Y. Yoneda, S. R. Allam, W. R. Kerridge-Johns, Y. Fujimoto, and T. Omatsu, *Laser Photonics Rev.* 2401403 (2024).
- [8] R. Tamura, S. R. Allam, N. M. Litchinitser, and T. Omatsu, *ACS Photonics* **11**(11), 4958-4965 (2024).

Numerical Simulation for Modeling Beam Dynamics in Structured Optical Systems

Naina Sharma¹, Sachin Sharma¹

¹ Department of Mathematics, Netaji Subhas University of Technology, Delhi, India

E-mail: naina.ma21@nsut.ac.in

1. Introduction

The advancement of photonic technologies increasingly relies on the integration of mechanically responsive elements, such as nanobeams, waveguide membranes, and microresonators, within optical circuits. These components often exhibit structural flexibility, where even minor mechanical oscillations can significantly influence optical behavior—particularly in nanoscale environments. Accurate modeling of such dynamic interactions is essential for the design and stability of nanophotonic and optomechanical devices. A fundamental mathematical model widely employed for analyzing such systems is the Euler–Bernoulli beam equation, which describes the bending and vibrational behavior of slender beams. The present study proposes a spline-in-tension technique, designed to effectively capture the dynamic response of beam-like elements within structured optical systems.

2. Computational Method and Result

The governing equation addressed in this work is the Euler–Bernoulli (EB) beam model, representing the transverse deflection of a uniform elastic beam under dynamic loading. Traditional finite difference approaches, though commonly applied, often face limitations in handling higher-order spatial derivatives and maintaining numerical stability across varying mesh densities. To enhance accuracy and robustness, we introduce a half-step spline-in-tension scheme, where the deflection profile is approximated using spline functions modulated by a tension parameter. The EB beam equation, which characterizes the dynamic response of slender, inextensible beams is of the type

$$\omega A(\zeta) \frac{\partial^2 z}{\partial t^2} + \frac{\partial^2}{\partial \zeta^2} \left(EI(\zeta) \frac{\partial^2 z}{\partial \zeta^2} \right) = g(\zeta, t), a < \zeta < b, t > 0$$

where the solution $z(\zeta, t)$ refers to the deflection of the beam. Moreover, the coupling between light and mechanical oscillations in nanostructured environments remains a driving force behind advancements in waveguide behavior and optomechanical device innovation [1-2]. Spline methods have also been used to solve equations such as Kuramoto–Sivashinsky and good Boussinesq equations [4-5].

The method is particularly advantageous for capturing transient beam behaviors, such as vibration modes and wave propagation patterns, that are critical in photonic devices incorporating mechanical degrees of freedom. A 3D plot of

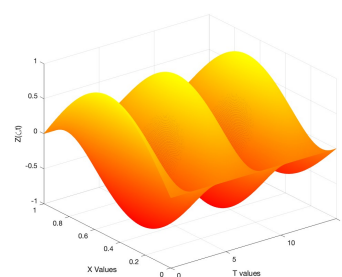


Fig. 1: 3D plot of EB model by employing Splines

The performance of the method is examined through simulations of beam dynamics at multiple time levels, and its stability is verified through numerical analysis.

3. Conclusions

The spline-in-tension technique presented in this study provides a reliable and high-resolution numerical approach for solving the Euler–Bernoulli beam equation, with specific relevance to the simulation of dynamic behavior in photonic and nanophotonic systems. This method supports the development of advanced photonic platforms, including optomechanical sensors, waveguide-based resonators, and integrated MEMS/NEMS optical systems. Its adaptability to more complex geometries and potential for extension to nonlinear domains further reinforce its relevance for future research in structured optics and photonic integration.

References

- [1] Gigan, S., Böhm, H. R., Paternostro, M., Blaser, F., Langer, G., Hertzberg, J. B., ... & Zeilinger, A. (2006). Self-cooling of a micromirror by radiation pressure. *Nature*, 444(7115), 67-70.
- [2] Barclay, P. E., Srinivasan, K., & Painter, O. (2005). Nonlinear response of silicon photonic crystal microresonators excited via an integrated waveguide and fiber taper. *Optics express*, 13(3), 801-820.
- [3] Sharma, N., & Sharma, S. (2024). A computational study of multi-soliton of good Boussinesq equation and Euler-Bernoulli beam model via non-polynomial spline algorithm. *International Journal of Modern Physics C*.
- [4] Sharma, S., & Sharma, N. (2024). A new spline method on graded mesh for fourth-order time-dependent PDEs: application to Kuramoto–Sivashinsky and extended Fisher–Kolmogorov equations. *Physica Scripta*, 99(10), 105275.

4 JSAP-Optica Joint Symposia 2025 | 一般セッション(口頭講演) : 4.7 Quantum Optics, Nonlinear Optics and Structured Optics

[7p-N204-1~8] 4.7 Quantum Optics, Nonlinear Optics and Structured Optics

[7p-N204-1]

[JSAP-Optica Joint Symposia Invited Talk] Integrated Lithium Niobate Photonics for Quantum Technology

Cheng-Chung Chiu¹, Po-Hsiang Huang¹, Sheng-Hung Wang², Po-Han Chen², Chien-Ming Wu³, Pin-Ju Tsai^{1,4}, Ray-Kuang Lee³, OYen-Hung Chen^{1,4,5} (1.Dept. of Optics and Photonics, National Central Univ., 2.Dept. of Physics, National Central Univ., 3.Inst. of Photonics Technologies, National Tsinghua Univ., 4.Quantum Technology Center, National Central Univ., 5.Center for Astronautical Physics and Engineering, National Central Univ.)

[7p-N204-2]

Performance Evaluation of Optical Quantum Communication Systems in Challenging Conditions

O(D)Venkateswara Rao Chilukuri^{1,2}, Prakash Pareek², Jitendra K. Mishra¹ (1.IIT Ranchi, 2.VIT Bhimavaram)

[7p-N204-3]

Coincidence of Two EP2s in The Parameter Space of a Gain-Loss Assisted Dual-Core Photonic Crystal Fiber

O(M2)Shamba Ghosh¹, Arpan Roy², Bishnu P. Pal³, Somnath Ghosh³ (1.IIT Jodhpur, 2.Calcutta Univ., 3.Mahindra Univ.)

[7p-N204-4]

Numerical Study on the Advantages of Different OPO Cavity Schemes in BBO

O(D)John Gregg^{1,2}, Jonathan Evans¹ (1.AFIT, 2.Leidos)

[7p-N204-5]

[JSAP-Optica Joint Symposia Invited Talk] High-power lasers and ultra-broadband optical parametric amplification technologies

OJumpei Ogino¹, Koji Tsubakimoto¹, Hidetsugu Yoshida¹, Yuki Tamaru¹, Noriaki Miyanaga^{1,2}, Akifumi Yogo¹ (1.ILE, The University of Osaka, 2.Inst. for Laser Technology)

[7p-N204-6]

Exact Localized Solutions in Modified Lugiato-Lefever Equation for Frequency Comb Applications

O(DC)Sanjana Bhatia¹, Kanishk Poria¹, C.N. Kumar¹ (1.Panjab University)

[7p-N204-7]

Coherence synthesis in nonlinear optics

O(D)Zihao Pang¹, Ady Arie¹ (1.Tel Aviv University)

[7p-N204-8]

Collective Emission Through Electron-Hole Plasma

O(D)Naresh Aggarwal¹, Dmitry Dirin², Maksym Kovalenko^{2,3}, K. V. Adarsh¹ (1.IISER Bhopal, 2.ETH Zurich, 3.Empa Dubendorf)

