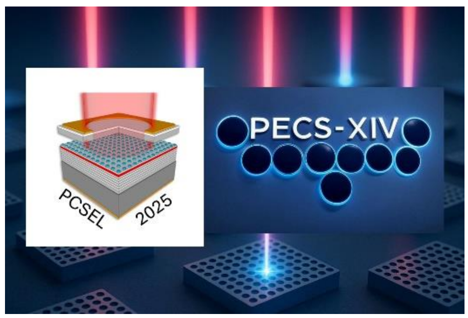

2025 PCSEL and PECS-XIV Workshop

Abstract Book

10 - 12 November 2025
https://www.pcsel.org

Contents

1. International Workshop on PCSELs & PECS-XIV 2025

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High Performance Thin Film Lithium Niobate (TFLN) Photonics

Prof Philippe Lalanne, CNRS-IOGS-Univ Bordeaux (Invited)
Electromagnetic resonators: revisiting the Coupled Mode Theory

Prof Dario Gerace, Università degli Studi di Pavia
Polariton condensation and emerging supersolidity in photonic crystal waveguides

Dr Daniel Muis, Delft University of Technology & AMOLF
Large-Area Optical Field Enhancement Using Landau Levels in Synthetically Strained Photonic Crystals

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Photonic crystal implementation for mode control in semiconductor lasers

Dr Yoshitaka Kurosaka, Hamamatsu Photonics, Taiwan (Invited)
A patterned light source based on PCSEL technologies

Prof Boubacar Kante, University of California, Berkeley
Progress on scale-invariant Berkeley Surface Emitting Laser (BerkSEL)

Mr Tong Xu, Chinese Academy of Sciences
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14:00-15:00 Session 3 (Chair: Prof Thomas Krauss)- PECS-XIV

Prof Eli Yablonovitch, UCLA/University of California, Berkeley (Plenary)
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Prof Marin Soljacic, MIT (Plenary)
Certain intersections of AI and Photonics

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Prof Susumu Noda, Kyoto University

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1.2 Agenda for Tuesday, 11th November (Parallel Sessions):

09:00-10:30 Session 4 (Chair: Dr Richard Taylor)- PCSEL

Prof Richard Hogg, Aston University (Invited)
Accelerating PCSEL Development

Mr Mei Emoto, Stanley Electric (Invited)
Progress in GaN-based photonic-crystal surface-emitting

Dr Kazuyoshi Hirose, Hamamatsu Photonics
Micro pattern projection from PCSEL-based on-chip pattern projector.

Ms Erin Raftery, University of Illinois, Urbana-Champaign
Photopumped buried dielectric topological-cavity surface-emitting lasers inP

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Prof Lucio Andreani, University of Pavia, (Invited)
Bound states in the continuum empowering chiral optical response in dielectric and metallic photonic crystals.

Dr Kazuhiro Kuruma, University of Tokyo (Invited)
Engineering photons and phonons in diamond for defect center

Dr Yue (Christina) Wang, Univeristy of York (Invited)
Photonic Crystals in Van der Waals Landscapes

Dr Augusto Martins, Univeristy of York
Robust photonic resonances in flat bands

Dr Shuma Ito, Keio University
Observation of high-Q flatband modes in twist-stacked moiré photonic crystals

10:30-11:00 Coffee Break

11:00-12:30 Session 6 (Chair: Dr Scott Watson)- PCSEL

Prof Chao Peng, Peking University (Invited)
Collective oscillations in photonic crystal surface emitting laser

Dr Samir Rihani, Huawei Technologies R&D (Invited)
High-Efficiency PCSELs for Next-Generation Photonic Communication

Prof Weidong Zhou, University of Texas at Arlington
Coherence in passively coupled coherent PCSEL arrays

Mr Matthew Robinson, University of Glasgow
Breaking symmetry in triangular lattice PCSELs: coupled wave theory analysis

11:00-12:30 Session 7 (Chair: Prof Thomas Krauss)- PECS-XIV

Prof Toshihiko Baba, Yokohama National University (Invited)

Photonic Crystal Slow-Light Modulator Toward Co-Packaged Optics

Prof Wei Li, Chinese Academy of Sciences (Invited)
Spatial and frequency dispersion engineering for optical information detection and processing

Prof Satoshi Iwamoto, University of Tokyo (Invited)
Semiconductor-based Topological Photonic Crystal Waveguides

Elise Burns, University of Strathclyde
Integration of Silicon Photonic Crystal Cavities on Multi-Core Optical Fibre

Dr Dominic Hallett, University of Sheffield
Independently tunable emitters chirally coupled to a chiral photonic crystal waveguide

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Dr Takuya Inoue, Kyoto University (Invited)
Dynamic control of photonic-crystal surface-emitting lasers toward satellite communications

Dr Yuhki Itoh, Sumitomo Electric (Invited)
Progress in High-power InP-based Double-lattice PCSELs

Prof Leon Shterengas, Stony Brook University
Progress in development of the GaSb-based PCSELs

Mr Zongliang Li, Chinese Academy of Sciences
Non-Hermitian Dirac theory of topological-cavity surface-emitting laser

14:00-15:30 Session 9 (Chair: Prof Toshihiko Baba)- PECS-XIV

Prof Thomas Krauss, Univeristy of York (Invited)
Optofluidic and electrophotonic tunable resonances

Dr Masashi Miyata, Device Technology Labs, NTT (Invited)
High-sensitivity Multi-color Imaging Based on Meta-optics

Prof Willem Vos, University of Twente (Invited)
Realizing the Anderson localization transition for light in 3D, here is attempt nr. 57-d

Prof Romuald Houdré, EPFL
Optical trapping in a photonic crystal hollow cavity for discrimination and status assessment of bacteria and bacteriophages viruses in the context of phage or antibiotics therapies

Dr Fabio Aldo Kraft, Kiel University
Liposome Sensing with Photonic Crystal Slabs: A Proxy for Extracellular Vesicle Detection

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1.3 Agenda for Wednesday, 12th November:

09:00-10:30 Session 10 (Chair: Prof Richard Hogg) – PCSEL

Prof Cunzhu Tong, Chinese Academy of Sciences

Triple-lattice photonic crystal surface emitting lasers

Dr Ivo Tanghe, Ghent University
PCSELs over the entire visible spectrum based on colloidal nanocrystals

Dr David Moodie, Huawei Technologies R&D
PCSELs at telecommunications wavelength using a heterolattice design

Dr Mindaugas Radziunas, Weierstrass Institute
Dynamic simulations of single-mode lasing in large emission area all-semiconductor PCSELs

Prof Hans-Peter Wagner, University of Cincinnati
Compact InP nanowire photonic crystal surface emitting lasers

Prof Ulrich Schwartz, TU Chemnitz
Far-fields of deep-UV PCSEL with shallow and deep-etched photonic crystal

11:00-12:30 Session 11 (Chair: Prof Satoshi Iwamoto)- PECS-XIV

Dr Dawn Tan, Singapore University of Technology and Design (Invited)
Bragg soliton dynamics on a CMOS chip

Prof Masaya Notomi, Institute of Science Tokyo & NTT Inc. (Invited)
Non-Hermitian Chirality and Singularity with Complex Photonic Crystals and Complex Perturbation

Prof Ling Lu, Chinese Academy of Sciences (Invited)
Photonic application of topological physics: in memory of John Joannopoulos (1947-2025)

Dr Kaiwen Ji, Université Bordeaux
Photonic Crystal Coupled Nanolasers at Lasing Exceptional Points for Chiral Light Emission

Davide Monopoli, Munster Technological University
Hybrid laser emission via a RSOA die coupled to an integrated side-coupled Fabry-Perot

12:30-14:00 Lunch

14:00-15:30 Session 12 (Chair: Mr Joe Gannicliffe)- PCSEL

Industry roundtable session led by a panel of PCSEL manufacturers, integrators, and end users, facilitating audience discussion on the potential for, and challenges of, PCSEL commercialisation.

15:30-17:00 Coffee Break

14:00-15:30 Session 13 (Chair: Dr Christina Wang)- PECS-XIV

Prof Shanhui Fan, Stanford University (Invited)
Photonic band physics: generation of light bullet, and non-Abelian lattice gauge field

Prof Ren-Min Ma, Peking University (Invited)
Singular Dispersion Equation: Breaking the Diffraction Limit in Dielectrics

Dr Jonathan Dietz, IonQ (Invited)
A scalable photonic quantum interconnect platform

Prof Kyoko Kitamura, Tohoku University (Invited)

Optical Pathways in Distorted Photonic Crystals

15:30-16:00 Closing Remarks

2. Abstracts

1.1 High Performance Thin Film Lithium Niobate (TFLN) Photonics

Marko Lončar, Harvard University
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Abstract – The last two decades have seen tremendous progress in the field of integrated photonics, and chip-scale photonic systems can now be found everywhere: from optical communications and sensing, to machine vision and precision measurements. However, traditional integrated photonic platforms, based on e.g. silicon and compound semiconductors, are reaching their limits and cannot keep up with the demands for more speed, less energy consumption, and advanced functionality. High performance thin film lithium niobate photonic platform [1] can overcome these limitations. For example, our electro-optic modulators [2] can power up high-speed optical communication systems, as well as enable realization of mm-wave and THz communication systems. Our frequency combs [3, 4] are important for environmental and biomedical monitoring, precision measurements and ranging. Finally, microwave-to-optical transducers [5], based on electro-optic frequency shifter [6] concept, can enable efficient and low noise interfaces between superconducting quantum computers, while TFLN photonic platform operating in visible [7] is important for realization of multiplexed quantum repeaters and quantum internet.

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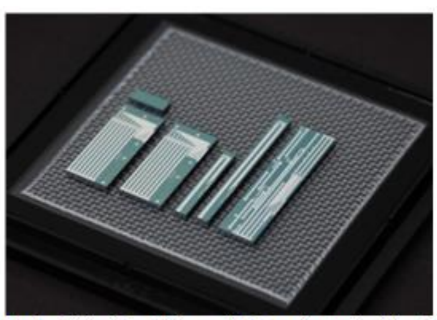

Fig. 1: Thin film lithium niobate photonic chips for applications in optical communications & computing, microwave photonics, and quantum communications

1.2 Electromagnetic resonators: revisiting the Coupled Mode Theory

Tong Wu and Philippe Lalanne
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Abstract – The temporal coupled-mode theory (CMT) is an acclaimed and widely used theoretical framework for modeling the continuous wave response and temporal dynamics of any integrated or free-space photonic resonant structure. Despite its widespread significance, the temporal coupled-mode theory (CMT) lacks a foundational validation based on electromagnetic principles and stands as a phenomenological theory relying on fitted coupling coefficients.

I. Introduction

Micro and nanoresonators are open systems and their modes (often called quasinormal modes or QNMs) are always leaky and have a finite lifetime (i.e. a complex frequency). The modal analysis of the non-Hermitian behavior of such resonators has posed great difficulty in the past, but the situation has changed drastically recently [1]. We have now reached a point where QNM freeware packages, like the one developed by my group for 10 years, presently compute/normalize/regularize the quasinormal modes of virtually any electromagnetic resonator that can be modeled with Maxwell solvers [2].

We are thus in a position where it become possible to employ an ab initio Maxwellian approach to derive an "exact" CMT using quasinormal-mode theory

II. Methods and Results

We recently obtained two results.

“Exact” Evolution Equation. The first concerns what is called the evolution equation for resonator dynamics, which is traditionally written dam/dt=−iω˜mam+⟨κ∗m |s+⟩dam/dt=−iω~mam+κm∗ s+, where |am|2am2 represents the energy stored in the mthmth mode of the resonator and ω˜mω~m is the complex-valued frequency of the mode, encompassing radiative decay to excitation channels, free space and absorption. This equation is central to CMT. The evolution equation that we have derived using QNM theory is different [4-5]. It bears resemblance to the classical one, but introduces novel terms embodying distinct physics, suggesting that the core equation of the CMT could be faulted by dedicated experiments, for instance carried out with short and off-resonance pulses [5].

Dissipative coupling between resonators. We have derived a coupled-quasinormal-mode (cQNM) framework for analyzing dissipative coupling with photonic and plasmonic resonators. The framework provides rigorous closed-form expressions for dissipative coupling coefficients and introduces novel features, such as a new coupling scheme via time derivatives of excitation coefficients [6], which are not present in the CMT. We will show that the formalism delivers transparent and accurate predictions of exotic phenomena—such as zero-coupling between very close photonic crystal cavities and level-attraction effects—that are only vaguely captured by traditional CMT models.

Dissipative coupling is not well understood, because the QNM field exponentially grow up outside resonators and then we have the impression that the coupling should diverge. We think that we have resolved this apparent contradiction [7].

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[5] T. Wu and P. Lalanne, "Exact Maxwell evolution equation of resonator dynamics: Temporal coupled-mode theory revisited," *Opt. Express* **32**, 20904-20914 (2024).
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1.3 Polariton condensation and emerging supersolidity in photonic crystal waveguides

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Abstract – I will review recent theoretical and experimental works demonstrating polariton Bose-Einstein condensation in topologically-protected bound-states [1,2], ultimately allowing to realize a supersolid phase due to parametric scattering from the condensate into finite momentum side-branches [3,4]. These findings enable exploration of novel matter phases through engineering of polariton dispersion in photonic lattices.

I. Introduction

Polariton condensation into gap-confined modes arising from a photonic bound state in the continuum has been realized in a one-dimensional (1D) photonic crystal waveguide [1], and its characteristics have been theoretically unraveled since [2]. Supersolidity is a counter-intuitive and very fascinating phase of matter, realized only in recent years in various configurations by using condensates of cold atomic clouds: it can be seen as a very coherent quantum system that simultaneously behaves as a superfluid, i.e., flowing without viscosity or friction, and possessing characteristics that are typical of crystalline solids (the periodic arrangement in space). Here we will describe on the theoretical prediction and the recent experimental demonstration of a polariton supersolid phase, realized from the nonlinear polariton-polariton parametric scattering into finite momentum side-branches, which creates a periodic real space modulation of the polariton condensate in close analogy to supersolid realizations in cold atomic clouds, and representing the first evidence of a supersolid phase in a quantum fluid of light.

II. Methods and Results

The main outcome of our theoretical investigation is reported in Fig. 1a, showing the nonlinear population of side-branches out of the polariton condensate [3], which gives rise to periodic modulations on top of the condensate. The corresponding experiment [4], realized in a 1D photonic crystal polariton device, is shown in Fig. 1b, in agreement to the theory. In this talk, the wider consequences of these findings will be discussed.

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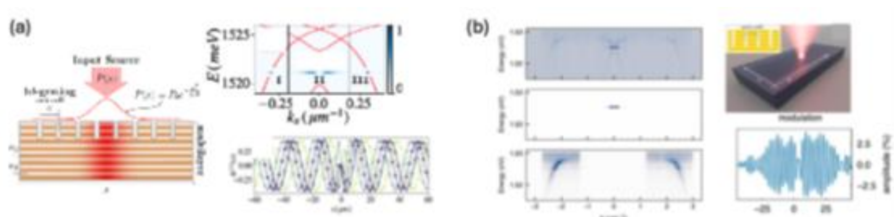

Figure 1 (a) Model of a non-resonantly pumped 1D PhC polariton waveguide, and calculated emission above condensation threshold as well as above OPO threshold, inducing randomly sampled periodic modulations in real space; (b) Corresponding experimental results, showing emission at finite momentum, and periodic modulations on top of the polariton condensate, which is interpreted as the emergent supersolid phase of the polariton fluid.

1.4 Large-Area Optical Field Enhancement Using Landau Levels in Synthetically Strained Photonic Crystals

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Abstract – We demonstrate the realization of photonic Landau levels enabled by synthetic strain in two-dimensional honeycomb photonic crystals. Tailoring the strain allows generation of flat bands with a high optical density of states and high Q-factor. We study the potential of these states for on-chip optical field enhancement over large areas.

I. Introduction

In this work, we study synthetically strained photonic crystals that feature Landau levels. Landau levels are most well known in condensed matter: Electrons in a two-dimensional electron gas subject to an external magnetic field move in cyclotron orbits with discrete energies which are manifested as flat-band Landau levels. The same discretization of energies can also be achieved without a magnetic field in graphene through the application of geometric strain. Similarly, synthetic strain in honeycomb all-dielectric photonic crystals can lead to photonic Landau levels where states have a near-zero group velocity with high degeneracy [1,2,3].

II. Methods and Results

We experimentally demonstrate the formation of flat bands for a design with strain in two dimensions, illustrated in Fig. 1(A). With Fourier spectroscopy we observe the photonic Landau levels, shown in Fig. 1(B), and map the linewidth as a function of wavevector to quantify the radiative losses. We show that the intrinsic linewidth does not significantly depend on the flatness of the band, therefore paving the way for these systems to enable large field enhancement. Our findings provide a viable route for future applications in large-area optical field enhancement, and its use in e.g. nonlinear photonics, light emission, and high-Q metasurfaces.

References:

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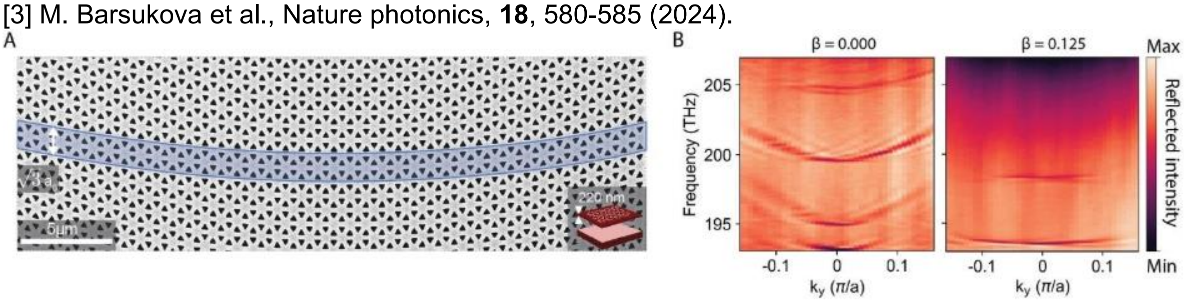

Fig.1 (A) Scanning electron microscope image of a strained photonic crystal, with the suspended nature and slab thickness depicted in the inset. Lattice points are displaced in the vertical and the horizontal direction. (B) Experimental dispersion diagrams showing the Landau levels. Application of horizontal strain, tuned by parameter β, flattens the Landau level and creates a highly degenerate band with a broad angular range.