Integrated Lithium Niobate Photonics for Quantum Technology

Cheng-Chung Chiu¹, Po-Hsiang Huang¹, Sheng-Hung Wang², Po-Han Chen², Chien-Ming Wu³, Pin-Ju Tsai^{1,4}, Ray-Kuang Lee³, and Yen-Hung Chen^{1,4,5*}

¹Department of Optics and Photonics, National Central University, Zhongli 320, Taiwan

²Department of Physics, National Central University, Zhongli 320, Taiwan

³Institute of Photonics Technologies, National Tsinghua University, Hsinchu 300, Taiwan

⁴Quantum Technology Center, National Central University, Zhongli 320, Taiwan

⁵Center for Astronautical Physics and Engineering, National Central University, Zhongli 320, Taiwan

*yhchen@dop.ncu.edu.tw

Abstract

Quantum photonics has advanced rapidly and become a leading approach for developing a broad range of quantum technologies, including quantum communications, quantum information processing, quantum computing, and quantum sensing. Besides, the emerging photonic integrated circuits (PIC) technology has been widely used to implement versatile optical elements advantageous for different quantum applications. For example, PIC-based devices have functioned as building blocks, such as photonic qubit sources, linear optical circuits, modulators, and even single-photon detectors, for realizing highly integrated, large-scale quantum computing schemes. In such a powerful quantum photonic integrated circuits (QPIC) scheme, the creation, manipulation, and testing of quantum entanglement states from the generated qubits via a reconfigurable photonic circuitry are essential.

Though the state-of-the-art PIC technology is established based on Si photonics due to its widely mature nanophotonic circuit (waveguide) fabrication technology supported by the existing immense semiconductor industry, Si-based PIC has limitations in implementing efficient and fast active elements that usually demand a quadratic nonlinearity. Lithium niobate (LN), renowned as “the silicon of photonics”, has long been a popular material widely used in integrated-optical and nonlinear-optical applications. A great variety of passive and active photonic elements have been realized in the LN platform. Recently, a novel material based on high-quality single-crystalline films of LN, known as thin-film LN on insulator (LNOI), has been developed and has soon drawn enormous attention for its greatly promising ability to realize nanoscale PIC/QPIC in this iconic optical material platform.

In this presentation, we report our recent studies on several key LN PIC building blocks for developing novel quantum photonic sources and circuits, including highly integrated photonic-circuit periodically poled lithium niobate (PPLN) chips for photon-pair generation and manipulation, for high-dimensional frequency-entangled qudit production, for time-frequency grid-state generation, for continuous-variable squeezed vacuum state generation, and their potential applications to quantum computing/communication/sensing technology. Besides, a PP-LNOI electro-optic (EO) polarization mode converter (PMC) useful for demonstrating fast control of quantum polarization states and other LNOI circuit elements as QPIC building blocks will also be presented.

Performance Evaluation of Optical Quantum Communication Systems in Challenging Conditions

Venkateswara Rao Chilukuri^{1,2}, Prakash Pareek², Jitendra K. Mishra¹

¹Department of ECE, Indian Institute of Information Technology Ranchi, Jharkhand, 835217, INDIA

²Department of ECE, Vishnu Institute of Technology, Bhimavaram, Andhra Pradesh, 534202, INDIA

Email : chilukuri.2023dr206@iiitranchi.ac.in

1. Introduction

In the digital era, secure communication has been extremely essential along with the high speed and large data rates. The conventional systems (optical wireless) for high-speed data transfer are affected by numerous environmental factors (fog, rain, dust). In addition, the security aspects are major limitation for future generation systems. Therefore, it is high time to explore the innovative techniques (quantum) in order to improve the performance and ensure enhanced data security of conventional systems.

2. System Model

The basic structure of optical quantum communication system has been represented in Fig.1.

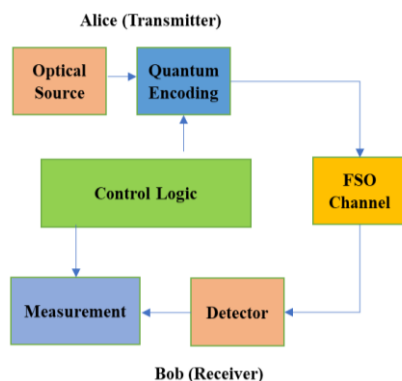


Fig.1: Basic optical quantum communication system

The photons are encoded by the quantum states and these states can be expressed as a linear combination of its basis states $|0\rangle$ and $|1\rangle$ and are represented using Eq. (1), where $|\psi\rangle$ is the quantum State α and β are the complex probability amplitudes. When transmitted via channel, the properties of these quantum states are collapsed due to channel losses.

$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle \quad (1)$$

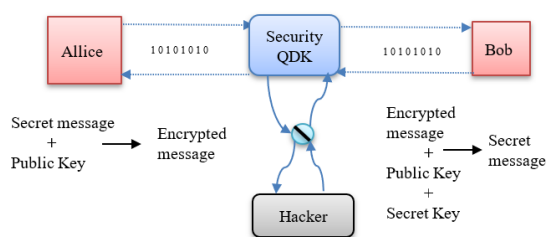


Fig.2: Representation of QKD between Alice and Bob [2]

After obtaining the quantum states, the quantum key distribution (QKD) allows two parties to generate a shared secret

key for secure communication (see Fig.2).

3. Performance Measures and Assumptions

The critical parameter for estimating the performance of optical quantum communication systems [3] employing QKD is quantum bit error rate (QBER) which is represented using Eq. (2). The assumptions for assessing the performance are summarized in Table1.

$$QBER = QBER_{En} + \left(\frac{P_{loss}}{P_{ini}} \right) \times 10\% \quad (2)$$

Table I Performance parameters

QBER _{En} (%)		Distance (km)	Attenuation dB/km	P _{ini} (dB)
Fog	Clear			
15	5	10-100	0.1 to 0.5	1-5

4. Discussions

The QBER for various environments with respect to distance are evaluated and is shown in Fig.3. As the distance increases, the QBER increases irrespective of the environment conditions.

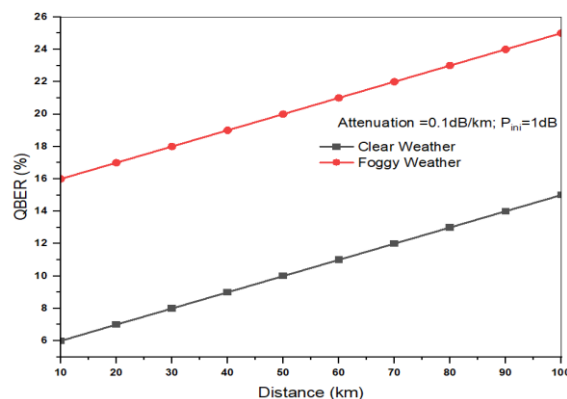


Fig.3: Performance analysis of QBER for different weather conditions

4. Conclusion

The QBER for an ideal condition range from 0.1% to 1%, under typical conditions it falls between 1% and 5%, and in challenging conditions, it varies between 5% and 10%. From Fig. 3, the QBER in foggy weather at a distance of 50 km ranges between 18% and 20%, while in clear weather it ranges between 8% and 10%. This can be reduced by the practical implementation of QKD and the use of various error-correcting codes.

References

- [1] R. Yuan, J. Cheng, *IEEE GC Wkshps.* (2018) 1.
- [2] Hasan S.R, Chowdhury M.Z, Saiani M, Jang Y.M, *IEEE Access.* **11** (2023) 15855.
- [3] Gisin N, Thew R, *Nature Photonics.* **1** (2007) 165.

Coincidence of Two EP2s in The Parameter Space of a Gain-Loss Assisted Dual-Core Photonic Crystal Fiber

Shamba Ghosh¹, Arpan Roy², Bishnu P. Pal³ and Somnath Ghosh^{3*}

¹ Department of Physics, Indian Institute of Technology Jodhpur, Rajasthan 342030, India

² Institute of Radio Physics and Electronics, University of Calcutta, Kolkata-700009, India

³ Department of Physics, École Centrale School of Engineering, Mahindra University, Hyderabad, Telangana, 500043, India

*Corresponding author: somiit@rediffmail.com

1. Introduction

Exceptional points (EPs) are the non-Hermitian degeneracies where both the eigenvalues and eigenvectors of the system's Hamiltonian coalesce [1]. Recently, Open photonic systems that house EPs have garnered increasing attention due to their potential for a variety of uses, such as asymmetric mode switching [2], optical isolators [3], and most importantly, ultra-sensitive sensors [4]. While EPs have been demonstrated in various integrated photonic platforms, their implementation in guided fiber geometries remains limited, particularly in systems supporting multiple coexisting EPs. Here, we present a gain-loss-assisted photonic crystal fiber (PCF) that simultaneously hosts multiple second-order EPs (EP2s) among different guided mode pairs, and interestingly, we have found that two EP2s coincide at the same point in the parameter space. This observation is an

$i\gamma$ and, $n_R = n_c + i\tau\gamma$ represents the same for the right core (cf. Fig. 1(a)).

These modes exhibit varying spatial profiles and confinement characteristics due to core-to-core power coupling in the photonic crystal structure. When γ is varied within the range $[0, 0.002]$ for a fixed $\tau (= 1)$, the system experiences a strong coupling. Within this range, three well-defined EP2s emerge between the specific mode pairs $\{\psi_0, \psi_1\}$, $\{\psi_3, \psi_4\}$, and $\{\psi_2, \psi_5\}$, which are confirmed by the coalescence of real and splitting of imaginary parts of the complex effective indices, as shown in Fig. 1(c), (d), and (e), respectively. Remarkably, it is observed that two independent EP2s between $\{\psi_0, \psi_1\}$ and $\{\psi_3, \psi_4\}$ coexist at the exact same point in the (γ, τ) parameter space, at $(0.0029, 1)$. This rare overlapping of EPs in

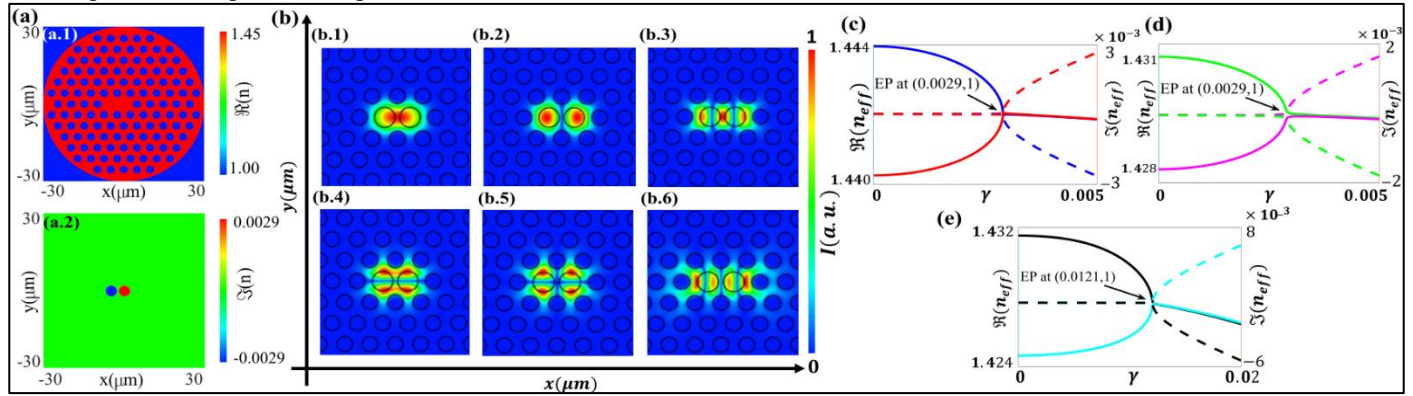


Fig 1. (a) The complex refractive index (n) profile of the modified PCF cross-section, where (a.1) represents the real part of n and (a.2) represents the imaginary part of the same for a specific set of parameters ($\gamma = 0.0029, \tau = 1$). (b) Normalized intensity profile of the supported guided modes ψ_0 to ψ_5 is shown in (b.1) to (b.6) respectively. (c), (d), and (e) respectively show variations of the real and imaginary parts of the complex n_{eff} of the guided modes with the loss parameters γ revealing coalescence of the real parts (solid line) and bifurcation of the imaginary parts (dotted line), simultaneously at an EP. Two EP2s between $\{\psi_0$ (blue), ψ_1 (red) $\}$ and $\{\psi_3$ (green), ψ_4 (magenta) $\}$ occur at $\gamma = 0.0029$ and another EP2 between $\{\psi_2$ (black), ψ_5 (cyan) $\}$ occur at $\gamma = 0.0121$.

attractive avenue for ultra-sensitive EP-based sensing and lays the foundation for developing next-generation photonic devices.

2. Results and discussions

The proposed PCF is designed with a hexagonal lattice of air holes embedded in a silica matrix, featuring two closely placed core defects that act as guiding regions. These adjacent cores allow enhanced modal interaction and support a higher number of guided modes. The refractive index of the cladding is fixed at $n_c = 1.45$. The pitch and the air hole radius are optimized and using finite element method (FEM), six guided modes denoted by $\psi_0, \psi_1, \psi_2, \psi_3, \psi_4$, and ψ_5 are identified. Fig. 1(b) illustrates the normalized intensity profile of each mode, where modes $\psi_0, \psi_1, \psi_2, \psi_3, \psi_4$, and ψ_5 are respectively shown in (b.1), (b.2), (b.3), (b.4), (b.5), and (b.6). The non-Hermiticity is introduced by applying optical gain to one core and an equivalent loss to the other, controlled via two parameters: the gain coefficient, γ and the loss-to-gain ratio, τ . The complex refractive index profile of the left core is expressed as, $n_L = n_c -$

a single parameter location, to the best of our knowledge, has not been reported before and opens up new avenues for studying multi-EP interactions in non-Hermitian systems.

3. Summary

In summary, we present a gain-loss-assisted dual-core PCF that hosts three independent EP2s between distinct pairs of modes. This unique phenomenon of hosting multiple EP2s in the system's parameter space and the coexistence of two independent EP2s at the same location not only enriches our understanding of non-Hermitian systems but also holds immense promise in engineering applications such as sensing, mode conversion, etc.

Funding: Shamba Ghosh acknowledges financial support from the Ministry of Education, Government of India.

4. References

- [1] W. D. Heiss, *Phys. Rev. E* **61**, 929 (2000).
- [2] A. Roy *et al.*, *Phys. Scr.* **99**, 055505 (2024).
- [3] A. Laha *et al.*, *ACS Photonics* **7**, 967 (2020).
- [4] J. Wiersig, *Phys. Rev. A* **93**, 033809 (2016).