2.1 Photonic Crystal Implementation for Mode Control in Surface Emitting Semiconductor Lasers

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Abstract – We review photonic crystal approaches for transverse mode control in VCSELs and TCSELs. High brightness single element VCSELs and coherently coupled VCSEL arrays using etched photonic crystals as well as buried dielectric photonic crystal surface emitting lasers using MBE epitaxial overgrowth are discussed.

I. Introduction- A periodic refractive index can dramatically modify the optical resonances within semiconductor laser diodes. The vertical cavity surface emitting laser (VCSEL) consisting of two distributed Bragg reflectors (DBRs) is an obvious example of a 1-dimensional photonic crystal (PC) with a 1-wavelenth thick defect active region. Introduction of a 2-dimensional etched PC into the top DBR can produce a complex refractive index profile that can sustain only a single Gaussian mode for emission parallel to the PC and perpendicular to the wafer surface. Alternatively, the photonic crystal surface emitting laser (PCSEL) utilizes a 2-dimensional PC to control the in-plane emission perpendicular to the photonic crystal, which can scatter single mode emission perpendicular to the wafer surface. In both cases the PC refractive index pattern introduced to the laser diode is used to engineer the laser beam emitted from the wafer surface.

II. Methods and Results- Photonic crystal VCSELs are fabricated by introducing an etched air-hole array with a periodicity greater than emission wavelength into the top DBR [1]. The light propagates parallel to the PC which induces a controlled reduction of index while holes partially etched into the laser cavity introduce scattering loss to higher order modes, providing complex index confinement around a missing hole (i.e. defect cavity). The complex cavity confinement allows the VCSEL diameter to increase while maintaining single mode emission for high brightness operation. Moreover, by combining with ion implantation and selective electrical contracts, leaky-mode coherently coupled VCSEL arrays can be obtained [2]. Examples of dual element, 6-element linear, and 6-element ring VCSEL arrays are shown in Fig. 1. We will discuss how the structure of the PC in coherent VCSEL arrays can be used to control the laser beam parameters, decrease the beam divergence, and even enhance the modulation properties.

The PCSEL has the in-plane optical propagation influenced by the PC creating out-of-plane single mode laser emission. To date, PCSEL have photonic crystals usually implemented by encapsulating air-voids. We recently demonstrated buried dielectric PCSELs that incorporated amorphous SiO2 as the low index and epitaxially lateral overgrown InP by MBE as the high index material [3]. The buried dielectric PC has the disadvantage of reduced index contrast, compared to air-void PCs. However a buried dielectric PC has the advantage of the full range of PC fill factor, no crystallographic orientation limitations, and potentially improved PC uniformity and thermal conductivity. Buried dielectric PCSELs have demonstrated pulsed photo-pumped lasing at 1.55 µm. More details of buried dielectric PCSELs and buried dielectric topological cavity surface emitting lasers (TCSELs) will be discussed.

III. References

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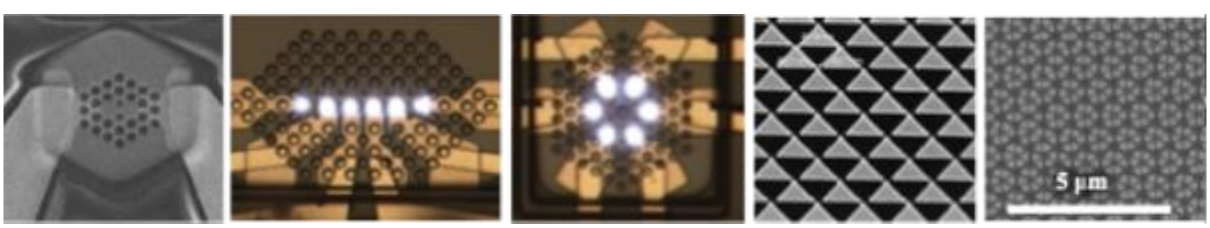

Fig. 1. Photonic crystals etched into VCSEL for (a) 2x1, (b) 6x1, and (c) 6-ring coherent arrays; notice independent bias contacts for each VCSEL in the array; (d) triangular and (e) hexagonal SiO_2 photonic crystal patterns on InP for long wavelength PCSELs and TCSELs, respectively.

2.2 A patterned light source based on PCSEL technologies

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Abstract – We have developed a patterned light source based on PCSEL technologies. Mesh noise and zero-order noise are eliminated, which is significant progress. In addition, experimental results on photonic band replication have paved the way toward a dynamically changeable patterned light source.

I. Introduction

The PCSEL [1-6] is a candidate for next-generation lasers. While maintaining the advantage of semiconductor lasers, it realises a high-quality lasing mode and even adds high functionality through a designed photonic crystal. We have developed a patterned light source [3] based on the PCSEL [1] and modulated PCSEL [2] technologies. In this presentation, we introduce our work involving elimination of mesh noise and zero-order noise. Furthermore, we have revealed that the photonic band structure is replicated through each bright spot of the beam pattern in the patterned light source [4]. This indicates every bright spot is simultaneously emitted (without scanning) and the beam pattern can be dynamically controlled by superimposing coupled multi-patterned beams [5].

II. Methods and Results

Initially, the output beam pattern has mesh noise as shown at the top left of Fig. 1(a). Photonic band measurement shows that this is due to anti-crossing of photonic bands between the fundamental mode and higher-order modes in the layer direction. Using epitaxial structure in which higher-order modes do not exist in the layer direction, we successfully obtained a beam pattern without mesh noise [3]. In the same way as for a modulated PCSEL [2], we also successfully eliminated zero-order noise using an M-point band edge [6] as shown at the bottom of Fig. 1(a).

Next, we designed and examined a structure in which two patterned regions are embedded in the same square lattice as shown in Fig. 1(b), where these two regions are labelled CH1 and CH2. When a current is applied for each pattern region, a corresponding patterned beam is emitted. Two horizontal stripe patterns with a phase difference of 90° were used as a proof-of-concept experiment. The stripe intensity ratio of each pattern region changes continuously when the beams are superimposed. This result indicates that two elemental patterns are superimposed as a complex amplitude distribution, and it paves the way to a dynamically changeable patterned light source consisting of multiple channels. We also demonstrate a continuous change in beam pattern.

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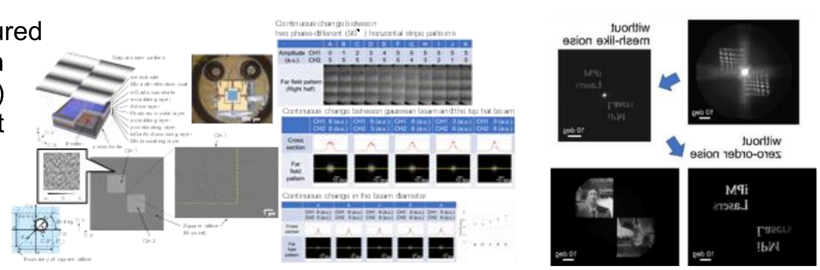

Figure 1. (a) Evolution of a measured beam pattern with elimination of mesh noise and zero-order noise. (b) Device structure and measurement results for a continuously variable semiconductor pattern emitter. It consists of two coherently coupled pattern emitters embedded within the same square-lattice photonic crystal

2.3 Progress on scale-invariant Berkeley Surface Emitting Laser (BerkSEL)

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Abstract – In 2022, the Berkeley Surface Emitting Laser (BerkSEL) was created which exhibited an unconventional flat mode in real space as the fundamental lasing mode instead of a conventional oscillatory gaussian mode [1]. We will discuss the physics of this mode and propose a novel experimental excitation scheme suitable for electrically injecting these devices.

I. Introduction -Since the discovery of photonic crystals, the perception of the modes' quantization has remained the same, i.e. integer quantization (n=1,2,3,...) [2]. We discovered that Berkeley Surface Emitting Lasers (BerkSELs) go beyond this limitation allowing a scale-invariant mode that enables n=0, i.e. n=0,1,2,... . This mode allows the suppression of higher order modes inhibiting the spatial hole burning, improving the laser's scaling properties.

II. Methods and Results -We study the physics of unconventional flat mode in BerkSELs. Figure 1a shows the linear dispersion of BerkSELs and the unit-cell mode mixing at any other point than the Γ-point [3]. The fundamental flat mode of BerkSELs is located at exactly the Γ-point where the quantization number, n, is zero. The zero-quantization number means that the fundamental mode will be uniform and pure, i.e. only the even unit-cell mode will exist (Fig.1b). The magnetic field (H_z) of the fundamental flat mode of the 3D devices was simulated using the Finite Element Method (FEM) and is presented in Fig.3c. The physics enabling such modes will be discussed as well as higher order modes in such systems. Furthermore, we investigated possible electrical excitation schemes for BerkSELs different from the traditional schemes [4]. We will discuss a novel electrical injection scheme suitable for suspended photonic crystals and maintaining the maximum index contrast with the environment. The scheme may enable the injection of arbitrary modes in photonic systems including topological structures that can have arbitrary geometries [5].

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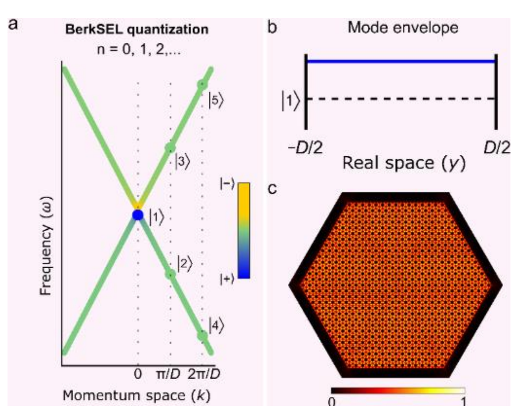

Figure 1: a) A schematic of the linear dispersion of BerkSELs overlapped with the cavity modes showing the existence of the unconventional flat mode at exactly the Γ-point. b) The envelope of the mode along one direction of the cavity shown in c. c) The absolute value of the z-component of the magnetic field as extracted from FEM simulations. The flatness of the mode is easily visible in two dimensions.

2.4 Room-temperature electrically injected GaN-based photonic-crystal surface-emitting lasers

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Abstract – Regrowth-free GaN-based photonic-crystal surface-emitting lasers (PCSELs) were developed. Under a room temperature (RT) pulsed injection, the characteristics of PCSELs were measured. The lasing peak is at 415.1 nm with a FWHM of about 1 nm. The threshold current density of PCSEL is 13.7 kA/cm^2 and the peak output power is 172 mW.

I. Introduction

PCSELs have recently attracted much attention due to their excellent performance. In 2023, Kyoto University reported GaAs-based 945 nm PCSELs with a continuous-wave (CW) single-mode output power of exceeding 50 W, and a narrow beam divergence angle of 0.05°, demonstrating a brightness of 1 GW cm^{-2} sr^{-1} [1]. However, the development of GaN-based PCSELs is hindered by its small refractive index, immature regrowth and device fabrication processing technology. So far, only Kyoto University [2] and Canon Corporation [3] have achieved RT electrically pumped lasing of GaN-based PCSELs with air holes retained via regrowth approach.

Compared to the regrowth-based methods, the regrowth-free approach reduces the fabrication complexity while maintaining the device performance, offering a cost-effective solution for mass production. In this study, regrowth-free GaN-based PCSELs were grew on sapphire substrate, and the RT electrically pumped lasing was demonstrated with a threshold current density of 13.7 kA/cm^2.

II. Methods and Results

The structure of regrowth-free GaN-based PCSELs is schematically illustrated in Fig. 1(a). The laser structure was grown on sapphire substrate by metal-organic chemical vapor deposition (MOCVD). The photonic crystal (PC) was fabricated by electron beam lithography (EBL) and inductively coupled plasma (ICP) etching. Then the indium tin oxide (ITO) was deposited on the PC layer by magnetron sputtering. The as-fabricated GaN-based PCSELs were characterized under pulse conditions at RT with 100 ns pulse width and 10 kHz repetition frequency. Figure 1(b) presents the normalized current-dependent electroluminescence (EL) spectra, showing a dominant lasing peak at 415.1 nm. The measured full width at half maximum (FWHM) is about 1 nm, primarily close to the limited spectral resolution of the spectrometer. Figure 1(c) shows the light-current-voltage (L-I-V) characteristics of the as-fabricated PCSELs. The threshold current is 21.96 A, corresponding to a current density of 13.7 kA/cm^2. The maximum output power is 172 mW at 38.5 A.

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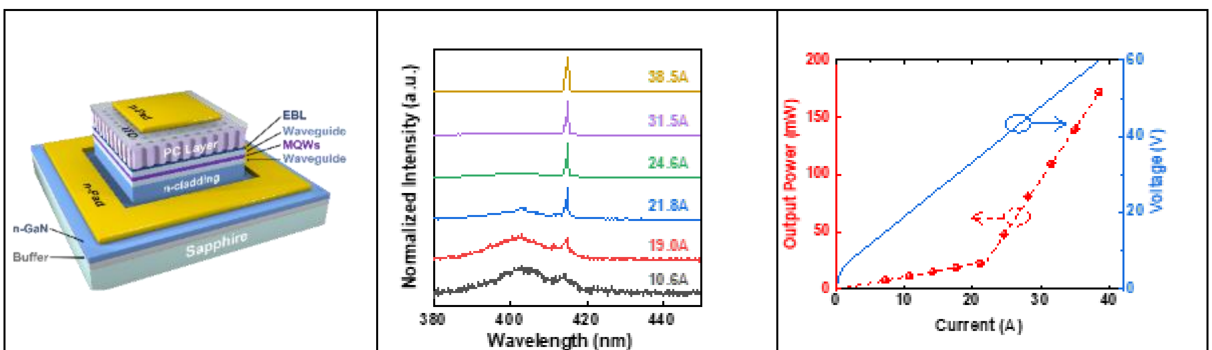

Figure 1. (a) Schematic diagram of the regrowth-free GaN-PCSELs. (b) Normalized EL spectra. (c) L-I-V curve.

3.1 What I Wish I Had Known, as I Searched for the First 3d Photonic Bandgap

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Abstract: The first 3-dimensional Photonic Bandgap was found by an Edison type search, trial-and-error, guided by physical intuition. The 4-year search was beset by pseudo-gaps, and required deep physical insights to find the right geometry (diamond unit cell in a face-centered-cubic lattice). Nonetheless, there do exist mathematical techniques for 3d geometry optimization that could have led to the right structure more quickly.

Summary: The optimization problem is exacerbated by the reality that any geometrical design could have millions of design parameters that define a desirable shape. With a particular goal in mind, the adjustment of any one design parameter, requires a revision of all the other parameters, making it hard, or impossible to converge on a good design. Essentially this is a problem in multi-variable calculus: How to co-optimize the millions of parameters that are implicit in any geometrical shape? It might be called “Shape Calculus”.

Fortunately there are elegant mathematical methods that have emerged that permit the co-optimization of millions of variables, but requiring only two solutions of Maxwell’s Equations [1]. The mathematical approach is sometimes called the “Adjoint Method”, and it is a merger the chain rule of calculus, with linear algebra [2].

The earliest application of the adjoint method was for military logistics in the 1950’s, and called Operations Research. Indeed the mathematics has been rediscovered numerous times in the past 70 years, within various fields, wherever some optimization over many variables is needed. This has many names. For example, in neural networks this is called “Back-Propagation”, in photolithography it’s called Inverse Lithography Technology, (ILT), but it is also used in Control Theory, mechanical design, etc.

One of the first electromagnetic applications of the “Adjoint Method” was toward the design of lithographic masks for the photographic process by which electronic chips are manufactured. These masks consist of thin-film Chromium on glass, intricately patterned, to photographically project out the sub-wavelength shapes of transistors, wires, and other components on an integrated circuit. These metal film masks, so heavily used in electronics manufacturing, can be regarded as the original “meta-surface” [3].

Sub-wavelength transistor images were desired, but it was not at all clear what the mask pattern should be, that would produce those desired sub-wavelength images. The first company founded to employ the “Adjoint Method” for photo-lithography was Luminescent Inc., (2002). Luminescent introduced the slogan ILT “Inverse Lithography Technology” to be understood as a sub-category of Inverse Electromagnetic Design. Today, almost all memory chips and micro-processors use thin-film chromium masks and ILT software in their design and manufacture, meta-surfaces indeed [4].

Whether it’s a meta-lens or any other type of electromagnetic function, there is no need to slavishly follow a periodicity constraint. Mathematical methods have been developed, to efficiently optimize any type of electromagnetic function. I will provide some examples: “Silicon Photonics” couplers, optical antennas, solar cell surface textures, etc.

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3.2 Certain intersections of AI and Photonics

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Advances at the interface of photonics and AI are beginning to reshape both computation and scientific discovery. I will discuss how photonics can accelerate and diversify AI hardware and, conversely, how modern machine learning catalyzes progress in photonics—with an emphasis on photonic crystals, data-efficient learning, and laboratory automation. On the hardware side, coherent nanophotonic circuits can perform linear layers optically and nonlinearities electronically, enabling ultra-fast and efficient optical or hybrid neural networks [1]. Multistable optical parametric oscillators (OPOs), when seeded with vacuum-level bias fields, act as controllable quantum probabilistic bits and open avenues for photonic probabilistic computing [2]. Building on this, biased OPOs with feedback form “photonic probabilistic neurons” capable of solving inference tasks [3]. On the algorithms front, surrogate- and symmetry-boosted contrastive learning improves representation learning when labeled data are scarce [4], while predictive and generative ML models accelerate forward simulation and inverse design of photonic crystals [5]. Finally, I will discuss AI-driven robotics for free-space optics (“OptoMate”), which integrates generative AI, computer vision, and precision manipulation to automatically plan, assemble, align, and measure tabletop optical experiments—pointing toward reproducible, high-throughput “cloud labs” for photonics and quantum optics [6].

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4.2 Progress in GaN-based photonic-crystal surface-emitting lasers

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Abstract – We present recent progress in GaN-based PCSELs with double-lattice photonic-crystal structures, enabling high-power and large-area operation. We also introduce a prototype underwater sensing system, highlighting the potential of these devices.

I. Introduction

Photonic-crystal surface-emitting lasers (PCSELs) are based on two-dimensional resonance in the photonic crystal, enabling high-power, high-beam-quality operation [1, 2]. Owing to these distinctive features, PCSELs have recently attracted considerable attention. The realization of GaN-based PCSELs operating in the blue wavelength range is of considerable industrial and academic value. This importance stems from the lack of practical gas or solid-state lasers in the blue wavelength region, despite its critical role in many advanced applications. Conventional blue semiconductor lasers also suffer from low beam quality, which limits their performance in these applications.

Here, we report recent progress in GaN-based PCSELs with double-lattice photonic-crystal structures, achieving watt-class power and narrow beam divergence. We also present a large-area oscillation strategy and an example application in underwater sensing.

II. Methods and Results

GaN-based PCSELs with double-lattice photonic crystals were fabricated using electron-beam lithography and metalorganic vapor-phase epitaxy (MOVPE) [3]. Figure 1 shows the *I–L* characteristics and far-field pattern for a device with a lattice separation of 0.46*a* (where *a* is the lattice constant). The threshold current density was 1.0 kA/cm², and the slope efficiency reached 0.5 W/A. A very narrow beam divergence angle of ~0.2° was observed from the far-field image.

In our talk, we will also present results from devices with a double-lattice separation of 0.25*a*, designed for large-area oscillation enabling high-power operation. Furthermore, we will demonstrate their application in underwater sensing, where we used a prototype system incorporating our PCSELs to successfully perform distance measurements in water.

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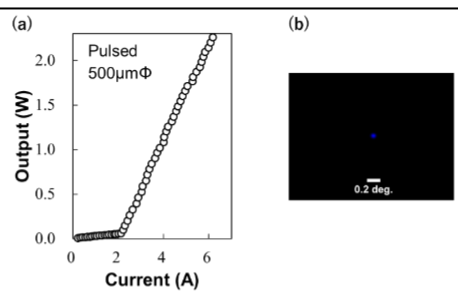

Figure 1. Lasing characteristics of a double-lattice GaN-based PCSEL with a lattice separation of 0.46a.
(a) *I-L* characteristic. (b) Far-field pattern

4.3 Micro pattern projection from PCSEL-based on-chip pattern projector

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Abstract – Various light patterns such as two-dimensional (2D) patterns, three-dimensional (3D) multiple focusing pattern, and micro-patterns (smaller than emission area) are directly projected by a PCSEL-based on-chip projector in which modulated photonic crystal is embedded. Here we reported recent progress of our developments and micro-pattern projection toward application including micro fluidics.

I. Introduction - The PCSEL [1] is attractive laser diode that simultaneously realize high output power and high beam quality. Moreover, it enables direct pattern projection based on modulated photonic crystal [2]. Since we collaborated with Prof Noda's group to introduce the PCSEL technology, we had developed the first PCSEL product (Hamamatsu, L13395-04), and then we have been developed the PCSEL-based on-chip pattern projector (iPMSEL) from 2D patterns [3-4] to 3D patterns [5]. Structured illuminations including multi dots and fringe patterns are suitable to 3D profilometry, while quality of pattern is highly required for practical application. In the case of fringe pattern, precisely shifted fringes are required for highly accurate 3D measurement using phase shifting methods, despite noise of fringe pattern causes positional error. In this work, we have examined our device into the microfluidics where micro fringe pattern is required in which interval of fringe is comparable to target micro particle and smaller than emission area. Recently, we have successfully achieved micro fringe pattern based on interference and demonstrated optofluidic velocimeter [6] which is important to control the trajectory of micro particle in microfluidics. Here, we report recent progress of micro pattern projection toward practical applications.

II. Methods and Results (Two demonstrations of fringe pattern projection) -Firstly, fig. 1A-C shows a demonstration of fringe pattern projection. The first LD chip is set on a USB drive circuit with sides of 2.5 cm operated via micro-USB type B under USB-1.0 standard with 5V, and the fringe pattern is projected on a screen 20 cm away that is observed by a camera (Toshiba teli, BU040MG) through a TV lens (Ricoh, FL-HC1212B-VG) and an IR filter (Fujifilm, IR90). Note that the fringes spaced 1.3º interval ranging 10.6º and total system are operated by a laptop computer. Secondly, for a demonstration of micro fringe pattern, the second LD chip are placed 0.7 mm away from focal point of an objective lens (Mitutoyo, M Plan Apo NIR-HR100X) where scale plate is set as shown in fig. 1D. The micro fringe pattern is observed by camera (Toshiba teli, BU238M) through the objective lens. As shown in fig 1E, micro fringes spaced 4 mm interval are observed which is comparable to micro particles without complex interference optical system.

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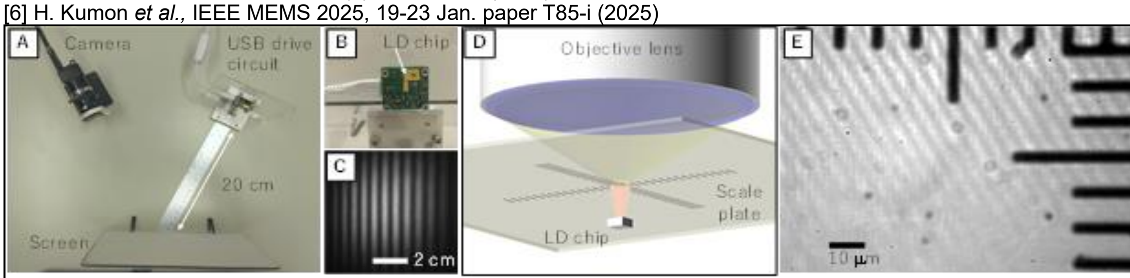

Figure 1. A. Setup of fringe pattern projection, B. fist LD chip on USB drive circuit, C. captured fringe image,
D. setup of micro fringe pattern of second LD chip, E. captured micro fringe image where unit division is 10 mm.

4.4 Photopumped Buried Dielectric Topological-Cavity Surface-Emitting Lasers in InP

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Abstract – We report lasing from photopumped buried dielectric topological-cavity surface-emitting lasers (TCSELs) in InP, marking the first demonstration of a monolithic buried epitaxial TCSEL of any material.

I. Introduction

While PCSELs [1] offer promising power scalability, practical implementation remains challenging due to the emergence of higher-order modes in larger devices. Increasingly complex photonic crystal (PhC) designs can help suppress these undesirable modes. One example is the topological-cavity surface-emitting laser (TCSEL) [2], which incorporates a quasi-periodic PhC structure that breaks the conventional free spectral range scaling relationship, thereby preserving single-mode operation for larger device sizes compared to the PCSEL. Due to the sensitivity in maintaining pattern fidelity during epitaxial regrowth, especially in InP-based systems, the TCSEL has not yet been demonstrated in the conventional epitaxial buried air holes. Here, we report the first demonstration of lasing from pulsed, photopumped, room-temperature buried dielectric (SiO_2) TCSELs in InP, emitting from 1.3 to 1.5 μm.

II. Methods and Results

We previously reported complete semiconductor overgrowth of solid dielectric PhCs for PCSELs and reported photopumped lasing without temperature control [3]. Using the same device structure and fabrication methods, as sketched in Fig. 1a, we replaced the conventional PCSEL PhC with a Kekulé-distortion-inspired vortex pattern of equilateral triangle holes arranged in a honeycomb supercell [2]. The unperturbed TCSEL band structure in Fig. 1b shows Dirac cone vortex modes around 0.3 a/l and 0.6 a/l. We initially fabricated and photopumped TCSELs corresponding to the 0.6 a/l mode for ease of fabrication, targeting 1.3- to 1.5-μm emission. An example pattern is shown in Fig. 1c. The lasing peak at 1392 nm matched the designed lattice constant a = 856.5 nm with an a/l ratio of 0.615 in Fig. 1d. This demonstration validates the buried dielectric platform as a design tool for fabricating complex and pattern-sensitive PhC designs. Ongoing work includes characterizing spectra, thresholds, and far-field patterns of photopumped buried dielectric TCSELs across varying PhC parameters, which will be presented at the conference. Research was partially sponsored by the AFRL Regional Network - Midwest under Cooperative Agreement Number FA8750-22-2-0501.

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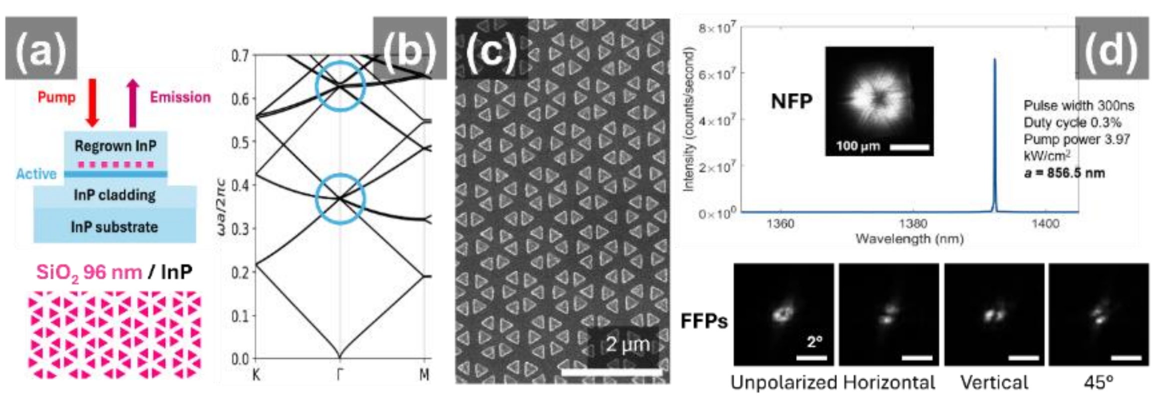

Figure 1. (a) Sketch, (b) Unperturbed PhC band diagram, (c) Top-view SEM image with e-beam resist post SiO_2 etch, and (d) Photopumped emission spectrum, near-field profile, and far-field profiles of a buried dielectric TCSEL.

5.1 Bound states in the continuum empowering chiral optical response in dielectric and metallic photonic crystals

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Abstract – A plasmonic metasurface with symmetry-broken nanoholes supports Bound States in the Continuum (BICs) with maximally chiral optical response. Interaction with an active medium gives rise to a strong coupling regime, yielding chiral polariton BICs. Similarities and differences between dielectric and plasmonic metasurfaces will be discussed.

I. Introduction

Maximing the chiral response in photonic and plasmonic systems is a key goal in current nanophotonics research. Bound states in the continuum (BIC) in dielectric photonic crystals yield ultra-narrow resonances, with intriguing topological properties [1-3]. In this work, we demonstrate that BICs can also appear in plasmonic metasurfaces and can be exploited to yield a strong chiral response and light-matter interaction.

II. Methods and Results

We consider a metasurface consisting of a gold layer on glass, etched with a square lattice of nanoholes, whose shape is deformed from circular to oval [4]. Upon symmetry breaking, a quasi-BIC appears in absorption spectra at the low-energy side of the surface-plasmon polariton (SPP) peak. At a finite angle of incidence along the direction perpendicular to the vertical mirror plane of the nanoholes, the BIC has a strongly chiral optical response with nearly maximum circular dichroism (CD). The maximum CD is nearly independent of the deformation, thus the chiroptical response is robust with respect to structure parameters.

Next, we include an active medium at the bottom of the nanoholes (which can consist, e.g., in colloidal quantum dots) and consider the interaction of the BIC with a Lorentz-like resonance of the active medium [5]. On increasing the oscillator strength of the resonance, the interaction between the BIC and the active medium gives rise to two absorption peaks that show a vacuum Rabi splitting, typical of the strong coupling regime. For oval holes at finite incidence angle, the strongly coupled quasiparticles are chiral with nearly maximum CD. Absorption maps as a function of the angle of incidence show the typical anticrossing behaviour of the strong coupling regime. Thus, the present metasurface with active medium supports the formation of chiral hybrid polariton BICs, which are the analog of polaritons in microcavities or in photonic crystal slabs.

In conclusion, metallic metasurfaces do support BICs that are only subject to dissipative losses. Upon symmetry breaking, the resulting quasi-BICs are much narrower than the SPP resonance and show stronger field enhancement. The chiral properties that were previously studied in dielectric metasurfaces do also occur in the metallic system, and are found to be robust against dissipative losses.

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5.2 Engineering Photons and Phonons in Diamond for Defect Centers

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Abstract We present high-*Q* diamond photonic crystal cavities at visible wavelengths, realized via a transfer-printed thin-film diamond platform. Furthermore, we demonstrate 1D phononic crystals with a complete 60 GHz bandgap that suppress spontaneous single-phonon processes in color centers, advancing integrated diamond nanophotonic–nanophononic systems for quantum networks.

Introduction and Results

Color centers in diamond have emerged as promising solid-state quantum emitters for quantum information processing, serving as stable single-photon sources and spin-based quantum memories. They also provide a platform for quantum network demonstrations, including long-distance entanglement between multiple color centers in diamond[1]. For practical quantum technologies, the development of an efficient photonic interface that enhances both emission and photon collection efficiency is essential. Incorporating color centers into nanophotonic structures, such as optical cavities and waveguides, offers a powerful route toward the goal. Photonic crystal (PhC) cavities are particularly attractive owing to their simultaneous realization of high quality (*Q*) factors and small mode volumes. Nevertheless, experimental *Q* factors in diamond PhC cavities at visible wavelengths have so far been limited to ~10^4, primarily due to challenges in fabricating suspended structures in single-crystal diamond.

In this talk, we present a novel fabrication approach based on transfer printing of thin-film diamond onto Si substrates[2], enabling the realization of fully suspended 1D and 2D PhC cavities. This method achieves *Q* factors exceeding 1.0×10^5 at visible wavelengths[3]. Furthermore, we demonstrate phononic engineering of color centers using 1D phononic crystals (PnCs) that exhibit a complete bandgap around 60 GHz (Fig.1)[4], thereby suppressing spontaneous single-phonon processes responsible for spin decoherence. Finally, we discuss the prospects of integrating diamond-based nanophotonic and nanophononic platforms toward scalable quantum network architectures.

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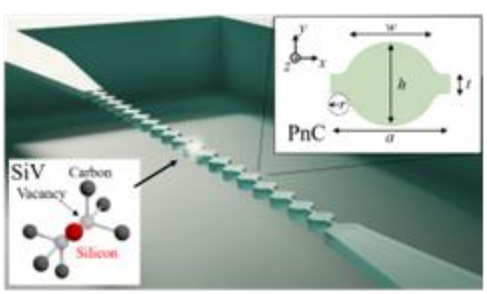

Fig.1 Schematic of 1D diamond phononic crystal (PnC) with a single silicon-vacancy (SiV) center.

5.3 Photonic Crystals in Van der Waals Landscapes

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Abstract – High-refractive-index van der Waals (vdW) materials can replace traditional semiconductors in nanophotonics due to a combination of superior optical properties and unique fabrication advantages. These characteristics enable the fabrication of complex three-dimensional photonic structures, allowing for novel integration and dynamic tuning. They are the essential building blocks for future integrated devices in waveguiding, nonlinear optics, and quantum photonics.

I. Introduction

Photonic crystal structures enable a range of applications, including optical waveguiding, enhanced Purcell effect and low-threshold lasing. While photonic crystals made from conventional dielectrics offer vast opportunities, using vdW materials significantly expands the possibilities of nanophotonics, particularly in the visible and near-infrared range, due to their high refractive indices (n>4), low absorption in this wavelength range, and compatibility with a wide range of substrates due to their weak vdW attraction [1].

II. Methods and Results

Here, we will present our recent development in fabricating subwavelength gratings and other nanostructures in quasi-2D vdW materials (i.e. 10s nm thick, see Fig. 1a and 1b). Thanks to the materials' weak vdW interactions with the substrate, we were able to make nanostructures in the quasi-2D vdW materials on a variety of substrates, integrate with light-emitting materials, and construct an inverted grating stack, shown in Fig. 1 [2, 3]. As an example, we demonstrated precise tuning and band inversion of 1D photonic grating modes in a stacked van der Waals device, yielding topologically-protected Jackiw-Rebbi (JR) interface states [3]. Such JR states exhibited clear spatial confinement to the boundary between topologically distinct gratings. By coupling the monolayer's photoluminescence with the JR state, we successfully demonstrated a strong enhancement of the exciton emission. The versatile nature of vdW photonic crystals establishes them as essential building blocks that shape the future of nanophotonics.

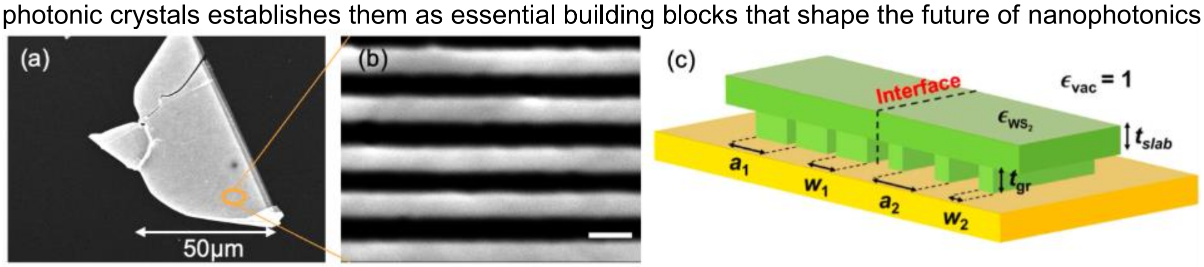

Figure 1. (a) and (b) SEM images of a 1D grating fabricated in an 80 nm thick WS_2 flake, with a scale bar representing 200 nm; (c) Schematic of the double inverted grating structure with respective periods and widths $a_{1,2}$ and $w_{1,2}$. The interface between the two gratings is denoted by the black dashed line.

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5.4 Robust photonic resonances in flat bands

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Abstract –We present recent developments on robust photonic resonances and Bound States in the Continuum. We show simple strategies to achieve tolerance to losses and angular dispersion and discuss the underlying physical processes.

I. Introduction

Photonic resonances are an important tool for controlling light matter interactions, and a major challenge is that their Q and amplitudes are limited by losses and angular dispersion [1]. Thus, much effort has recently gone into achieving robust high Q resonances. Here, we will show two simple strategies leading to loss tolerant high Q resonances and Bound States in the Continuum (BICs) on flat bands.

II. Methods and Results

First, we will discuss how Brillouin zone-folded photonic crystals (PhC) lead to planarized bands and angular tolerance ten times higher than symmetric protected BICs [2] (Fig 1a). We discuss the relationship between angular tolerance and effects of finitude in PhC and show a simple model revealing that the mode penetration length scales with the root square of the band curvature. We also show how zone folding PhCs support air modes [3] with high tolerance to absorption losses (Fig 1b), which leads to a fivefold enhancement of Q for the same resonance amplitude.