Numerical Study on the Advantages of Different OPO Cavity Schemes in BBO

John Gregg^{1,2}, Jonathan Evans¹

¹Department of Engineering Physics, Air Force Institute of Technology, 2950 Hobson Way, Wright-Patterson AFB, Ohio 45433, USA

²Leidos, 3745 Pentagon Blvd, Dayton, OH 45431, USA
E-mail: John.Gregg@leidos.com

1. Introduction

Optical parametric oscillators (OPOs) are critical devices for tunable sources. While the decision to use a linear, ring, or nonplanar cavity is often driven by size requirements, here evaluation is isolated to energy conversion efficiency (ECE) and phase front at the output. Numerical simulation of BBO linear, ring, and Rotated Image Singly-Resonant Twisted RectAngle (RISTRA) cavities followed by evaluation of the wavefront error (WFE) at the exit port offers a different perspective on cavity selection.

2. Simulation Description

Cavity Description

The simulation geometry was built around the RISTRA system previously sold by AS-Photonics by using their manual with specific dimensions [1]. It was adapted for a type II phase matched $E \leftrightarrow O + E$ for $532 \text{ nm} \leftrightarrow 800 \text{ nm} + 1588 \text{ nm}$ mix in BBO. The geometry was modified to accommodate a linear or ring cavity while maintaining a constant total cavity length. All systems were single-pass pump and idler. The ring cavity was set up to force an up-down flip of the resonant signal which was perpendicular to the direction of walk off in the pump on each round trip. The nonplanar cavity was a RISTRA device imparting a 90-degree rotation on each round trip for the resonant signal. All systems used a walk-off compensated design with a total crystal length of 28 mm and a cavity length of 10.9 cm. Surface reflections on the crystals were 0.5%, and all mirrors were considered ideal except the input and output couplers. The in-coupler was 99% reflective for the signal and 1% reflective for the pump and idler. The pump was a 500 mJ Gaussian pulse with 30 ns FWHM and 3 mm $1/e^2$ radius. The seed was 1 mW, matching the pump's beam radius. The output coupler reflectance was 50% for the signal in all designs, and fully transmissive for both the pump and idler.

Simulation Results

The Zernike error at the exit port of the laser and the output pulse envelope for each cavity is shown in Figure I. The energy conversion efficiency was 34% for the linear cavity, 44% for the ring, and 45% for the RISTRA. The distinctly lower energy conversion in the linear cavity is due to reflections and additional absorption in the crystal during the return trip.

Discussion

Initial results suggest that despite the forced one-fold symmetry, the ring has a similarly chaotic Zernike profile as

the linear cavity. The RISTRA Zernike profile was limited to terms with two-fold symmetry but with amplitudes two to three times higher than in linear or ring cavities.

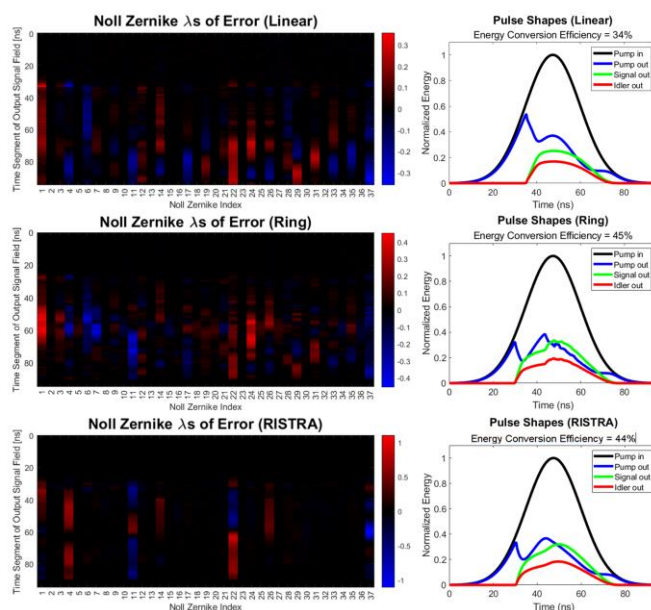


Figure I Signal Output: the left column shows Zernike aberrations by Noll index for each time slice. The right column shows the envelope of the output and the total ECE of the system.

3. Conclusions

For the same cavity length, the RISTRA device shows a smaller net WFE due to fewer aberrations that contribute significantly. This expands on previous work where these cavities were noted to suppress astigmatism [2]. More notably these simulations suggest that the RISTRA devices may have a resonant enhancement of two-fold symmetric aberrations when compared to linear and ring cavities.

Acknowledgements

We thank Robert Stegeman for all matter of χ^2 discussion.

References

- [1] AS-Photonics, User's manual and tutorial for the image rotating RISTRA OPO, https://as-photonics.com/RISTRA_files/as-photonics_ristra_doc.pdf (Accessed: 17 June 2025)
- [2] G. Stoeppler, N. Thilmann, V. Pasiskevicius, A. Zukauskas, C. Canalias, and M. Eichhorn, Opt. Express **20** (2012) 4509.

High-power lasers and ultra-broadband optical parametric amplification technologies

Osaka Univ., ILE¹, Inst. for Laser Technology², ○Jumpei Ogino¹, Koji Tsubakimoto¹,

Hidetsugu Yoshida¹, Yuki Tamaru¹, Noriaki Miyanaga^{1, 2}, Akifumi Yogo¹

E-mail: ogino.jumpei.ile@osaka-u.ac.jp

High-intensity, ultrashort-pulse lasers are foundational technologies for generating high-charge electron beams via Laser Wakefield Acceleration (LWFA) and realizing high-repetition-rate laser-driven neutron sources. Such neutron sources, emitting 10^{10} – 10^{11} neutrons in nanoseconds from compact ~ 1 cm targets, have enabled emerging time-resolved analysis techniques. Since neutron yield scales with the fourth power of laser intensity, increasing peak intensity via pulse shortening is critical [1]. However, amplifying ultrabroadband pulses is challenging with conventional Chirped Pulse Amplification (CPA) due to compression and scalability limitations.

In this study, we propose a novel amplification scheme termed Ultra-wideband FDOPA (Frequency Domain Optical Parametric Amplification) to efficiently amplify spectra spanning several hundred nanometers. FDOPA uses a 4-f optical system to spatially and temporally separate spectral components for independent amplification, mitigating gain narrowing and phase mismatch [2]. It enables broad gain bandwidth and integrates stretching, amplification, and compression in a compact system. Furthermore, by introducing a wide-angle pump geometry into the Fourier plane, our method ensures phase matching across all wavelengths. This builds on the Wide-angle Non-collinear Optical Parametric Amplification (WNOPA) principle, maintaining output stability ($\sim 10\times$ improvement over conventional NOPA) [3]. Unlike earlier FDOPA systems requiring multiple crystals, our method amplifies a continuous

spectrum on a single crystal, improving scalability and alignment. The system is pumped by our cryogenic Yb:YAG active mirror laser “SENJU,” delivering 10 J, 100 Hz (1 kW average power) [4]. The output is frequency-doubled to 515 nm and temporally compressed to sub-ns by Stimulated Brillouin Scattering (SBS)(Fig.1). Our goal is to realize high-energy, high-repetition, ultra-broadband laser amplification for enhanced laser-driven neutron generation. This technology will also support compact, high-charge LWFA and high-temporal-resolution neutron imaging, marking a critical advancement in high-power laser applications.