Second, we will present a simple method to obtain BICs on flat bands by strong coupling between guided modes in PhC (Fig. 1c). We model it with a Hamiltonian of three modes coupled through the radiation continuum and our experiments reveal a fourfold decrease of the scattering losses due to mode hybridization.

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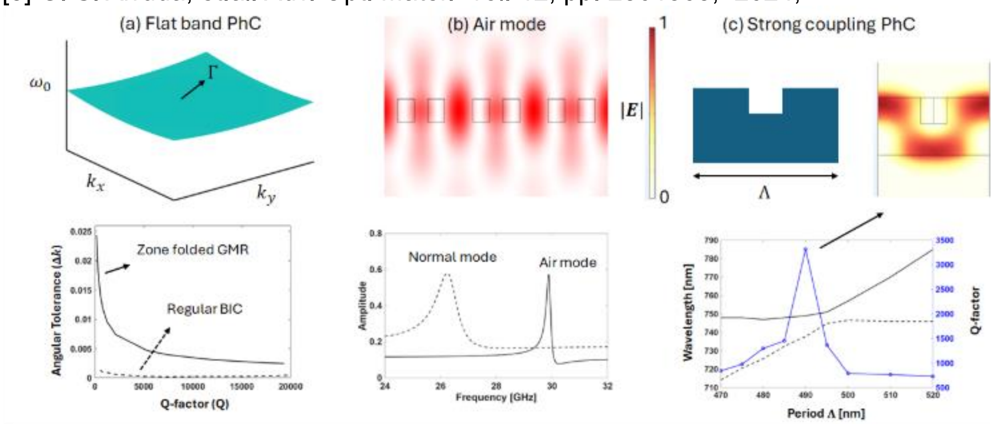

Fig.1 a) top – flatbands (top) lead to higher angular tolerance (bottom). b) air modes (top) lead to resonances robust to absorption (bottom). c) strong coupling between guided modes lead to field confinement (top) and high Q resonances tolerant to scattering losses (bottom)

5.5 Observation of high-Q flatband modes in twist-stacked moiré photonic crystals

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Abstract - We observed high-Q flatband localization in a moiré photonic crystal bilayer. Two photonic crystal slabs are twist-stacked using transfer printing while precisely controlling the interlayer spacing by inserting a glass thin film. High-Q optical resonance peaks with spatial localization were observed.

Introduction – Flatband light localization is a hallmark phenomenon of moiré photonic crystals and has been observed in moiré monolayer structures merging two lattices into a single layer [1, 2]. However, such monolayer structures lack the layer degree of freedom. Bilayer moiré structures in the optical regime are more challenging in design and nanofabrication. Indeed, experimentally-reported Q factors of flatband modes in twist-stacked moiré nanostructures are limited to only a few tens [3, 4]. In this work, we demonstrate high-*Q* flatband localized modes in bilayer moiré photonic crystals in the optical regime by precisely controlling the interlayer spacing.

Result - The investigated structure is shown in Fig. 1(a). It consists of two triangular lattice photonic crystal slabs made of GaAs incorporating quantum dots. The two layers were stacked with a twist angle of $\theta = 6.01°$. A 60-nm-thick SiO_2 layer was inserted as an interlayer spacer. A simulated field distribution of a flat-band mode in the structure is presented in Fig. 1(b). Strong field localization is observed near the center of the moiré pattern with a high *Q*-factor of $\sim 4.2 \times 10^4$.
The designed structure was fabricated using transfer printing. The optical properties of the fabricated structure were characterized by photoluminescence measurements under pulsed excitation at low temperature. We observed a spatially localized resonance peak with a high Q factor exceeding a few thousands [Fig. 1(d)].

Acknowledgement: This work was supported by KAKENHI (22H01994、22H00298).

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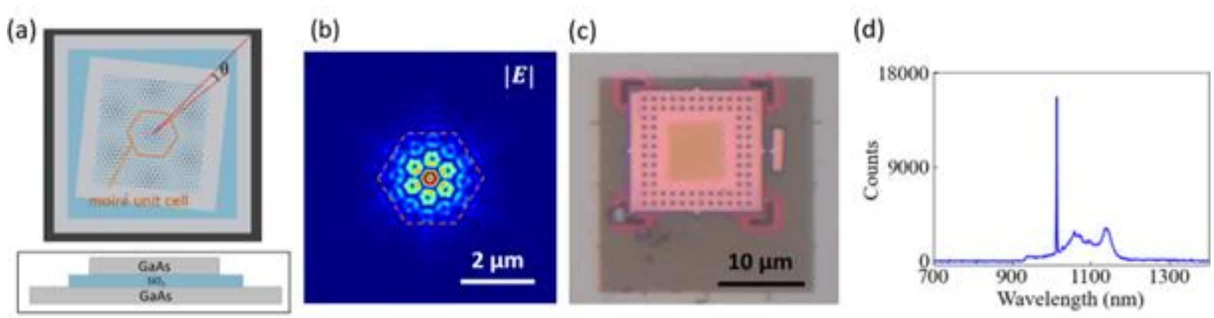
Figure. 1 (a) Investigated twist-stacked moiré photonic crystal. (b) Field distribution of a cavity mode. (c) Optical microscope image of a fabricated structure, and (d) its measured spectrum.



6.1 Collective Oscillations in Photonic Crystal Surface Emitting Laser

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Abstract – We report diverse and exotic collective behaviours in two-dimensional photonic crystal slabs, potentially opening pathways to a new class of photonic crystal surface-emitting lasers (PCSELs). These lasers exhibit unconventional radiative patterns, suggesting unexplored opportunities in photonic device engineering and light manipulation at the nanoscale.

I. Introduction-Collective oscillation describes a group of individual resonances acting together as a unified mode, exhibiting behaviours distinct from isolated resonances. As an example, consider the guided resonances in photonic crystal (PhC) slabs, where inter-mode coupling in momentum space gives rise to collective oscillations in real space. By tuning the crystal geometry and guided mode dispersion, we can engineer unusual near- and far-field patterns in PCSELs. For instance, chiral emission happens from single-mode lasing but without any defined optical paths. Our finding offers new ways to manipulate light through collective effects, advancing both fundamental understanding and applications in sensing, control, and optical communications.

II. Methods and Results

Specifically, we consider a round-shaped finite-sized PhC slab. This non-uniform boundary would alter the propagation directions of Bloch waves and hybridize them, giving rise to the collective oscillation named collective guided resonances (CGRs). To keep the harmonic stability, all the Bloch modes participating in the coupling can have different in-plane momenta, but must possess the same frequency. As a result, their locations in momentum space must align with an existed iso-frequency counter. Here, since we consider an isotropic circularly-shaped boundary, all Bloch modes upon the quasi-isotropic iso-frequency counter can hybridize together, giving rise to the omnidirectional mixing. Under this omnidirectional mixing, a pair of degenerate CGRs with opposite orbital angular momentum (OAM) emerge, having helical motions in real space and giving rise to the phase vortex in the radiation [1].

Based on the chiral CGR, PCSELs with chiral emission can be demonstrated accordingly. Here we build a PCSEL in III-V/Si heterogeneous platform [2], gaining the benefits of superior luminescent properties of III-V materials as well as the CMOS compatibility and scalability of silicon. The PhC cavity is fabricated on silicon-on-insulator (SOI) substrate with high quality, and a III-V epitaxy is directly bound to it to provide the optical gain. A round-shaped carrier confinement region is defined to act as the circular boundary and induce the collective oscillation. Further, two defects are added to the confinement region to morph the asymmetric gain profile and introduce the non-Hermitian coupling between the degenerate chiral CGRs. As a result, a stable single-mode chiral lasing is achieved without any pre-defined light path, shown in Fig. 1. Our findings offer new ways to manipulate the emission properties of PCSELs, broadening its application scope, advancing both fundamental understanding and applications in sensing, control, and optical communications.

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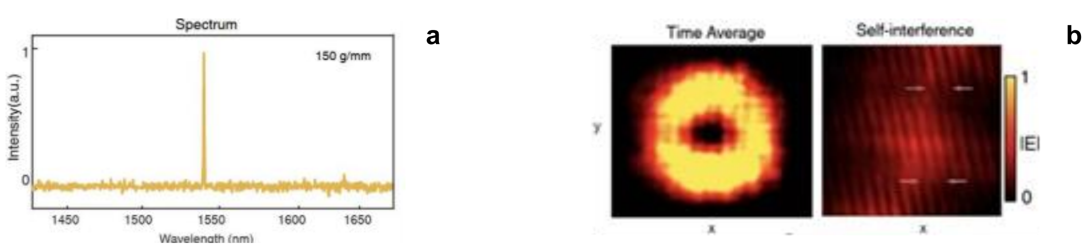

Figure 1. PCSEL with chiral emission based on collective oscillation. (a) Single-mode lasing spectrum of the proposed PCSEL. (b) Near-field image of the lasing pattern and self-interference pattern of the lasing beam. Forks pattern in self-interference frame indicates the chiral lasing.

6.2 High-Efficiency PCSELs for Next-Generation Photonic Communication Systems

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Abstract – PCSELs combine surface emission, scalability, and high beam quality, achieving record power and linewidth. They are emerging as high-power light sources for FSO and datacom systems. Competing with established lasers requires major specification gains. This talk reviews recent progress towards commercialisation and presents our latest InP-based multi-wavelength PCSEL 2D array using advanced multi-lattice designs for scalable, efficient optical interconnects.

I. Introduction-PCSELs combine the beam quality of surface-emitting devices with the power scalability of broad-area lasers, creating a unique platform for high-power coherent light sources. Their 2D photonic crystal resonator enables both single-mode operation over large apertures and flexible wavelength engineering through lattice design.

Recent breakthroughs, including GaAs-based PCSELs exceeding 50W CW and InP-based devices achieving 700mW CW at 1.3 µm with >25% Wall plug Efficiency (WPE) [1,2]; highlighting the rapid progress and the strong potential of PCSELs for industrial, free-space, and communication systems. Furthermore, the orthogonality between optical feedback and emission direction in PCSELs provides unique design degrees of freedom, enabling novel functionalities such as engineered beam profiles and tuneable beam steering.

As a relatively new technology, PCSELs are progressing rapidly through the hype cycle of innovation (Fig. 1 a). Following their early academic introduction many impressive demonstrations have shown the flexibility in the design and material platform. The field is currently transitioning towards optimisation characterised by significant improvement in efficiency, manufacturability and integration readiness.

Historically, communication industry has been the engine of innovation in semiconductor photonics. The demand for faster, cheaper, and more efficient links has successively driven the developments of DFBs, VCSELs and EMLs. Continued improvements in PCSEL WPE could allow it to challenge more established laser technologies in communication applications.

Now, with the explosive growth of AI/ML workloads, data centres are evolving into large scale AI factories, where bandwidth and energy efficiency have become critical bottlenecks [3]. This new era is redefining the requirements for light source engines: high power, multi-wavelength scalability and compatibility with co-packaged optics (CPO) and optical I/O (OIO). Within this context, the unique attributes of PCSELs could offer an attractive solution combining surface emission and scalability while remaining compatible with 3D packaging.

To try and address the new light source engine requirements, we will explore and demonstrate a multi-wavelength InP-based PCSEL platform achieving precise wavelength control, excellent channel power flatness, and high efficiency. Figure 1 (b) & (c) shows CW operation of a quad-PCSEL device emitting four distinct wavelengths simultaneously, each delivering 90 mW output power and having >60 dB SMSR. These initial results illustrate the strong potential of multi-wavelength PCSELs as a scalable, energy-efficient light source for future CPO and OIO architectures.

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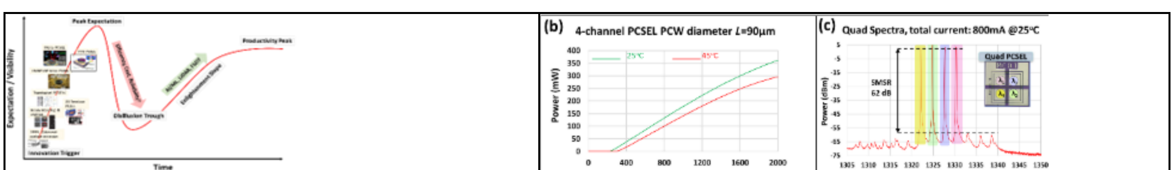

Figure 1. (a) The PCSEL hype cycle b) CW LIV curves of Quad PCSEL chip operating at RT and 45C. (c) RT emission spectral of Quad PCSEL.

6.3 Coherence in Passively Coupled Coherent PCSEL Arrays

Chuanhao Nie[1], Mingsen Pan[1], Yudong Chen[1], Ming Zhou[2], Chhabindra Gautam[3], Hyemin Jung[1], Thomas Rotter[4], Shanhui Fan[2], Ganesh Balakrishnan[4] and Weidong Zhou[1,*]
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Abstract – This report investigates the coherence in beam combining of a passively coupled PCSEL array composed of identical individual emitters. To evaluate the optical phase locking in the array, an imaging setup was used to filter the laser beam. Coherent beam is observed with enhanced power output between neighbouring two emitters.

I. Introduction- Photonic-crystal surface-emitting laser (PCSEL) is a new type of semiconductor lasers that enables surface-emitting of laser beams with high-power single-mode operation over a broad area. Remarkable achievement has been made: continuous-wave (CW) operation PCSEL devices with 50 W of output power has been achieved from a 3 mm by 3 mm emitting area [1]. Owing to its unique structures, the optical modes in a PCSEL cavity can be controlled laterally by modulating its waveguide properties. In recent years, investigations of the cavity modes modulated by lateral boundaries are carried out. Lateral designs of PCSEL cavities have been investigated for enhancing cavity mode confinement [2], size scaling [3], and coupling control [4]. We demonstrated coherent PCSEL arrays can be accomplished by passive coupling of cavities when they are placed closely [5]. Here, to further investigate the coherence between emitters, we fabricated PCSEL array devices with different numbers of individual emitters and characterized the optical beam properties of selected emitters. An enhanced laser power output and far-field coherence were observed. The results show phase-locking PCSELs can be implemented in multi-emitter arrays.

II. Methods and Results- The PCSEL array devices are fabricated with GaAs-based epitaxial growth, with lattice design the same as Ref. [5]. Figure 1 shows the experimental characterization setup and results of the PCSEL array containing 5 closely packed emitters, with effective current injection area of 270 um diameter, and total emission power of 2.7 W at 5 A (pulse operation: 1μs width and 1% duty cycle). A pin hole was used to select the light emitted from site #2 and #4 for laser testing. A boost of laser output efficiency was found for the emitters at about 2.6 A (Figure 1c). A coherency testing of the output beam from laser #2 and #4 was carried out by the interferometer setup, and visible fringes appeared at 3A (Figure 1e). In summary, we found the coherent operation of selected emitters from a PCSEL array by characterization of LI, spectrum and far-field self-interference. The results offer us insights on how the PCSEL array performances scales with the size/number of individual emitters. Our future work will focus on the relation of phase locking and array performances, as scaling into larger arrays. **The work is supported by US JDETO/ARO W911NF2410005.**

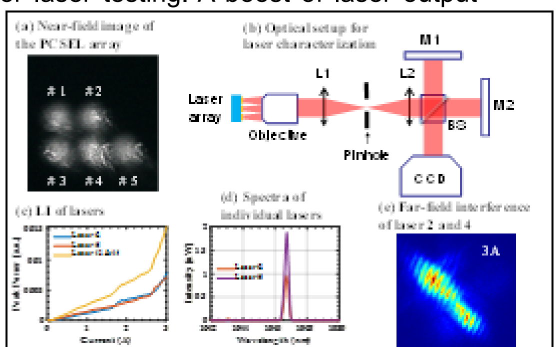

Figure 1. Optical characterization of coherency of laser beams from PCSEL array. (a) Near-field electroluminescence image of a PCSEL array with 5 passively coupled emitters. (b) Optical characterization of laser beam for coherence testing. (c, d) Power (c) and spectra (d) analysis of laser #2 and #4. (e) Self-interference pattern of laser #2 and #4 at 3A current injection.

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6.4 Breaking Symmetry in Triangular Lattice PCSELs: Coupled Wave Theory Analysis

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Abstract – Breaking the symmetry of the square lattice photonic crystal (PC) unit cell was a key advancement in achieving single-mode high-power PCSELs. We discuss symmetry breaking in triangular lattice PCSELs through use of the 3D Coupled Wave Theory (CWT).

I. Introduction

The first PCSELs were achieved using a triangular lattice PC in 1999 [1]. Since then, the majority of PCSEL research has utilised square lattice PCs with TE-polarised modes and a large index-contrast provided by air/semiconductor contrast. Using this route, single-mode higher power lasing has been achieved [2]. The first such Watt class single mode device was demonstrated in 2014 [3], facilitated by breaking the symmetry of the electromagnetic modes with a right-angle triangle unit cell and vertical asymmetry. Triangular lattices allow for direct 2D coupling of TE waves, which is forbidden in square lattices, but suffer from additional competing band-edge modes. If this competition can be overcome the triangular lattice may provide a platform for high-power single-mode PCSELs.

II. Methods and Results

This report explores strategies for symmetry breaking for a triangular lattice using 3D CWT[4]. For example, a triangular air hole PC unit cell is shown in Fig. 1(a). Fig 1(b) plots its corresponding Fourier transform components. The resultant photonic band-structure, Fig. 1(c), radiation constants, Fig 1(d), and(e) are then determined. The asymmetry of this unit cell is evident in Fig. 1(b). The band edges shown in Fig. 1(e) are observed to possess non-zero and distinct radiative constant at Γ which could enable efficient single-mode lasing. In contrast circular unit cells exhibit 4 degenerate modes of zero radiative constant due to the high symmetry. We will discuss the engineering of PC atom shape and finite device size effects. We discuss opportunities for high performance single mode lasing by returning to the triangular lattice, enhancing the scope of PCSEL applications.

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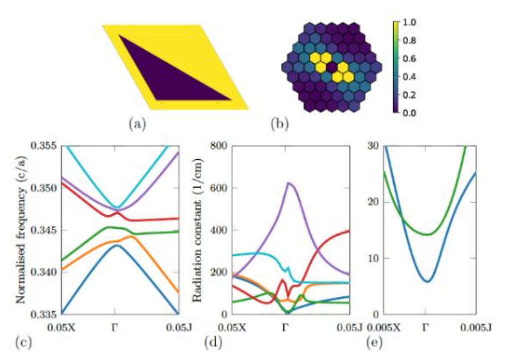

Figure 1: Triangular lattice unit cell (a) and corresponding Fourier transform (b). Photonic band-structure across $X-\Gamma-J$ with frequency components (c) and radiation constant (d). Lowest radiation constant modes at Γ point showing finite and non-degenerate values (e).

7.1 Photonic Crystal Slow-Light Modulator Toward Co-Packaged Optics

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Abstract – Slow-light modulator exploiting photonic crystal waveguides allows high speed, compact size, and low power consumption suitable for co-packaged optics. We give an overview of its principle, development, and recent performance up to 64 Gbps.

A compact Si photonic crystal slow-light Mach-Zehnder modulator [1-4] and open collector driver amplifier dramatically improve the performance of optical transmitter. The length of the modulator was shortened to less than 200 mm and its driving voltage was reduced to up to 0.87 V for 64 Gbps modulation, thanks to the slow-light effect in the photonic crystal phase shifter and the electro-optic phase matching in RF delay line electrodes. The power consumption, which is dominated by that at termination resistors, can be reduced due to the increase in inductance and larger termination registers under impedance matching condition. As a result, the power consumption of the modulator was reduced to 3.8 mW, corresponding to a bit energy of 59 fJ/bit [3]. The transmitter power consumption can also be reduced by removing the load resister between the modulator and the driver amplifier and maintaining the frequency response by electrooptic co-design [5]. The driver amplifier was fabricated in a BiCMOS process and hybrid-integrated with the modulator, achieving a total power consumption of 50 mW and 0.78 pJ/bit [6]. 100 Gbps class operation will also be available [7].

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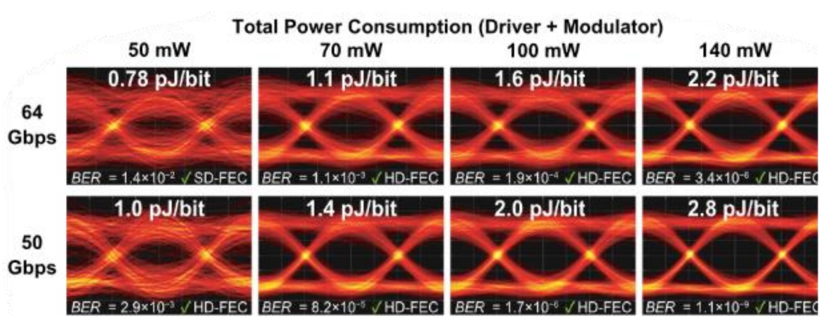

Fig. 1 Development of optical transmitter including modulator and driver amplifier. (a), (b) Hybrid integration of Si photonic crystal slow-light modulator chip and BiCMOS driver amplifier chip. (c) EO co-simulator based on Keysight ADS with in-house Verilog-A photonic device model library. (d) Eye patterns of light output, satisfying a bit error rate below the threshold of hard or soft forward error correction.

7.2 Spatial and frequency dispersion engineering for optical information detection and processing

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Abstract

Light carries rich and multidimensional information, including intensity, polarization, wavelength, and spatial distribution. The ability to detect and process this information is of both fundamental scientific interest and technological significance. In this talk, I will present our recent progress in exploiting spatial and frequency dispersion in photonic systems to achieve compact and multifunctional optical information processing. First, I will discuss how spatial dispersion (nonlocality), in conjunction with frequency dispersion, can be harnessed to realize single-shot detection of light intensity, polarization, and wavelength using simple planar optical interfaces. This approach addresses challenges faced by conventional methods that rely on complex spatial or temporal integration of polarization- or wavelength-sensitive components. Pathways toward full-Stokes polarization and broadband spectral detection will also be outlined. Second, I will describe how introducing a spatial band-pass filter in momentum space enables size-selective image processing, including edge detection and real-time dynamic denoising. Such functionality can be implemented using a simple metal–dielectric–metal architecture, offering a promising route toward ultra-compact, cost-effective, and multifunctional optical image processors.

7.3 Semiconductor-based Topological Photonic Crystal Waveguides

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Abstract – We discuss semiconductor valley photonic crystal (VPhC) waveguides supporting topologically protected edge states. Using an interface configuration, known as a bearded interface, we realize a slow-light topological mode and demonstrate strongly reduced bending losses compared with a non-topological mode. We also introduce VPhC heterostructure structures, functioning as large-mode-area single-mode waveguides.

Topological photonics [1,2] has attracted significant attention not only for its fundamental interest but also for its potential applications. Incorporating the concept of band topology into photonic systems enables the realization of a variety of topological states of light. Photonic crystals (PhCs) serve as one of the most important platforms for such studies. A hallmark of topological photonics is the appearance of topologically protected edge states. Optical waveguides leveraging photonic topological edge states enable robust light transport even in the presence of certain types of disorders including sharp bends. Among the structures that realize such topological waveguides, valley photonic crystals (VPhCs) [3] have been widely investigated owing to their straightforward implementation. The edge states at the interface of two topologically distinct VPhCs, known as valley kink states, enable efficient light guiding even around sharp corners, making them highly attractive for integrated photonics [4].

In this presentation, we will briefly introduce VPhC waveguides and discuss their use as slow-light waveguides. By employing a bearded interface, which is one of the interface structures hosting valley kink states, we can realize valley kink states with reduced group velocity [5]. In such VPhC waveguides, both topological and non-topological slow-light modes coexist, allowing direct comparison of their bending losses within a single device. Our experiments confirm that losses at sharp bends are significantly suppressed for the topological slow-light mode compared with the non-topological one [6]. We further discuss VPhC heterostructure waveguides composed of two topologically distinct VPhCs sandwiching a photonic graphene, which enable the realization of single-mode optical waveguides with a large mode area. Our recent theoretical and experimental studies on semiconductor VPhC heterostructure waveguides, including their application to slow-light waveguides [7.8] will be introduced.

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7.4 Integration of Silicon Photonic Crystal Cavities on Multi-Core Optical Fibre

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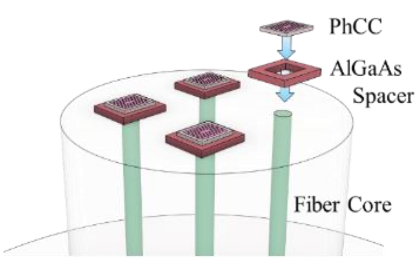
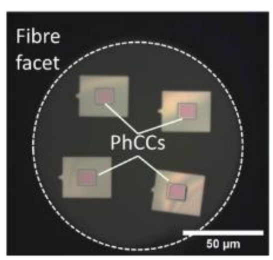
Abstract – We present the integration of silicon photonic crystal cavity devices directly on the tip of multi-core optical fibre with cavity suspension achieved through a 2-stage transfer-printing process. Spatially resolved thermal measurement of the individual cavities is achieved in reflection mode, demonstrating the potential of the system for compact probe applications.

I. Introduction- The compact form factor of optical fibre probes and their compatibility with direct optical measurement through low loss fibre connections have made such devices attractive solutions for remote sensing of temperature, mechanical deformation, pressure and refractive index [1]. Sensitivity and spatial resolution of fibre sensors can be enhanced by integrating high refractive index elements onto the fibre tip, for example, photonic crystal cavities (PhCCs) [2]. In this work we present a method by which compact PhCCs can be directly integrated onto optical fibre tips, whilst maintaining the strong optical confinement of air cladding on either side of the device. Furthermore, we demonstrate the integration of multiple PhCCs on a 4-core optical fibre, and individual measurement of temperature from each device.

II. Methods and Results

The silicon PhCC devices are first transferred from their native SOI wafer onto a spacer element, fabricated in AlGaAs material, using high-accuracy transfer printing [3]. The silicon cavity is suspended over an air gap in the AlGaAs spacer, allowing for high optical confinement in the vertical dimension, and maintaining Q-factors in the 10^5 range. The AlGaAs spacer and silicon PhCC are then transfer-printed together onto the optical fibre core, Fig 1, where alignment is achieved using real-time monitoring of the transmitted signal through the PhCC. Scanning laser measurements through the fibre cores are taken to measure the PhCC resonances in the 1550nm wavelength range, an example of which is shown in Fig.1(c). The thermal response of the devices was characterized, showing the expected thermo-optic shift of the cavity resonances, dependent on the local thermal environment, with spatial resolution provided by the inter-core distances.





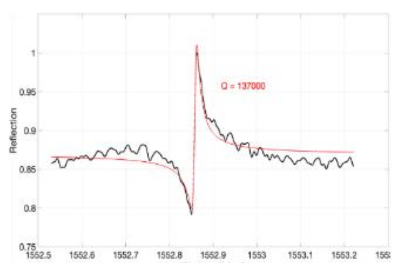


Fig.1 (a) Schematic and (b) Microscope image of PhCCs integrated on multi-core fibre, (c) PhCC reflectivity spectrum.

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7.5 Independently tunable emitters chirally coupled to a chiral photonic crystal waveguide

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Abstract – We present independent Stark tuning of waveguide-coupled emitters through resistive ion implantation, enabling independent tuning of chirally-coupled emitters in an on-chip photonics crystal (PhC) waveguide. We demonstrate the ability to tune different spin states of the emitters into resonance, and explore the interactions between different states.

I. Introduction

Chiral interfaces are nanophotonic devices that couple the different spin states of a quantum emitter to different propagating directions in a waveguide. These interfaces offer the potential for spin transfer, non-reciprocal light-matter interactions, or a cascaded quantum system where information flow is unidirectional. A central challenge in scaling these quantum systems is overcoming the inhomogeneity of different emitters without compromising the performance of the chiral interface.

II. Results

In this work, we use ion implantation to enable separate Stark tuning of the optical transitions in two quantum dots (QDs) coupled to a glide-plane PhC waveguide. We demonstrate independent tuning, allowing the spin states of the QDs to be brought into resonance. These QDs are chirally coupled – meaning that each spin state couples to either the left or right propagating direction in the waveguide. Photon correlation measurements reveal an interaction between states that are coupled to the same propagating direction, while the states coupled to opposite propagating directions do not interact.

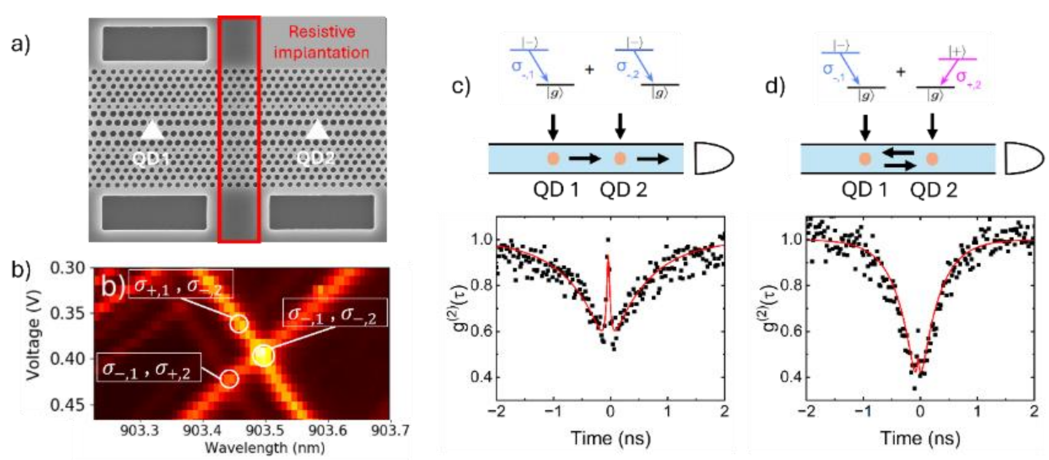

Fig.1 (a) Ion implantation is used to isolate separate areas of a chiral glide-plane photonic crystal waveguide. (b) Stark tuning is used to bring the different spin states of two quantum dots into resonance. (c, d) Diagrams and HBT measurements of the emission from two resonant states coupled to (c) the same propagating direction or (d) opposite directions.

8.1 Dynamic control of photonic-crystal surface-emitting lasers toward satellite communications

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Abstract – Photonic-crystal surface-emitting lasers (PCSELs) have various unique features such as high power, lens-free narrow divergence, and narrow linewidths, which are potentially suitable for optical transmitters in long-distance free-space optical (FSO) communications including satellite communications. In this talk, we review our recent demonstration of dynamic control of PCSELs and their application to high-power FSO communications.

I. Introduction- In recent years, the application of high-power lasers to free-space optical (FSO) communications including satellite communications has been rapidly expanding, where the transmission of optical signals over a long distance (>1000 km) are demanded. Conventional transmitters require various bulky optical components such as optical amplifiers, modulators, optical fibres, and lenses, because conventional semiconductor lasers cannot afford high-power operation while maintaining single-mode lasing. On the other hand, PCSELs can realize high-power single-mode operation with narrow divergence and narrow spectral linewidths [1,2], which are potentially applicable for compact and high-efficiency FSO transmitters as shown in Fig. 1. In this talk, we review our recent results on dynamic control of PCSELs and their application to high-power high-speed FSO communications.

II. Results- We first numerically and experimentally investigate the modulation bandwidth of PCSELs, and demonstrate that watt-class operation with a direct bandwidth of > 3GHz is feasible [3]. By employing the above high-power and high-speed PCSEL to FSO communications with quadrature amplitude modulation (QAM), we demonstrate the transmission of 256 QAM signals at 2 Gbaud, without using a fibre amplifier nor a transmission lens. We also investigate the method to further increase the modulation bandwidth via photon-photon resonance, and experimentally demonstrate a watt-class operation with a direct bandwidth of > 10 GHz [4].

To further improve the signal-to-noise ratio of FSO communications, we also investigate the application of PCSELs to coherent FSO communications [5]. For this purpose, we propose two-section PCSELs that incorporate two photonic crystals with slightly different lattice constants into the gain section [6]. By injecting anti-phase modulation current with the same amount of bias current into the two sections, we successfully generate watt-class frequency-modulated (FM) signals with suppressed AM. Then, by employing the FM PCSEL as a coherent FSO transmitter, we demonstrate a Gbps-class signal transmission even when the laser power is attenuated by more than 80 dB. Such a large laser power attenuation corresponds to the link loss in satellite communications, and thus our directly modulated PCSELs are potentially suitable for compact FSO transmitter for satellite communications in the future.

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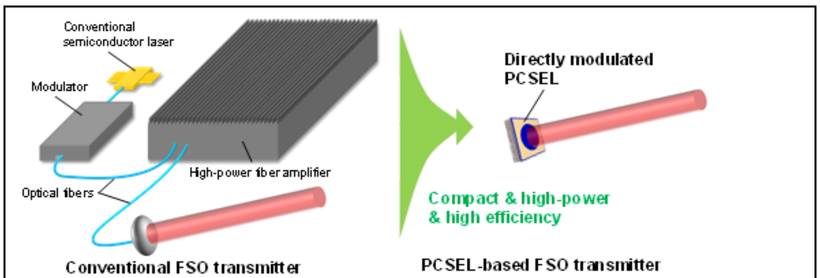

Figure 1. Concept of PCSEL-based high-power free-space optical (FSO) transmitter.

8.2 Progress in High-power InP-based Double-lattice PCSELs

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Abstract –Our InP-based PCSELs exhibit stable single-mode lasing with output power over 700 mW at 25°C, utilizing core technologies such as double-lattice photonic crystals, metal mirrors, and in-plane heterostructures.

I. Introduction- Photonic-crystal surface-emitting lasers (PCSELs) are attracting attention as next-generation light sources enabling single-mode operation with high output power. In particular, operating wavelengths at 1.3 μm and 1.55 μm are important for optical communication and sensing applications. The high output power of over 50 W with single-mode lasing has already been demonstrated in the 940 nm wavelength using GaAs-based PCSELs[1]. In our group, these technologies have been extended to InP-based PCSELs operating at the wavelengths of 1.3 μm and 1.55 μm. PCSELs utilize a two-dimensional photonic crystal (PC) formed near the active region, and the two-dimensional broad-area cavity in the PC leads to high output power, narrow beam emission, and single-mode lasing with a narrow linewidth[1]. In this workshop, we introduce the core technologies for the design and fabrication of InP-based PCSELs, specifically, double-lattice PCs[2, 3], a metal mirror[2], and an in-plane hetero structure[3], which have led to both high output power and high slope efficiency. We also report on the device performance achieved at both 1.3 μm[2] and 1.5 μm[3] wavelengths.

II. Device structure and laser characteristics - Figure 1 (a) illustrates the device structure of a 1.3 μm-wavelength PCSEL. The details of the fabrication process have been described in reference [2]. Our PCSEL incorporates the double-lattice PC structure to enhance surface emission efficiency by the asymmetry of a PC structure. By introducing a metal mirror and adjusting the phase of the reflected light through the thickness of the p-InP cladding layer, we achieved twice the output power compared to devices without a mirror. The mirror also serves as a current injection electrode, with a diameter of 200 mm. In addition, an in-plane hetero structure is introduced to suppress lateral light leakage due to the distribution of the refractive index caused by self-heating under continuous-wave (CW) operation. By slightly reducing the size of air holes near the device periphery for its compensation, the photonic band-edge frequency is lowered, thereby enhancing in-plane optical confinement. As a result, output power improves at high current injection by reducing in-plane optical losses [4]. This in-plane hetero structure brings about an increase of approximately 30% in output power. Figure 1 (b) shows the light–current–voltage (*L*–*I*–*V*) characteristics of the fabricated 1.3 μm-wavelength PCSEL. The maximum output powers of 700 mW at 25°C and 430 mW at 50°C are achieved, with corresponding the wall-plug efficiencies of 27% and 19%, respectively. The far-field pattern (FFP) at 2 A and 25°C reveals a circular beam with a narrow divergence angle of 0.75°. Figure 1 (c) presents the lasing spectra at maximum output power for various temperatures, demonstrating stable single-mode lasing with a high side-mode suppression ratio (SMSR) exceeding 70 dB across all temperatures.

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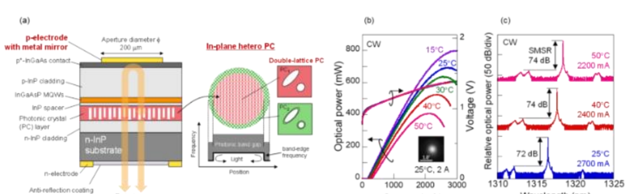

Fig. 1. (a) Schematic of InP-based PCSELs. (b) *L-I-V* characteristics with FFP and (c) lasing spectra under CW operation.