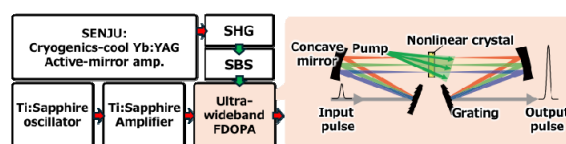


Fig.1 Schematic of Ultra-wideband FDOPA system

Acknowledgment

This work was supported by JSPS KAKENHI Grant Number 25H00860.

Reference

- [1] Y. Arikawa et al., Phys. Rev. Res. **5**, 013062 (2023).
- [2] B. E. Schmidt et al., Nat. Commun. **5**:3643 (2014).
- [3] Z. Li et al., Opt. Express **26**, 28848 (2018).
- [4] J. Ogino et al., Opt. Continuum **1**, 1270 (2022).

Exact Localized Solutions in Modified Lugiato-Lefever Equation for Frequency Comb Applications

Sanjana Bhatia¹, Kanishk Poria¹, and C. N. Kumar¹

¹*Department of Physics, Panjab University, Chandigarh-160014, India*

E-mail: sanjana.bhatia577@gmail.com

1. Introduction

In this work, we investigate solitary wave solutions of the ac-driven nonlinear Schrödinger equation, commonly referred to as the Lugiato-Lefever Equation, in the presence of localized gain and loss. By modifying the governing equation to include distributed loss, we obtain exact analytical solutions describing both localized structures and wave-train patterns, for scenarios with and without chirping. These results strengthen the theoretical understanding of dissipative solitons and highlight their relevance for practical applications in high-capacity telecommunications and optical frequency combs. Our study supports the refined control and design of nonlinear optical systems, contributing to advancements in Kerr-frequency comb dynamics.

2. Methodology

To capture the diversity of nonlinear effects enclosed in Kerr-comb dynamics, Renninger and Rakich have developed a single closed-form analytical solution of the driven NLSE that reproduces a large class of patterns in Kerr-comb systems, including solitons and periodic wavetrains [1, 2] using damped-driven NLSE in linear loss settings given by:

$$i \frac{\partial E}{\partial z} = -i \frac{\alpha}{2} E + \delta E - \frac{\beta}{2} \frac{\partial^2 E}{\partial t^2} - \sigma |E|^2 E + i \mu e^{i\phi}, \quad (1)$$

where $E(z, t)$ is the electric field inside the cavity, α is the linear cavity loss, δ represents the pump detuning, β is the dispersion, σ signifies the Kerr-nonlinearity, μ is the external drive strength, and $\phi(z, t)$ is the phase of the drive. As pointed out in [1], this equation does not have any known exact solutions when the loss term is linear. Inspired by the stable dissipative solitons observed in the models with nonlinear and localized gain-loss terms, we propose a modified version of the master equation to model the dynamics of Kerr-frequency combs in a microring with $\alpha \rightarrow \alpha_{NL}(t)$, where the latter is now distributive or nonlinear function of t , while all other parameters retain the same physical meanings as in Eq. (1).

3. Conclusions

We find exact bright, dark, and periodic solitons, as shown in the Figure 1, with various loss functions.

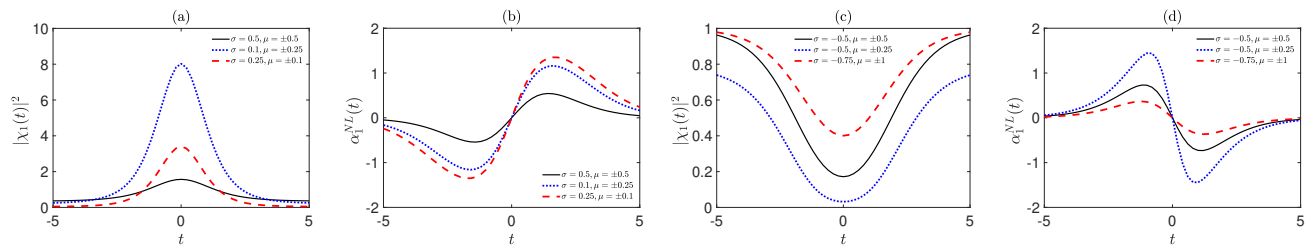


Figure 1: (a) Intensity and (b) Loss profiles for Möbius transform Bright Solitons (BS), (c) Intensity and (d) Loss profiles for Möbius transform Dark Solitons (DS). Other parameters are dispersion $\beta = 1$ and chirp parameter $a = 1$.

- [1] W.H. Renninger, P.T. Rakich, "Closed-form solutions and scaling laws for Kerr frequency combs", Sci. Rep. **6** 24742 (2016).
- [2] S. Bhatia, A. Goyal, T.S. Raju, C.N. Kumar, "Solitary wave solutions of ac-driven nonlinear Schrödinger equation supported by localized gain-loss", Phys. Lett. A **536** 130288 (2025).

Coherence Synthesis in Nonlinear Optics

Zihao Pang¹ and Ady Arie¹

¹ School of Electrical Engineering, Iby and Aladar Fleischman Faculty of Engineering, Tel Aviv University, Tel Aviv, Israel
E-mail: its.zihaopang@gmail.com

1. Introduction

Nonlinear frequency conversion has traditionally relied on highly coherent light sources. This assumption has deeply shaped the field, yet it overlooks the broader role that spatial incoherence can play in nonlinear optics. In this work, we break that paradigm by demonstrating, for the first time, that second harmonic generation (SHG) can be performed with spatially incoherent light, and more importantly, that the spatial coherence of the generated second harmonic field can be customized with precision. Our work unlocks spatial coherence as an active and designable parameter in nonlinear optics.

2. Results

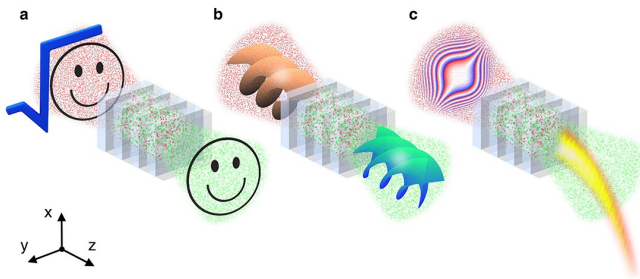


Fig. 1 Nonlinear synthesis of spatial coherence. a. Infra-red-to-visible incoherent imaging of a smiley face. b. The second harmonic incoherent vortex beams carrying $4h$ orbital angular momentum (OAM) are nonlinearly generated from the fundamental frequency ones carrying $2h$ OAM. c. Nonlinear synthesis of incoherent Airy beams that preserve self-acceleration in the second harmonic.

We demonstrate this concept through three representative cases of coherence synthesis (Fig. 1). First, we synthesize second harmonic coherence patterns that replicate object-induced coherence from the fundamental light, enabling incoherent imaging of arbitrary shapes across infra-red-to-visible wavelengths (Fig. 1a). We further demonstrate the nonlinear shaping of incoherent structured beams, including the generation of second harmonic incoherent vortex beams carrying $4h$ orbital angular momentum (OAM) from fundamental one with $2h$ OAM (Fig. 1b), and the generation of self-accelerating incoherent Airy beams that preserve their trajectory in the second harmonic regime (Fig. 1c).

Our approach (Fig. 2a) involves retrieving the speckle

statistics of the fundamental frequency, applying a complex square-root filter to counteract the nonlinear interaction, and modulating each speckle frame on a spatial light modulator before its propagation through a periodically poled nonlinear crystal. The modulated field then undergoes SHG in a PPKTP crystal, and the second harmonic coherence is reconstructed through the superposition of multiple speckle realizations.