8.3 Progress in development of the GaSb-based PCSELs.

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Abstract – The GaSb-based PCSELs operate within a spectral range of 2 to 3 µm. The brightness of these devices is limited by the excitation of higher order modes, resulting in a cross-shaped far field pattern. The design of buried photonic crystal unit cells intended to suppress multimode lasing will be discussed.

I. Introduction -We have developed an air-pocket retaining epitaxial regrowth technology within antimonide material system. Highly uniform regrowth over nanopatterned surface resulting in perfectly uniform and well controlled shapes of the buried voids was achieved (Figure 1). Using this technology, we were able to fabricate diode and cascade diode PCSELs operating in 2 – 3 µm spectral range. The first continuous wave (CW) room temperature operation of the monolithic epitaxially regrown III-V-Sb PCSELs emitting near 2 µm was reported in year 2023 [1] and the corresponding device power, efficiency and beam quality were enhanced in the year 2024 [2] following implementation of multiple-void unit cell design. However, the devices demonstrate multimode far field patters even for 200 µm diameter shallow mesa design.

II. Methods and Results -The increase in the number of voids within the unit cell of the buried photonic crystal has contributed to improved outcoupling efficiency and output power of GaSb-based PCSELs. We implemented multiple-void unit cell designs inspired by the dual-void design strategy developed by the Kyoto University group, which led to devices producing hundreds of watts of optical power close to 1 µm in nearly diffraction-limited beams [3]. Nevertheless, GaSb-based PCSELs exhibited multimode cross-shaped far-field patterns with intersecting lines oriented along orthogonal X-directions [2]. This phenomenon can be attributed to the excitation of low radiative loss non-zero in-plane wavevector modes linked to the low dispersion band edge (band C in Figure 1). It can be argued that the radiative loss for non-zero in-plane wavevector modes may be increased by fine-tuning the placement and dimensions of individual voids within multiple-void unit cells. For instance, the three-void unit cell design (Figure 1) led to the elimination of multimode lasing in one of the X-directions compared to devices reported in [3]. The devices generate ~100 mW of power in linearly polarized beam broadened in one of X directions.

This work was supported by US Army Research Office, grant W911NF2210068, and in part by the U.S. Department of Energy, Office of Basic Energy Sciences, under Contract DE-SC0012704.

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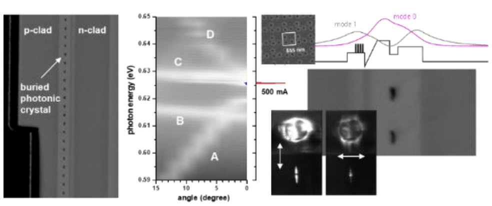

Figure 1. (left) Cross-sectional SEM image of the fully fabricated shallow mesa PCSELs; (middle) Angle resolved electroluminescence intensity map measured in X-direction overlapped with lasing line. (right) Calculated vertical index and mode profiles (top) and polarization resolved near and far field patters.

8.4 Non-Hermitian Dirac theory of topological-cavity surface-emitting laser

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Abstract – We develop the minimal analytical theory for describing the topological-cavity surface-emitting laser (TCSEL). This non-Hermitian Dirac model provides a comprehensive understanding of the mode selection mechanism and lasing performance, that can guide device optimization.

I. Introduction

As the two-dimensional counterpart to the well-established distributed feedback lasers (DFB) and vertical-cavity surface-emitting lasers (VCSEL), TCSEL[1] represents a promising way towards high-performance, single-mode semiconductor lasers. However, the common topological theory is Hermitian and neglects the non-Hermitian properties (gain, loss, and radiation), which are indispensable to lasers. To address this, we developed a comprehensive theoretical framework considering both the Hermitian and non-Hermitian properties based on the Dirac equation through three-dimensional coupled-wave theory (3D CWT)[2].

II. Methods and Results

Our model describes the complex physics of the TCSEL with two fundamental coefficients: the Hermitian mass (m) representing the in-plane optical couplings and the non-Hermitian mass (μ) accounting for the out-of-plane couplings. The mode selection mechanism is primarily determined by the parameter m, achieving stable single-mode lasing for scalable device sizes. The overall lasing properties—including the threshold, efficiency, and the far-field radiation pattern—are determined by the interplay between both m and μ. We also predict that the radiation field is a vector beam whose polarization direction is determined by the initial phase of the Dirac mass.

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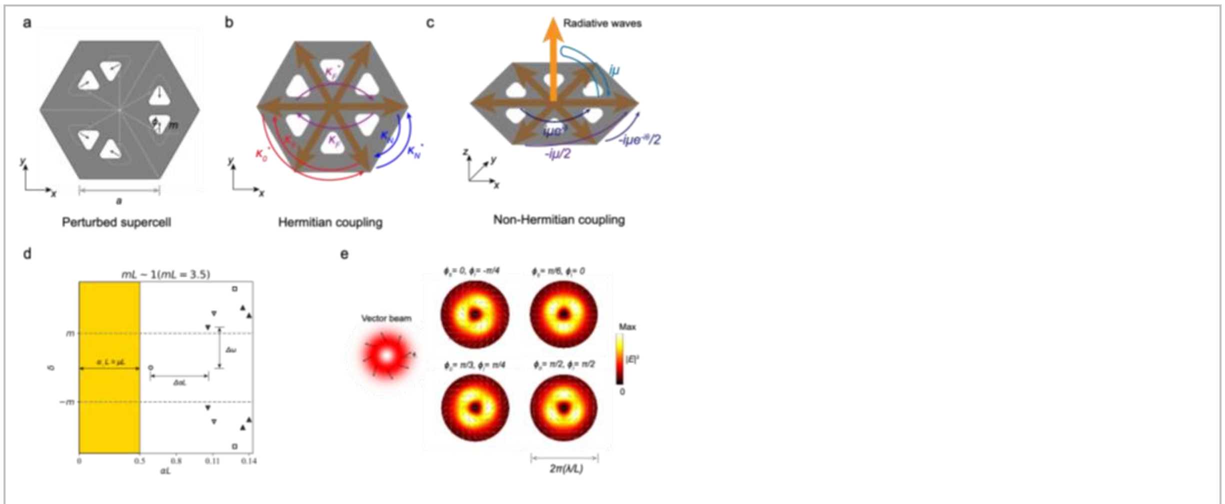

Figure 1. (a) Generalized Kekulé modulation in TCSEL. (b, c) Hermitian and non-Hermitian optical couplings in TCSEL. (d) Mode spectrum when mL=3.5mL=3.5 and μL=0.5μL=0.5 . (e) Polarization control in TCSEL.

9.1 Optofluidic and electrophotonic tunable resonances

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Abstract. We demonstrate the efficient modulation of guide mode resonances via optofluidic control. By exploiting the difference between electronic and ionic carriers, we show a nearly 2p phase shift with an applied voltage of only ±3V.

I. Introduction. The dynamic control of light in photonic nanostructures has been a long-standing challenge in photonics. Researchers have explored electro-optics, nonlinear optics and thermo-optics to address this challenge, but the corresponding refractive index shift has typically been small and/or has required high voltage, high energy, or long interaction lengths. More recently, fluidics has been added to the toolkit, leveraging liquid properties as a new degree of freedom for tunability. Here, we present a tunable architecture that integrates an optofluidic layer with a periodic nanophotonic structure. We use a guided mode resonance (GMR) platform, whereby a silicon nitride grating is coated with indium tin oxide (ITO) as the active material, operating in the NIR wavelength range around 800 nm. Our design employs an all-dielectric structure with a fluidic gate to overcome the efficiency-loss trade-off typical of other dynamic photonic crystals and metasurfaces. We demonstrate spectral and phase tuning, achieving a near-2p phase shift with a low voltage swing of ±3V, as well as maintaining a strong resonance amplitude (R≈80%) with an all-pass filter configuration. In addition, we show the capability of detecting bacterial biofilm growth with high sensitivity, highlighting the versatility of our optofluidic approach – liquid crystals would not be able to accommodate biological media. These results establish optofluidic tunable nanostructures as a basis for broad cross-disciplinary applications [1].

II. Result. The mystery of the much lower Voltage and much lower loss of our structure compared to previously published approaches [2] lies in the proper understanding of the modulation mechanism. Here, the modulation mechanism is based on a combination of charge accumulation in the ITO layer, which is balanced by the ions in the liquid; when applying a voltage, the ions in the liquid accumulate at the electrochemical double layer, while the carriers accumulate in the ITO. All being equal, the accumulation of positive charges on one side of this capacitor would have a very similar but opposite optical effect as the accumulation of negative charges on the other, resulting in a very small overall optical modulation. In our optofluidic case, however, the charge carriers are not the same; the ions in the liquid have a far greater mass than the electrons in the ITO. According to the Drude model, the impact of charge carriers on the permittivity scales as ($\omega_p^2 \propto e^2/m$), so the ions as the heavier charge carriers have a much smaller impact on the refractive index than the electrons. This means that the optical modulation incurred on the (electronic) ITO side of the capacitor is not being opposed by an opposite (ionic) modulation on the other, which explains the strong optical modulation we observe.

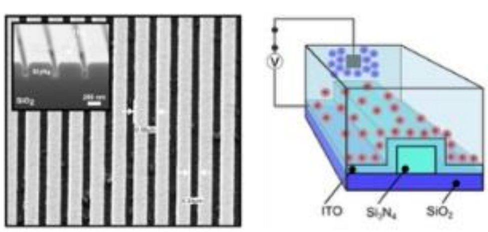

Figure 1. a) Top view and cross-section of the ITO-coated grating supporting an electrically tunable guided mode resonance; b) modulation mechanism exploiting the heavier mass of the ionic charge carriers compared to the electronic charges in the ITO.

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9.2 High-sensitivity Multi-color Imaging Based on Meta-optics

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Abstract – This talk presents color-dispersive optical elements based on metasurface optics (meta-optics) and demonstrates how they create high-sensitivity, multi-color imaging devices. Specifically, the talk outlines our recent work on prototyping meta-optics-based RGB/RGB-NIR image sensors and spectral cameras.

Color imaging devices such as color image sensors and cameras provide vision not only to humans but also to machines, making them indispensable in a variety of modern technology ranging from smartphones to autonomous vehicles. Unfortunately, most of these imaging devices are inevitably limited in their imaging sensitivity because they typically rely on light-absorptive optical filters for color extraction and can detect only a limited portion of the incident light [1]. This limitation becomes more pronounced in multi-color or multi-wavelength imaging devices beyond red-green-blue (RGB), which have been actively developed to meet the growing demand for image analysis based on diverse optical information. For example, in a typical multi-wavelength image sensor based on n different band-pass filters, only $1/n$ of the incident light amount reaches the photodetectors. These challenges have created a fundamental barrier to enhancing imaging sensitivity in today's mainstream imaging devices.

The emergence of dielectric-based metasurface optics (or meta-optics) provides a promising solution to this issue. The recent advances have enabled the creation of ultrathin, light-transmissive, and color-(wavelength-) dispersive optical elements with high functional flexibility, which drives the creation of color imaging devices with completely different architectures from conventional ones. Our recent works have presented the use of meta-optics to create several multi-color imaging devices, including RGB/RGB-near-infrared (NIR) image sensors and spectral cameras (Fig. 1) [2–6]. This talk introduces these devices and demonstrates their great potential for enhancing the sensitivity and functionality of color imaging.

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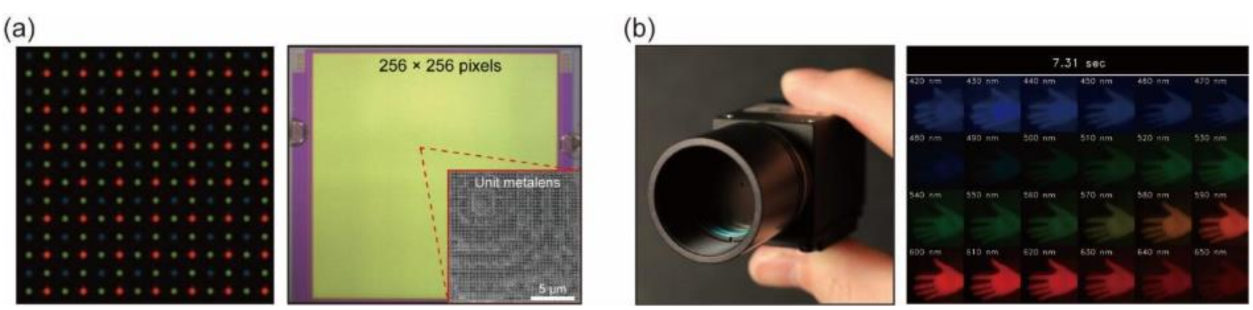

Fig. 1 Multicolor imaging devices based on meta-optics. (a) Prototype image sensor with a color-splitting metalens array. (b) Prototype spectral camera with a computationally optimized metalens.

9.3 Realizing the Anderson localization transition for light in 3D, here attempt nr. 57-d

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Abstract – We discuss experiments to observe the 3D Anderson localization transition of light. As platform we pursue 3D superlattice of cavities in a 3D photonic band gap, where light is forced to hop in "*Cartesian*" directions. By tailoring the disorder, we aim to realize this exciting phase transition for light.

I. Introduction

In 2025, we take it for granted that photonic crystals mold the flow of light by interference. In 1957, it took the genius of Philip Anderson to propose that wave transport is halted by interference when disorder exceeds a threshold [1]. He modeled the transport by a tight-binding Hamiltonian with on-site disorder and discovered a conductance-insulator transition. The *gang of four* found that dimensionality *d* is key, with a transition occurring at *d*=3 [2]. Sajeev John and Anderson then realized that localizing light is an exciting prospect [3].

II. Methods and Results

While John and Anderson jumpstarted our field of nanophotonics, they threw a *curve ball* by proposing to study disordered samples [3]. This led to many experiments – see the tongue-in-cheek in the title - yet 40 years onward, it is realized that disordered samples don't reveal 3D Anderson localization [4]. Following [2], we confine the light to lower dimension while keeping the underlying system 3D. In our study, we revert to Anderson's original model [1], namely a tight-binding Hamiltonian, yet for light [5]. To this end, we use CMOS-compatible means to fabricate 3D superlattices of coupled cavities from silicon that are isolated from the vacuum by a surrounding 3D photonic band gap crystal, see Fig. 1 [6]. Hence, photons are forced to "*hop*" from cavity to cavity (tight-binding) in high-symmetry directions: "*Cartesian light*". The unavoidable variations of cavity resonances play the role of on-site disorder. Today, we discuss experiments, theory, and prospects for future work, including applications. We thank Bart van Tiggelen, Sergey Skipetrov, Julia Costa, Marcel Filoche, Margaux Vrech, Ad Lagendijk, and the COPS Maël, Melissa, Bert, Niels, Timon, Nicole, Geert for pleasant collaborations.

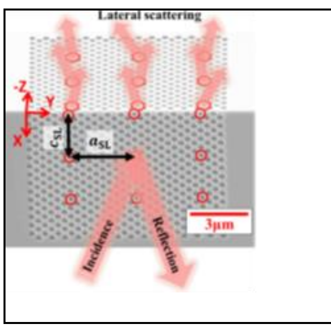

Fig. 1 *Scanning electron micrograph of a 3D cavity superlattice embedded in a silicon 3D photonic band gap crystal [(X, Z) view] with lattice constants a = 0.68 μm (Y direction) and c = 0.48 μm (X, Z directions). The designed pore radius is r = 0.16 μm for the main nanopores and r' = r/2 = 0.08 μm for the defect pores. This superlattice has unit cell dimensions (c_{SL}, a_{SL}, c_{SL}) = (5c, 5a, 5c) [6].*

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9.4 Optical trapping in a photonic crystal hollow cavity for discrimination and status assessment of bacteria and bacteriophages viruses in the context of phage or antibiotics therapies

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Abstract – The development of new faster tools for the discrimination and assessment of the stress status of bacteria and for antimicrobial susceptibility testing are becoming essential for a better use of antibiotics. In parallel, alternative approaches to antibiotics, such as phage therapy, are strongly needed due to the emergence of multi or pan-drug resistant bacteria strains. We will discuss how photonics and in particular optical trapping in hollow photonic crystals cavities can contribute to solve these issues.

Antimicrobial resistance is becoming a major public health concern. This resistance is due to multiple factors such as natural bacterial mutations and natural selection, which are amplified by the excessive and improper use of antibiotics in agronomic and medical practices. Consequently, the development of new tools for the identification, discrimination and assessment of the stress status of bacteria, as well as faster tools for antimicrobial susceptibility testing to antibiotics are becoming essential for a better use of antibiotics; and finally new alternative approaches to antibiotics are strongly needed. Among these alternative approaches, phage therapy, which uses viruses called bacteriophages to cure bacterial infections is a very promising candidate. We will discuss how photonics and in particular optical trapping in hollow photonic crystals cavities can contribute to solve these issues.

The system used is a photonic chip containing hollow photonic crystal cavities topped by a microfluidic system for transporting bacteria and phages. We will discuss the optical signature of bacterial and phage trapping in the transmitted light that excites the optical trap. A detailed analysis of these optical signature makes it possible to discriminate between different phage and bacteria families, as well as the level of stress or death of a bacterium. We will present preliminary results showing how machine learning techniques can improve such analysis.

Antibiotic or phage susceptibility tests are performed with single phages or bacteria trapped in the same optical chips. We will show that they allow to obtain important parameter in the interaction of the bacterium with antibiotics such as the Minimum Inhibitory Concentration (MIC) and the Minimum Bactericidal Concentration (MBC) and discuss the optical signature of the lysis of a single bacterium infected by a phage and corelate these results to biological parameters such the burst size during the phage infection.

9.5 Liposome Sensing with Photonic Crystal Slabs: A Proxy for Extracellular Vesicle Detection

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Abstract – Extracellular vesicles (EVs) have been identified to play a major role in cancer signal pathways. Yet, their diameter distribution of 30 nm to 150 nm renders their detection challenging. We show the label-free detection of 100 nm diameter synthetic liposomes with a photonic crystal slab as an EV detection proxy.

I. Introduction

Extracellular vesicles (EVs) have been shown to play an important role in inter- and intracell communication pathways, particularly in oncogenetic processes. EVs are abundantly found within the human blood. Yet, due to their small size and heterogeneity a separation and detection is challenging [1].

The detection of EVs might be facilitated by the use of label-free optical measuring setups based on photonic crystal slabs (PCS). The binding to an immobilized recognition elements leads to local changes in the refractive index, which can be read out optically. Here, we proxy the EV detection capabilities of a PCS by sensing synthetic biotinylated liposomes with a diameter of 100 nm with an intensity-based camera setup.

II. Methods and Results

The PCS are fabricated by a nanoimprint lithography process and have a period length of 370 nm and groove depth of 45 nm. The surface is functionalized with a silanization and crosslinking process [2]. Streptavidin spots of 100 µg/ml are immobilized. The synthetic DOPC biotinylated liposomes are fabricated at a concentration of 1 mol-% biotinylated lipid and used at a molarity of approximately 16 mM [3]. After binding, the surface is coated in 100 µg/ml streptavidin conjugated with fluorescein isothiocyanate (FITC).

Fig. 1 (a) Logarithmically enhanced difference image after binding. (b) Intensity change at specific regions of interest over time. The baseline is taken with dubelcco's phosphate buffered saline (DPBS). A sodium chloride (NaCl) step is used as a normalization step. (c) Fluorescence image of the left binding spot. (d) Schematic of the photonic crystal surface.

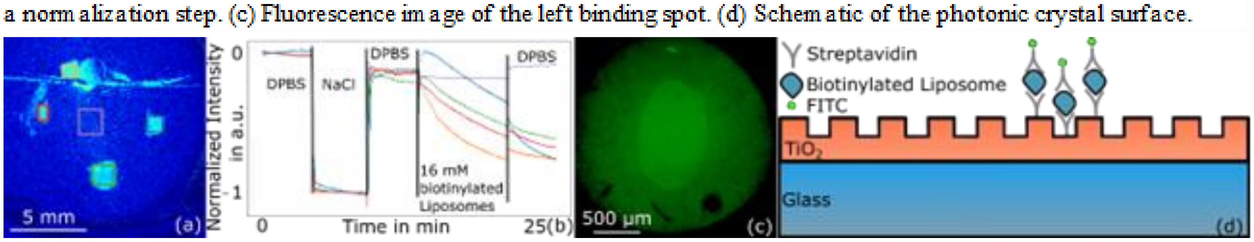

Fig. 1(a) shows the logarithmically enhanced difference images after binding, illustrating distinct binding spots. The temporal shift of the intensity is shown in Fig 1. (b). A clear signal change is visible once the surface is exposed to the biotinylated liposomes. In Fig. 1(c) the exposure to streptavidin FITC of the left spot of Fig. 1(a) after binding is shown. It illustrates that a binding of biotinylated liposomes took place, due to the clear fluorescing spot, induced via streptavidin-FITC. These results showcase the label-free detection of liposomes with a camera-based system. The schematic of the binding is shown in Fig. 1(d). Potentially, this could be used to detect EVs directly from whole blood. Funding via HORIZON-MSCA-2022-DN-01, grant no. 101120186.

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10.1 Triple-lattice Photonic Crystal Surface Emitting Lasers

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Abstract – Triple-lattice structure PCSEL was proposed and demonstrated in the 905nm, 940nm,1.246mm GaAs-based quantum well (QW) and quantum dot (QD) PCSELs, and 1.55mm InP based QW PCSELs.

I. Introduction

Photonic crystal surface-emitting lasers (PCSELs) have recently attracted much attention as novel semiconductor lasers because of the extreme brightness and narrow spectral linewidth. These lasers use two-dimensional photonic-crystal resonators to achieve optical feedback, and light amplification and lasing are realized at the band edge by forming a broad-area standing wave in the lateral direction, with the light extracted from the normal direction by first-order diffraction. Recently, a narrow-divergence far-field pattern was achieved due to the broad-area coherent resonance with a record output power above 50 W [1], which indicates the enormous potential of PCSELs. However, it is difficult for PCSEL to be applied for high-speed direct modulation due to the limitation of large device size and high threshold current. In this work, a triple-lattice photonic crystal structure was proposed to enhance the optical feedback of in-plane for the operation under a short cavity with low threshold current.

II. Methods and Results

Using triple-lattice photonic crystal structure, a three-fold increase in in-plane 180°coupling compared to a normal single-lattice structure was realized and hence the threshold current density decreased. The triple-lattice PCSELs were demonstrated experimentally based on 905 nm, 940 nm InGaAs/GaAs QWs, 1.246mm InAs/GaAs QD and 1.55mm InP based QW material [2-8]. The low threshold current ~ 29 mA was realized in 940nm PCSEL [7], which is comparable with traditional DFB lasers. The continuous wave (CW) operation of 1.246mm InAs/GaAs QD [8] and 1.55mm QW PCSEL were realized with emission power of a few milliwatts. Our structure provides a new strategy for the miniaturization of photonic crystal lasers and will contribute to the development of high-performance PCSELs in the future.

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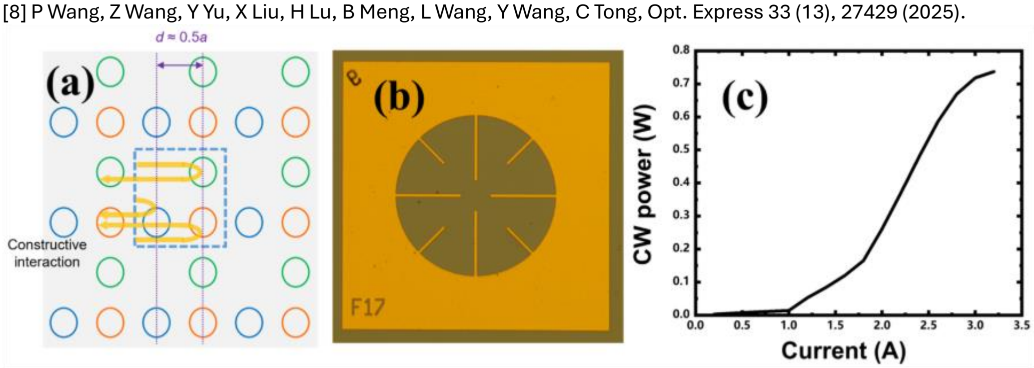

Figure 1. (a) Principle of triple-lattice PCSELs, (b) top-view of PCSEL chip, (c) CW power performance of 940 nm PCSEL fabricated by nano-imprint.

10.2 Photonic Crystal Surface Emitting Lasers over the Entire Visible Spectrum based on Colloidal Nanocrystals

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Abstract – We demonstrate visible-wavelength lasing from colloidal nanocrystal-integrated silicon nitride photonic crystals, with optical excitation. Numerical simulations and Fourier imaging confirm strong agreement between experimental and theoretical photonic band structures in these hybrid, CMOS-compatible systems.

I. Introduction- Silicon nitride (SiN_x) has become a leading material in silicon photonics due to its low propagation losses—down to 1 dB/m[1]—CMOS compatibility, and transparency across the visible to near-infrared spectrum, making it ideal for compact, high-Q photonic devices. However, its indirect bandgap limits on-chip light generation, prompting hybrid integration strategies to incorporate active materials. A promising approach involves solution-processable colloidal nanocrystals (cNCs), which offer size-tunable emission, strong confinement, and compatibility with low-cost deposition methods like spin-coating. Recent work has demonstrated high optical gain and lasing in green and red spectral regions using cNCs deposited on SiN_x photonic crystal (PhC) cavities.[2,3,4] These PhC structures, fabricated in a single etch step, support surface-emitting lasing and allow efficient integration and testing, opening a path toward visible-wavelength on-chip lasers.

II. Methods and Results- In this work, we demonstrate visible-range lasing from hybrid SiN_x photonic crystal devices integrated with two types of colloidal nanocrystals: CdS bulk nanocrystals (BNCs) emitting in the green (~520 nm) and CdS/CdSe/CdS/ZnS quantum shells (QSs) emitting in the red (~660 nm). The CdS BNCs, optically resembling bulk material due to their size,[2] and the QSs, which confine carriers in a core-shell geometry mimicking a curled-up quantum well,[3] both exhibit excellent gain properties. These nanocrystals are deposited via simple spin-coating on SiN_x, illustrating the versatility of solution-based integration. Using finite element simulations, we model the photonic band structure of the low-index contrast SiN_x/NC system, identifying mode symmetries and dispersions, which we experimentally validate through 2D Fourier imaging.[5] The strong agreement between measured and simulated band diagrams confirms the lasing modes and paves the way for scalable fabrication approaches, such as inkjet printing or lithographic patterning, to combine multicolor nanocrystal emitters on a single chip for directional output—ideal for AR/VR/XR applications.

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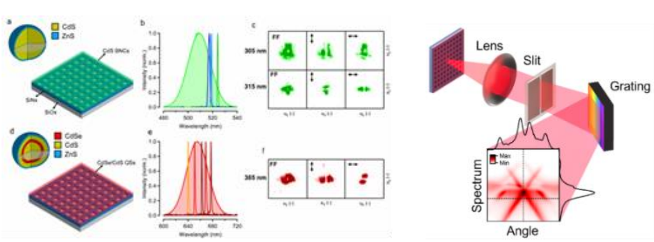

Figure 1. PhC surface emitting lasers based on green– and red emitting cNCs. (a) and (d) show schematics of the materials and devices. (b) and (d) show the normalised PL spectra and lasing peaks for various device periods. (c) and (f) show the (polarised) far fields. On the right, the 2D Fourier Imaging technique is displayed, used to directly measures photonic band structures.

10.3 PCSELs at 1550nm using a heterolattice design

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Abstract – It is experimentally shown that an outer reflecting photonic crystal region can increase the output power and single-moded current range of a PCSEL compared to the case where the photonic crystal configuration is unchanged across the device. In this way, 249mW emission at 1550nm and 25^{o}C was achieved.

I. Introduction

Attributes of photonic crystal surface emitting lasers (PCSELs), such as high power that can scale with area, narrow far-field, and narrow linewidth, make them promising across a range of wavelengths, material systems and applications [1]. To increase the PCSEL slope efficiency - especially as the pumped area decreases - it is important to make the in-plane loss of the photonic crystal (PC) small relative to its out of plane loss associated with the vertical emission. A novel PC design comprising a heterostructure has been proposed, where an outer PC region - intended to laterally reflect light - surrounds a vertically emitting inner PC region [2]. This paper describes some initial experimental results with this type of heterolattice (HL) design.

II. Methods and Results

The fabrication route with an InGaAlAs active layer was similar to a previous report [3], except, to allow the round-trip phase from the PC to the p-metal reflector to be varied, different chips had different p-InP etches, targeting either 0nm, 61nm, 122nm, or 183nm, before the top p-contact layers were grown. In the HL design, the inner PC occupies a 200μm square area - its unit cell is a double lattice design, in which one lattice is shifted both vertically and horizontally by one quarter of its 477nm pitch, and has a 12.6% air fill factor (FF). The surrounding PC continues outwards from the perimeter of the inner PC to fill the remainder a 300μm square area – its unit cell is a single 15.5% FF circular hole with half the pitch of the inner PC. A benchmark design has the same PC design as the inner PC of the HL, but extends over the same total area of the HL PC. Measured characteristics at 25^{o}C of PCSELs with a p-InP etch step of 0nm, 300μm square area PCs, and circular 200μm diameter p-contact windows, are presented in Fig. 1. For the HL design, powers of 249mW and 145mW were achieved at 25^{o}C and 55^{o}C respectively; the SMSR at 2.5A was >65dB at 25^{o}C and 55^{o}C.

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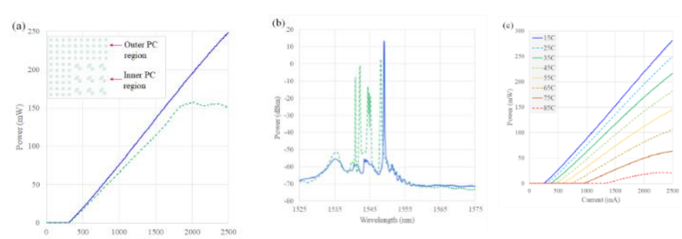

Fig.1 (a) Comparison of continuous wave LI characteristics with HL (solid line) and without HL (dashed line) with inset schematic of part of HL PC design (b) Comparison of spectra at 2A with HL (solid line) and without HL (dashed line), (c) DC characteristics over temperature.

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10.4 Dynamic simulations of single-mode lasing in large emission area all-semiconductor PCSELs

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Abstract – We theoretically analyze single-lattice, all-semiconductor PCSELs. Properly designed PC features suppress 1D field coupling and widen the cold-cavity gain gap between the main modes, enabling single-mode lasing in large-area (>1mm²) devices.

I. Introduction

Photonic crystal (PC) surface-emitting lasers (SELs) are designed for single-mode operation and narrow far-field emission. The best PCSELs currently use dual-lattice PCs with air voids in the semiconductor layer [1]. While these PCSELs can demonstrate lasing of several tens of Watts from a single device, they have a considerably lower efficiency than the best edge-emitting lasers and are intensely challenging to manufacture. The use of all-semiconductor PC layers could enable higher efficiency and improved manufacturability.

II. Methods and Results

We investigate the potential of using GaAs PC layers with InGaP features. In simulations, we use a 3D coupled wave model [2] similar to the one introduced in [3]. Since the refractive index contrast in all-semiconductor PC layers is much weaker than that of conventional air-void PC layers, we must consider PCSELs with 1mm² and larger PC areas to achieve sufficient field coupling and lasing threshold. To increase overall field coupling and simplify manufacturing, we aim for relatively large, well-separated features. We have found that special stretched isosceles triangular (SIT) features with a base angle of

tan−13≈71.5°tan−13≈71.5°

and a base of [Equation] ([Equation]: lattice constant) fully suppress 1D coupling induced by direct interaction of counterpropagating fields ([Equation]). This is similar to the action of perfectly symmetric feature pairs shifted by [Equation] from each other along the PC cell's diagonal in dual-lattice PCs. In [4], we demonstrated that once the shape of the features closely resembles that of the special SIT, one can reduce 1D coupling and increase the gain gap between the fundamental and first higher-order modes in finite-size, cold-cavity PCSELs. Here, building on our work in [2], we show that, even though the gain gap in hot PCSELs is reduced, we can still have single-mode lasing. Figure 1 shows typical multimode lasing in the PCSEL with right isosceles triangular (RIT) PC features and single-mode operation in the equivalent SIT-PCSEL.

This work was part of the project "PCSELence" (K487/2022), funded by the German Leibniz Association.

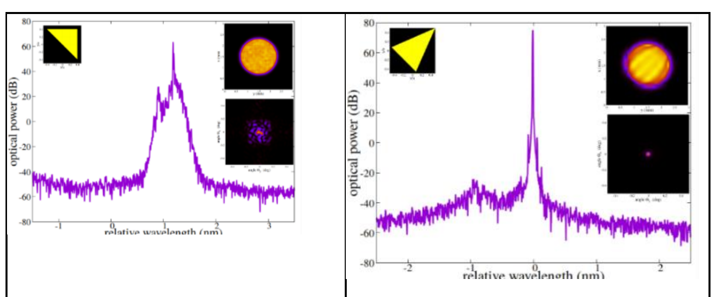

Figure 1. Left and right: calculated optical spectra of well above threshold operating RIT- and SIT-PCSELs. Insets: PC feature's geometry (left), time averaged near- (top right) and instant far-fields (bottom right).

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10.5 Compact InP nanowire photonic crystal surface emitting lasers

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Abstract – The lasing characteristics of compact InP nanowire hetero- and small area photonic crystal surface emitting lasers (PCSELs) have been investigated. PCSELs with lasing areas smaller than the pump focus area but exceeding a certain critical size showed a reduced threshold gain compared to large area PCSELs.

I. Introduction- Rising internet traffic and increasing energy demands of data centers are driving the need for high-performance, energy-efficient integrated circuits. A promising evolution in information technology involves merging silicon-on-insulator (SOI) electronics with photonic components to form hybrid platforms [1]. PCSELs have the potential to meet the size demands for on-chip coherent light sources in emerging photonic integrated circuits. Recently, we reported on Γ-point edge lasing from hexagonal InP nanowire (NW) PCSELs [2, 3]. These arrays are fabricated via selective area epitaxy on InP substrates. A key advantage of this bottom-up synthesis method is the formation of nanostructures with atomically smooth crystal facets minimizing non-radiative recombination and scattering losses. Here, we demonstrate Γ-point edge lasing from InP NW hetero-PCSELs consisting of a hexagonally shaped inner lasing array surrounded by a non-lasing photonic crystal area, as well as from compact NW PCSELs with hexagonal array side lengths of only a few micrometers.

II. Methods and Results- The hetero- and small area PCSELs were designed using finite-difference time domain (FDTD) simulations like those described in [2, 3]. For a pitch of 500 nm and a NW length of 1 µm, the simulations for dipole allowed TE polarized light resulted in a slow Bloch mode (SBM) at the Γ point at a wavelength of ~840 nm for a NW apothem of 93 nm which is close to the electronic bandgap of wurtzite InP at 77 K. For the outer array in hetero-PCSELs, a NW apothem of 97 nm was chosen which has a Γ point edge at 865 nm, lying below the bandgap of wurtzite InP. To characterize the emission from the devices, samples with different inner PCSEL sizes were placed in a temperature variable nitrogen-flow cryostat on a xyz translation stage. Ultrashort ~150 fs laser pulses with a repetition rate of 80 MHz as well as CW) light provided by a Ti-Sapphire laser were used as the excitation source at a wavelength of 735 nm. The laser spot size was measured to be 17 µm in diameter ($1/e^2$ diameter of a Gaussian beam). A detailed description of the experimental setup is given in Refs. [2, 3]. We conducted power-dependent laser experiments at 77 K and elevated temperatures up to room temperature, examining the influence of the PCSEL area under both pulsed and quasi-CW excitation. PCSELs with inner size smaller than the pump beam focus (but exceeding a certain size) exhibited reduced threshold power and threshold gain relative to large-area PCSELs. For these PCSELs the improvements are attributed to an enhanced in-plane reflection at the interface between the inner PCSEL and outer array, where the lasing energy lies in the forbidden photonic bandgap of the outer photonic crystal array. For the small area PCSELs the threshold gain reduction is attributed to an improved back reflection of the laser emission at the PhC array-to-air boundary. Our findings can be extended to other NW material systems and to NW hetero-PCSELs grown on SOI substrates paving the path towards compact low-threshold electrically pumped NW PCSEL designs for photonic integrated circuits.

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10.6 Far-fields of deep-UV PCSEL with shallow and deep-etched photonic crystal

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Abstract – We achieved lasing in optically pumped AlGaN deep-UV PCSEL with shallow and deep-etched photonic crystals. For shallow PC we observe coherent emission at the lasing wavelength from a non-lasing band, caused by scattering. For deep PC, lasing at finite k-vectors (i.e. not at the Γ-point) is caused by cladding modes.