Experimentally, we synthesize 800 frames of second harmonic speckle patterns. Although each frame is random, their statistical average (Figs. 2b-2e) reveals the reappearance of the smiley face in the second harmonic. These results confirm that the coherence pattern induced by the object at the fundamental frequency has been faithfully reconstructed in nonlinear frequency conversion, providing strong experimental validation of our coherence synthesis approach.

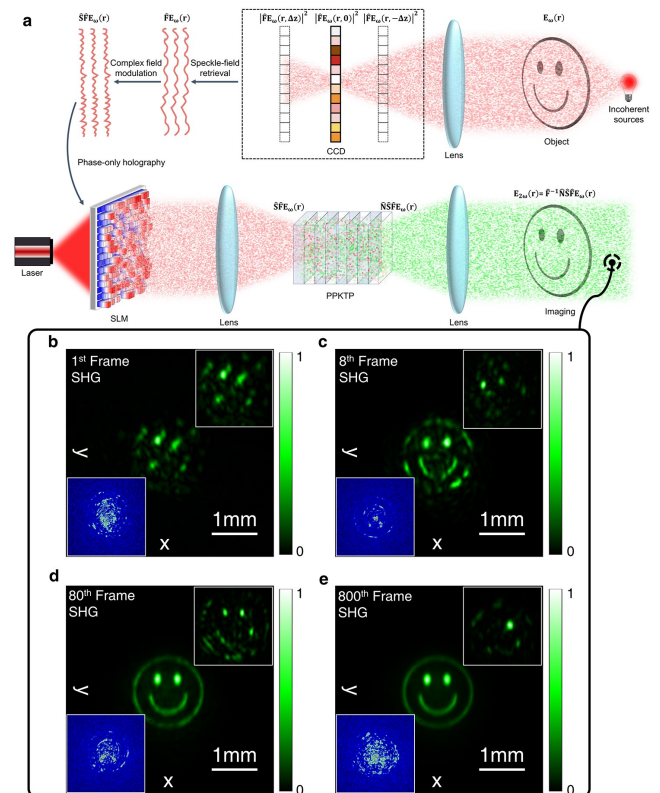


Fig. 2 Coherence synthesis setup and experimental demonstration. a. A schematic shows the optical system for modulating retrieved fundamental speckles and generating second harmonic light in a nonlinear crystal. b. The smiley face is synthesized by the frame accumulation of second harmonic speckles.

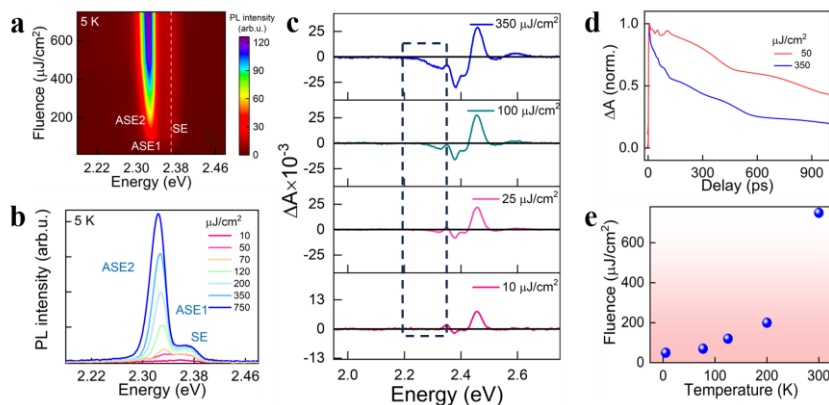
Collective Emission Through Electron-Hole Plasma

Naresh Aggarwal¹, Dmitry N. Dirin², Maksym V. Kovalenko^{2,3}, K. V. Adarsh^{1*}

E-mail: naresh19@iiserb.ac.in, adarsh@iiserb.ac.in



Electron-hole plasma (EHP), a high-density correlated state, plays a pivotal role in influencing the optical properties of semiconductors, which has recently observed in various materials such as group II-VI semiconductors, transition metal dichalcogenides (TMDCs) and halide perovskites. This macroscopic population of charge carriers presents potential applications for high-temperature optoelectronic and photonic devices. However, the collective emission phenomena such as amplified spontaneous emission (ASE) and superfluorescence (SF) induced by the EHP state in perovskites nanocrystals not investigated thoroughly, without using any external stimuli such as external magnetic field or complex micro/nano structures. In this study, we presented that this EHP state can produce broadband and sizable optical gain in metal halide perovskites nanocrystals. By using the temperature and fluence dependent femtoseconds photoluminescence and transient absorption (TA) measurements, we identify two distinct ASE bands at 5 K with the threshold fluences of 25 and 100 $\mu\text{J}/\text{cm}^2$ attributed to excitonic and EHP state, represented by ASE1 and ASE2 in **Fig. 1a** and **1b**. Our TA study presents that the EHP state produces a remarkable optical gain of ~ 150 meV, See **Fig. 1c**, with fast radiative rate, **Fig. 1d**. This EHP-induced ASE behaviour persisted up to 125 K. At 300 K, this dual-band ASE behaviour vanished due to the large contribution of thermal fluctuations and non-radiative recombination. Furthermore, the gain threshold for excitonic ASE enhanced by more than one order by increasing the sample temperature to 300 K, See **Fig. 1e**. Our study further explain that the carrier localization prevents long-range phase coherence which is a prerequisite for observation of SF. Our work provides a comprehensive and detailed study of the application of many-body correlated states in optoelectronic devices and many other macroscopic quantum phenomena.



4 JSAP-Optica Joint Symposia 2025 | 一般セッション(ポスター講演): 4.7 Quantum Optics, Nonlinear Optics and Structured Optics

[8p-P08-1~3] 4.7 Quantum Optics, Nonlinear Optics and Structured Optics

[8p-P08-1]

High Fidelity Greenberger–Horne–Zeilinger and W State Generation using Resonator-Qubit-Resonator Tripartite System.

○Abhishek Mandal¹, Joy Ghosh², Maruthi Manoj Brundavanam¹, Shailendra Kumar Varshney^{2,3}
(1.Department of Physics, Indian Institute of Technology Kharagpur, 2.School of Nanoscience and Technology, Indian Institute of Technology Kharagpur, 3.Department of ECE, Indian Institute of Technology Kharagpur)

[8p-P08-2]

A Lightweight Deep Learning Pipeline for Label-Free Classification of Prostate Tissue via Two-Photon Imaging

○(DC)Gagan Raju¹, Kausalya Neelavara Makkithaya¹, Jackson Rodrigues², Nirmal Mazumder¹, Guan-Yu Zhuo² (1.Department of Biophysics, Manipal School of Life Sciences, Manipal Academy of Higher Education, Manipal, Karnataka 576104, India, 2.Institute of Biophotonics, National Yang Ming Chiao Tung University, Taipei 11221, Taiwan)

[8p-P08-3]

Quantitative texture analysis and machine learning aided classification of two photon microscopy images of Oesophageal cancer

○(D)Kausalya Neelavara Makkithaya¹, Guan-Yu Zhuo², Nirmal Mazumder¹ (1.Manipal Univ., 2.NYMC Univ.)

High Fidelity Greenberger–Horne–Zeilinger and W State Generation using Resonator-Qubit-Resonator Tripartite System

Abhishek Mandal^{1,*}, Joy Ghosh², Maruthi Manoj Brundavanam¹ and Shailendra Kumar Varshney^{2,3}

¹Department of Physics, Indian Institute of Technology Kharagpur, Kharagpur, 721302, West Bengal, India.

²School of Nanoscience and Technology, Indian Institute of Technology Kharagpur, Kharagpur, 721302, West Bengal, India.

³Department of ECE, Indian Institute of Technology Kharagpur, Kharagpur, 721302, West Bengal, India.

* mandalabhi350@gmail.com

Abstract The generation of multipartite entangled states is fundamental tool for a wide range of quantum information processing tasks, including teleportation, superdense coding, and quantum key distributions. This work demonstrates a scheme for high-fidelity Greenberger–Horne–Zeilinger (GHZ) and W states in a weakly coupled resonator- qubit-resonator system by exploiting quantum destructive interference and strategically suppresses higher-order transition pathways in the joint photonic Fock space to enable controlled and efficient tripartite entanglement.

Model and Discussion

Consider a hybrid quantum system consisting of two micro resonators vibrating at frequency $\omega_{1,2}$ is evanescently coupled by a photon tunneling rate J . A two-level atom is directly interacting with the first resonators via Jaynes-Cummings coupling g . This configuration introduces a nonlinear energy distribution in the joint Fock space of the qubit-resonator system that can be characterized by tuning coupling coefficients, while both resonators are coherently driven by a weak pump field amplitudes Ω_1 and Ω_2 . The complete Hamiltonian for this setup can be written in the rotating-wave approximation as (taking $\hbar=1$),

$$\mathcal{H}' = \Delta_1 a_1^\dagger a_1 + \Delta_2 a_2^\dagger a_2 + \Delta_a \sigma_z + J(e^{i\phi} a_1^\dagger a_2 + e^{-i\phi} a_2^\dagger a_1) + g(a_1^\dagger \sigma_- + a_1 \sigma_+) + \Omega_1(a_1^\dagger + a_1) + \Omega_2(a_2^\dagger + a_2) \quad (1)$$

Where Δ_1, Δ_2 are the detunings of the resonators and ϕ is an arbitrary phase difference of the propagating fields respectively. Also, Δ_a is the detuning frequency of the two-level atom. Initially we consider the atom is in the superposition state $1/\sqrt{2}(|0\rangle + |1\rangle)$ while both resonators are in the vacuum state $|0\rangle$. We use conditional photon exchange interactions by Jaynes–Cummings interaction to entangle the atom with first resonator directly. Through controlled time evolution, the excitation is coherently transferred to the second resonator such that when the atom is excited, both resonators are also excited simultaneously. After symmetric photon exchange by controlling each distinct photon excitation paths with corresponding probabilities computed from the Schrödinger equation and interaction blocking (via quantum interference), the final state collapses to a GHZ-like entangled state [1] i.e. $|\psi\rangle = 1/\sqrt{2}(|000\rangle + |111\rangle)$ involving the atom and both resonators. Similarly, $|\psi\rangle = 1/\sqrt{3}(|001\rangle + |010\rangle + |100\rangle)$ represents the W state involving a single excitation symmetrically delocalized over the three subsystems. Here we begin with one excitation localized in the atom or one of the resonators. By applying symmetric, weak coupling between the atom and both resonators to allow the single excitation to coherently distribute among all three subsystems. With fine-tune the coupling strengths and interaction times such that

destructive interference blocks multi-excitation pathways, while constructive interference amplifies the single-excitation symmetric state. The system evolves into a coherent superposition where exactly one of the three subsystems holds the excitation, forming a robust W state. Now, we compute the fidelity of both states by solving the Lindblad master equation with resonator and atomic dissipation parameters κ and γ in the open-source python framework Qutip [2].

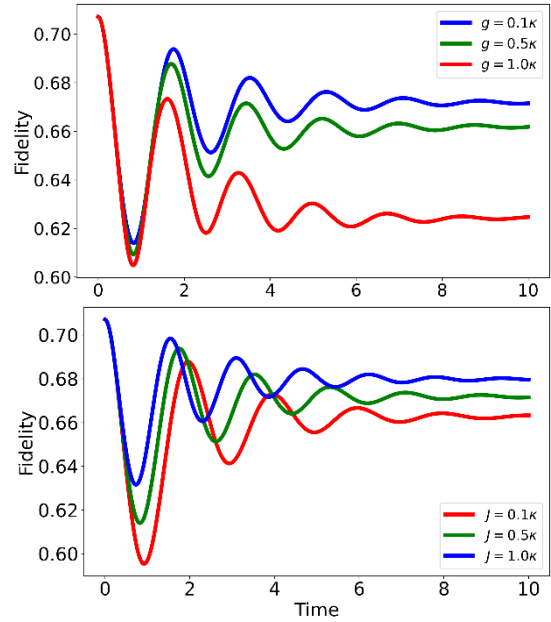


Fig. Fidelity dynamics for GHZ state numerically computed with resonant condition $\Delta_1 = \Delta_2 = 2\kappa$ vs g/κ and J/κ . The other parameters are taken as $\gamma = \kappa/10$, $\Omega_{1,2} = 0.6\kappa$ and $\phi = \pi/2$.

References

- [1] Pont, Mathias, et al. "High-fidelity four-photon GHZ states on chip." *npj Quantum Information* 10.1 (2024): 50.
- [2] Johansson, et al. "QuTiP: An open-source Python framework for the dynamics of open quantum systems." *Computer physics communications* 183.8 (2012): 1760-1772.

A Lightweight Deep Learning Pipeline for Label-Free Classification of Prostate Tissue via Two-Photon Imaging

Gagan Raju^{1,†}, Kausalya Neelavara Makkithaya^{1,†}, Jackson Rodrigues^{2,†}, Nirmal Mazumder^{1,*}, and Guan-Yu Zhuo^{2,*}

¹ Department of Biophysics, Manipal School of Life Sciences, Manipal Academy of Higher Education, Manipal, Karnataka 576104, India

² Institute of Biophotonics, National Yang Ming Chiao Tung University, Taipei 11221, Taiwan

[†] Contributed equally to this work
Phone: +886-2-23267962; FAX: +886-2-28235460
Email: zhuo0929@nycu.edu.tw

Introduction: Prostate cancer ranks among the most frequently diagnosed malignancies in men worldwide, with current diagnostic processes being time-consuming and invasive. Two-photon microscopy, capable of label-free, subcellular-resolution imaging, is well-suited for capturing the architectural and molecular features of the tumor microenvironment [1] from tumor microarray (TMA) samples. In this study, MobileNetV3, a compact and efficient network, was used for automated feature extraction and subsequently performed classification using support vector machine (SVM).

Materials and methods: Two photon images were captured using a custom-built laser scanning microscope. The two-photon fluorescence (TPF) images obtained were preprocessed and input to MobileNetV3 Small for automated feature extraction. The spatial and textural characteristics of the tissue samples served as input for subsequent classification using support vector machines (SVM). The dataset was divided into 80:20 ratio for training and testing sets. The performance of the trained SVM model was assessed using accuracy, precision, sensitivity (recall), and F1-score.

Results: The two photon images from prostate tissue microarrays belonging to tumor, normal, and control tissues were classified. The performance evaluation of the model is shown in Fig. 1. The confusion matrix Fig. 1(a) revealed high sensitivity for tumor (97%) and control (100%) groups, with slightly lower sensitivity (80%) for the normal class. Precision values were 95%, 85%, and 100% for normal, tumor, and control classes, respectively, while corresponding F1-scores were 0.87, 0.9, and 1.0. These results indicate that the model effectively classified control and tumor tissues, with slightly reduced performance in distinguishing normal tissues. This could be due to subtle histological features overlapping with early tumor features. Additionally, the ROC curves in Fig. 1(b) showed excellent class-wise AUC values of 0.96 for both

normal and tumor classes, and 1.0 for control, with overall classification accuracy of 91%.

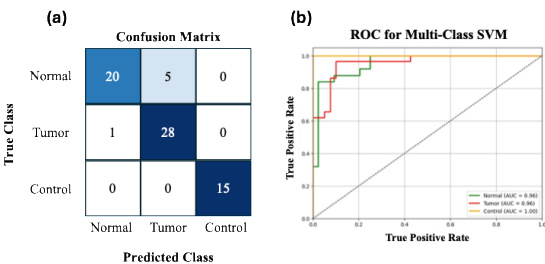


Fig. 1. Performance evaluation of the trained multi-class SVM model depicted in (a) confusion matrix, and (b) receiver operator curve (ROC).

Conclusion: The two photon images obtained from prostate TMA belonging to normal, tumor, and control classes. The TPF images were subjected to preprocessing and feature extraction using MobileNetV3Small. The obtained features were used to classify using SVM. The high discriminative potential of the model demonstrated that, this integrated approach can be a reliable tool for prostate cancer screening and diagnosis, with promising implications for clinical pathology and future AI-assisted diagnostic systems.

Acknowledgment: GYZ acknowledges the financial support from the National Science and Technology Council, Taiwan (Project number: 110-2112-M-039-001-MY3, 113-2628-M-A49-010-MY3). Authors thank Institute of Biophotonics, National Yang-Ming Chiao Tung University, Taipei, Taiwan and Manipal School of Life Sciences, MAHE, India, for infrastructure and facilities. Authors would like to thank Ms. Macline Crecsilla Lewis for her assistance in deep learning.

Reference:
1. Chakraborty, I., Mazumder, N., Gogoi, A., Chen, M. C., & Zhuo, G. Y. (2024). Recent advances in label-free imaging techniques based on nonlinear optical microscopy to reveal the heterogeneity of the tumor microenvironment. *Biophysical Reviews*, 16(5), 581-590.

Quantitative texture analysis and machine learning aided classification of two photon microscopy images of Oesophageal cancer

Kausalya Neelavara Makkithaya¹, Guan-Yu Zhuo², Nirmal Mazumder^{1*}

¹Department of Biophysics, Manipal School of Life Sciences, Manipal Academy of Higher Education, Manipal, Karnataka, India -576104

²Institute of Photonics, National Yang Ming Chiao Tung University, Taipei, 11221, Taiwan

*Corresponding Author: nirmaluva@gmail.com

Background/Introduction: Diagnosing oesophageal cancers like SCC and precancerous HGD is challenging due to their similar tissue structures, often delaying detection until advanced stages—especially in high-risk regions like Asia. Current methods struggle to spot subtle collagen changes in the extracellular matrix, relying too much on subjective analysis of cell appearance. Combining advanced imaging (two-photon microscopy) with AI algorithms offers a promising solution, objectively tracking collagen patterns to improve early diagnosis and monitor disease progression.

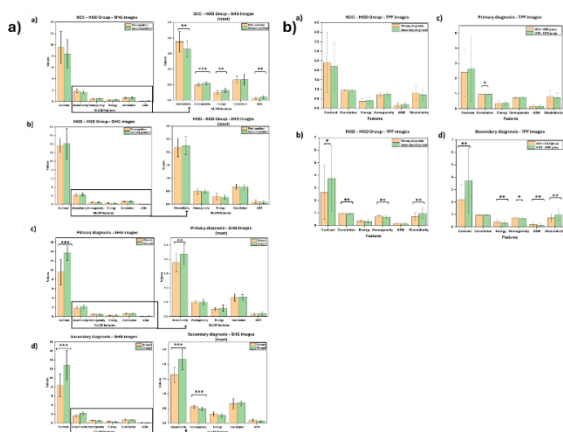


Figure 1: Texture analysis of (a) SHG images (b) TPF images

Methodology: The study analysed oesophageal tissue samples from a cohort of patients with head and neck squamous cell carcinoma (SCC), focusing on those who developed metachronous HGD or SCC. Two-photon microscopy was employed to obtain high-resolution images, capturing SHG signals (collagen fibres) and TPF signals (other tissue structures). For quantitative analysis, the gray-level co-occurrence matrix (GLCM) method was used to extract texture features—such as Contrast, Dissimilarity, Homogeneity, Energy, and Angular Second Moment (ASM)—from the images [1]. These features were then used to train an SVM classifier to distinguish between tissue types and stages. Receiver operating characteristic (ROC) curves and area under the curve (AUC) metrics were used to evaluate classification performance [2].

Results and Discussion: The GLCM-based texture analysis uncovered quantitative differences in ECM organization. SCC-progressing cases showed chaotic initial collagen patterns that simplified in subsequent dysplasia, while primary HGD progression exhibited escalating matrix complexity. Post-SCC dysplasia displayed more uniform collagen than untreated HGD progression, suggesting therapy-driven ECM changes or distinct biological pathways. SVM classifiers trained on GLCM features achieved higher accuracy in distinguishing SCC from HGD than in differentiating between types of HGD, with ROC-AUC values supporting the potential of this approach for early cancer detection [3].

Conclusion: This research demonstrates that integrating two-photon microscopy with quantitative texture analysis and machine learning offers a promising avenue for improving the early diagnosis and characterization of oesophageal SCC and HGD. While the current study is limited by sample size, the methodology provides a foundation for broader clinical application and the development of predictive models for cancer relapse. Future work should focus on expanding datasets, incorporating additional imaging modalities, and refining feature extraction to enhance classification accuracy and generalizability.

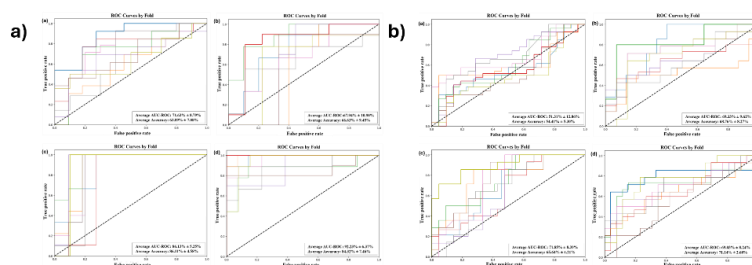


Figure 2: SVM models of (a) SHG images (b) TPF images

Acknowledgement: We thank Global Innovation and Technology Alliance (GITA), Department of Science and Technology (DST), India [Project Number- GITA/DST/TWN/P-95/2021] for the financial support. We also thank Manipal School of Life Sciences, Manipal Academy of Higher Education, Manipal, Karnataka, India, for providing the infrastructure and facilities.

References: [1] Vironicka AS, Sathiaselvan JG. Texture Feature Extraction With Medical Image Using Glcm And Machine Learning Techniques. ICTACT Journal on Image & Video Processing. 2022 May 1;12(4). [2] Huang S, Cai N, Pacheco PP, Narrandes S, Wang Y, Xu W. Applications of support vector machine (SVM) learning in cancer genomics. Cancer genomics & proteomics. 2018 Jan 1;15(1):41-51. [3] Hajian-Tilaki K. Receiver operating characteristic (ROC) curve analysis for medical diagnostic test evaluation. Caspian journal of internal medicine. 2013;4(2):627.