I. Introduction

While first deep-UV LEDs are commercially available, semiconductor lasers in this wavelength range are at their infancy. We demonstrated optically pumped PCSELs at [Equation] and believe that deep-UV PCSELs can provide high efficiency, superior beam quality and low-cost semiconductor lasers, eventually replacing excimer or higher harmonic frequency converted lasers in certain applications. However, the AlGaN material system poses certain challenges and restrictions to the PCSEL optimization.

II. Methods and Results

Deep-UV PCSEL structures based on three quantum wells in an un-doped $Al_{0.70}Ga_{0.30}N$ waveguide with AlN claddings were grown by metal-organic chemical vapor phase epitaxy. The hexagonal photonic crystal (PC) lattice with single holes per unit cell is dry etched into the top AlN waveguide. For shallow-etched PC, the etch depth is 65 nm into a 100 nm-thick top AlN cladding and for the deeply-etched PC, the etch depth is 300 nm into a 320 nm-thick top AlN cladding. For some specific PCSEL parameter set (fill factor, lattice constant, mesa size) we observe the desired doughnut-shaped low-divergent far-field, but for a larger parameter set we observe distorted far-fields. For the shallow etched PC the far-field has dual emission lines over a large angular range when lasing in the A mode. These emission lines have the exact same wavelength as the lasing Γ-point and are caused by light scattering of the lasing A mode into the B_2 band (and possibly B_1 band). For the deep-etched PC we instead observe simultaneous lasing at the ΓΓ-point and at a finite *k* and these have different wavelengths. The finite *k* lasing is believed to be caused by cladding modes, where simulations by guided mode expansion show that forbidden crossings cause regions of vanishing group velocity within the first Brillouin zone which is responsible for these additional lasing modes. Overall, the detailed comparison of experiments on parameter variation series with corresponding simulations allows to identify artefacts which are particular to or pronounced in deep-UV PCSEL, and thus to optimize the deep-UV PCSEL design.

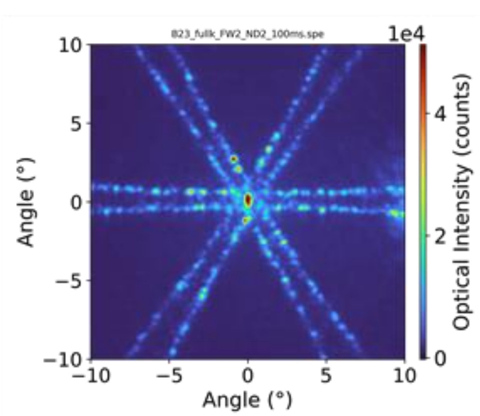

Figure 1. Far-field intensity distribution for (a) shallow etched PCSEL showing emission from dual bands; parameters are: 140 nm lattice constant, 23% fill factor, pumped at 1.2 P_{th} (b) deep-etched PC with lasing both at ΓΓ -point and at finite *k*; parameters: 103 µm diameter mesa with 750 unit cells and 137 nm lattice constant, pumped at 2 P_{th}.

11.1 Bragg soliton dynamics on a CMOS chip

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Abstract – We report Bragg soliton phenomena experimentally observed on a CMOS-compatible, ultra-silicon-rich nitride chip. Bragg soliton-effect compression and fission, picosecond pulse generation and tunable slow light based on gap solitons are driven by the grating induced dispersion and moderate slow light effect at the stopband edge.

I. Introduction

Bragg solitons are optical solitons which form in one-dimensional periodic structures. When the propagation frequency resides on the stopband edge, light experiences a strong grating-induced dispersion while maintaining high transmissivity. [1] Cladding modulated Bragg gratings (CMBGs) are on-chip gratings where the periodic effective index modulation is implemented via cylinders next to a central waveguide [2]. The gap between the cylinders and central waveguide are modulated for apodization. We utilize CMBGs fabricated on ultra-silicon-rich nitride to take advantage its high nonlinear figure of merit at telecommunications wavelengths.

II. Methods and Results

Fabrication of the CMBGs is performed by first performing low temperature deposition of 300nm thick USRN on a thermal oxide on silicon substrate using chemical vapor deposition. The CMBGs are patterned with electron-beam lithography, etched using reactive ion etching, and cladded 2μm of SiO_2 using plasma enhanced chemical vapor deposition. Measurements using a dispersion analyzer show that close to the grating stopband, the dispersion may be three orders of magnitude larger than in a USRN photonic waveguide.

Experimental characterization using picosecond pulses reveal that the temporal compression has strong wavelength dependence – a signature of Bragg solitons [3]. Power dependent measurements trigger formation of Bragg solitons of increasing orders, with the highest Bragg soliton order exhibiting fission.

Leveraging the grating-induced band edge dispersion and the large Kerr nonlinearity in USRN, a strong red-shift in the grating stopband may be induced towards the formation of gap solitons. Through temporal measurements of the arrival time of pulses, we observe a power dependent delay and slow light group velocity reduction to 35%–40% of the speed of light in vacuum [4]. We further experimentally observe the generation of picosecond pulses from continuous-wave light using the CMBGs.

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11.2 Non-Hermitian Chirality and Singularity with Complex Photonic Crystals and Complex Perturbation

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Abstract – We discuss various ways to manipulate chirality and singularity in complex nanophotonic systems. We apply our hybrid photonic crystal fabrication process to realize non-Hermitian photonic crystals and generate various types of chirality, singularity and their interplay. Furthermore, we show how even the slightest complex perturbations to a symmetric Hermitian system generate a chiral response.

Various novel chiral and singular phenomena have been observed in topological and non-Hermitian photonics. These properties can be controlled by manipulating the symmetry of the refractive index distribution [1], and various types of singularity points—topological singularity, polarization singularity, and exceptional points—appear and play non-trivial roles. For example, we discovered that high transmission in photonic-crystal (PhC) waveguide bends, including valley PhCs, can be explained by the polarization singularity which can be manipulated by symmetry [2]. Recently, we succeeded in fabricating hybrid PhCs consisting of a Si PhC loaded with a patterned phase-change material (GST) film, and achieved photonic topological phase transition by the material phase transition [3]. The key point is that the pattern and symmetry of the loaded film can freely differ from that of the host PhCs.

In this talk, we apply this technique to fabricated unique complex PhCs whose real and imaginary parts of the refractive index can be controlled independently. We show that these specially-designed complex PhCs exhibit intriguing band structures and wavefunction. This leads to interesting chirality resulting from the interplay of different types of singular points. We also demonstrate that these systems effectively generate the reciprocal non-Hermitian skin effect, and chiral responses including orbital angular momentum states [4, 5].

Furthermore, we discuss the impact of complex perturbations on nanophotonic systems. Recently, we found that a very tiny localized complex perturbation to symmetric Hermitian systems produces chiral states. We show how this concept can be extended to various types of resonators and waveguides.

These results demonstrate that the complex degree of freedom opens new possibilities for nanophotonic systems in various manners.

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11.3 Photonic application of topological physics: in memory of John Joannopoulos (1947-2025)

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Abstract – I will discuss our endeavors to find commercial applications for topological physics through the development of two topological photonic devices. The first device is the topological-cavity surface-emitting laser (TCSEL), the topological version of PCSEL. The second device is the topological microwave isolator with >100 dB isolation level.

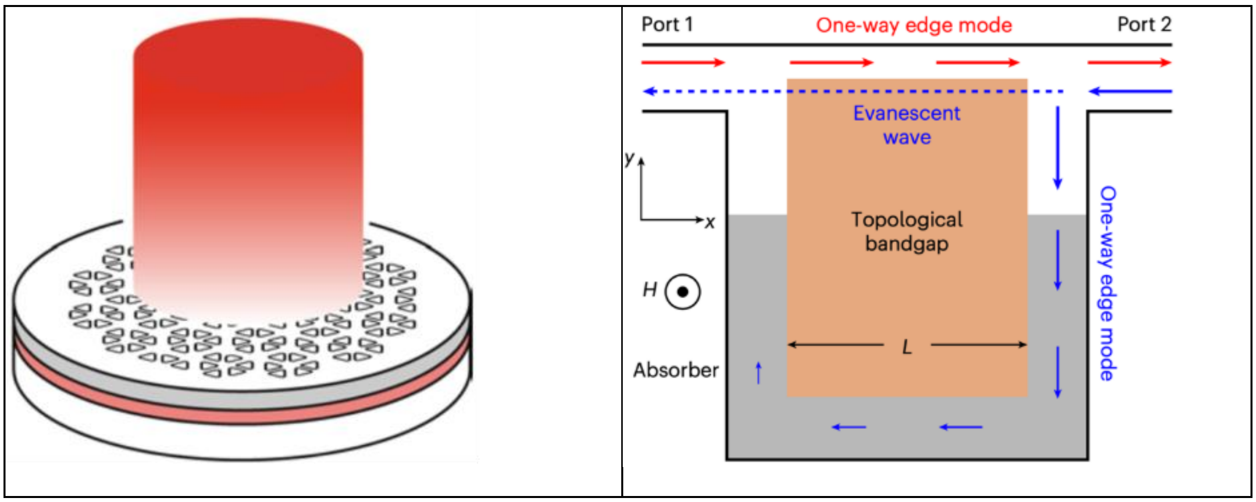

Fig.1 Schematics of the TCSEL and the topological microwave isolator.

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11.4 Photonic Crystal Coupled Nanolasers at Lasing Exceptional Points for Chiral Light Emission

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Abstract –Exceptional points (EPs), representing degeneracies in the non-Hermitian systems, have attracted considerable attention in the recent years. In this work, we experimentally demonstrate that EP can be accessed above the lasing threshold in coupled semiconductor photonic crystal nanolasers. Furthermore, we also show experimentally that the lasing EP can give rise to chiral light emission in a four coupled nanolaser ring.

I. Introduction- The growing capability for precise parameter tuning in photonic crystal (PhC) nanolasers has led to remarkable advances across diverse areas of photonics. In particular, photonic-barrier engineering offers wide-range control of evanescent wave coupling without altering the physical separation of the cavities [1,2]. Such flexibility facilitates the access to lasing exceptional points (EPs)—non-Hermitian degeneracies where both eigenvalues and eigenvectors coalesce. In this work, we experimentally track the lasing EP in the two-coupled PhC nanolasers. Furthermore, leveraging the distinctive phase profile at the EP, we demonstrate the generation of non-zero orbital angular momentum (OAM) in a four-coupled nanolaser ring configuration.

II. Methods and Results- Experiments are implemented on III-V semiconductor PhC L3 cavities with embedded quantum wells as illustrated in Fig. 1. In this case, a subtle interplay between cavity-coupling and linear detuning—introduced at the fabrication stage [highlighted by the yellow hole in Fig. 1(a)]—is necessary to compensate for nonlinear dispersion effects, thereby enabling access to the lasing EP via applying unbalanced optical pumping [3].

The barrier engineering technique allows us to extend the EP concept to a more complex architecture, specifically a ring structure consisting four coupled nanolasers [Fig. 1(b)]. At the EP, a phase singularity arises owning to the consecutive $\pi/2\pi/2$ phase difference along the ring, unveiled using a Sagnac interferometer. In conclusion, the exceptional tunability of coupled PhC nanocavity parameters provides a novel platform for systematic exploration of the interplay between nonlinearities and non-Hermitian phenomena.

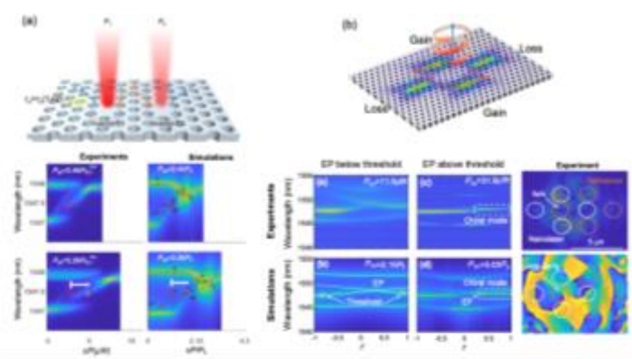

Fig. 1 (a) Tracking EP about lasing threshold using two coupled nanolasers. (b) Chiral light emission from the EP in the four coupled ring structure.

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11.5 Hybrid laser emission via a RSOA die coupled to an integrated side-coupled Fabry-Perot

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Abstract – We present design and experimental characterization of a hybrid external-cavity laser composed of a reflective semiconductor optical amplifier (RSOA) chip coupled to a SiN photonic integrated circuit (PIC). An integrated side-coupled Fabry-Perot cavity acts as a resonant mirror, yielding narrow-linewidth lasing and 45 dB side-mode suppression (SMSR), benefiting sensing applications.

I. Introduction

Hybrid lasers exploiting PIC cavities aims for compact, and spectrally versatile laser sources for applications including on-chip frequency comb generation, high-resolution refractive-index (RI) sensing, and coherent communications. We have designed side-coupled Fabry–Perot cavity to provide spectral filtering and optical feedback, enabling single-mode (and multi-mode) lasing with narrow linewidths and combined with the gain efficiency of the RSOA offering design flexibility and a scalable path toward application-specific laser systems.

II. Methods and Results

The external laser combines a commercial angled RSOA, with a gain curve extending between 1500 nm to 1560 nm, with a 300 nm thick SiN chip patterned in-house via electron beam lithography with positive resist. RSOA is temperature stabilized while mounted on a 5-axis manipulator. The output from the PIC is collected via a lensed fiber. Lasing is obtained from both FP with 500 and 600 nm side-coupler gaps, showing bright single wavelength emission for short cavity lengths. Side coupled FP are characterized in transmission and in reflection and a tapered transition between the straight waveguide and DBR sections [2] is used to reduce cavity losses, achieving a loaded Q-factors over 100,000. Overall, we achieved performance comparable to side-coupled 1D photonic crystal cavities [3], while demonstrating reduced sensitivity to fabrication tolerances. Experimental results show successful lasing with up to 45 dB SMSR for the 500 nm gap, demonstrating narrow-linewidth, high-performance lasers with improved mode selectivity aiming for RI-based sensors application.

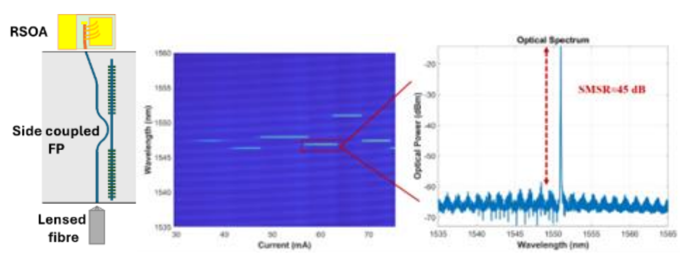

Figure 1: (left) sketch of the hybrid laser(middle) L-I curve showing the optical power as a function of the injection current. (right) Narrow-linewidth single-mode lasing with a SMSR of ~45 dB has been demonstrated.

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13.1 Photonic band physics: generation of light bullet, and non-Abelian lattice gauge field

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In this talk we discuss two aspects of the physics of photonic bands, related to the generation of light bullet and the implications of lattice non-Abelian gauge field.

In free spaces, typical pulses, such as Gaussian pulses, diffract and disperses. On the other hand, there in fact exist pulse solutions of free-space Maxwell's equations that do not diffract or disperse but rather maintain its shape as it propagates [1]. Moreover, the speed of propagation can be arbitrary. These solutions are referred to as space-time wavepackets, or more colloquially, light bullets. Unlike solitons, light bullets arise from a pure linear-optics effect. Their unusual properties are due to selective excitations of a set of plane-wave components that have specific space-time correlations. Here, we show theoretically that light bullets can be generated by reflecting a standard Gaussian pulse against a suitably designed photonic crystal slab [2]. The photonic band structure of guided resonances in a photonic crystal slab imposes the required space-time correlation in the reflected light. The group velocity of the light bullet thus generated depends on the band curvature. We also provide initial experimental results demonstrating the generation of light bullet using this technique [3].

Non-Abelian gauge fields provide the framework for the description of the physics of particles having spins. The theoretical importance of non-Abelian gauge fields motivates its experimental demonstration and exploration. Here we provide an experimental demonstration of non-Abelian lattice gauge field for photons [4], by observing Dirac cones at time-reversal symmetric momenta. Such a Dirac cone is a unique signature of non-Abelian gauge field in the SU(2) lattice gauge field model. Our demonstration utilizes the platform of synthetic frequency dimensions, which enables the study of lattice physics in a scalable and programmable way. Our work explores the complex interplay between the physics of non-Abelian gauge field and topology and may lead to ways to control light propagation in topologically non-trivial ways.

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13.2 Singular Dispersion Equation: Breaking the Diffraction Limit in Dielectrics

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Abstract – The diffraction limit, imposed by light's wave nature and the uncertainty principle, defines a fundamental barrier to optical resolution and device miniaturization. We present a singular dispersion equation that formulates a lossless dielectric framework beyond this limit, supporting narwhal-shaped wavefunctions that unite exponential decay with power-law enhancement for extreme, dissipation-free confinement.

I. Introduction

Photonic devices have long lagged behind electronics in the race to shrink. The reason is fundamental: the uncertainty principle ties light's spatial confinement to its wavelength, which in the visible and near-infrared can be up to a thousand times larger than the de Broglie wavelength of electrons in circuits. This mismatch has kept photonic chips bulky and placed hard limits on the resolution of optical imaging.

Plasmonics once offered a way around the barrier, using metals to squeeze light into subwavelength volumes. But metals dissipate energy as heat — a trade-off that has blocked progress toward efficient, large-scale integration.

II. Methods and Results

We propose the singular dispersion equation, which establishes a theoretical framework to surpass the optical diffraction limit in lossless dielectric systems [1]. At its core lies the narwhal-shaped wavefunction—an optical mode that combines smooth global exponential decay with localized power-law divergence and enhancement, enabling extreme spatial compression of light without energy dissipation (Fig. 1) [2].

Building on this mechanism, we construct singular dielectric nanolasers with atomic-scale modal features, pushing the spatial confinement of laser fields to an unprecedented limit [1]. The device is implemented by integrating a dielectric bowtie nanoantenna into a twisted lattice nanocavity [3-5], achieving synergistic enhancement of both localization and feedback. This advance opens a new pathway toward extreme light localization, providing a key platform for exploring light–matter interactions at the ultimate scale, atomic-resolution optical imaging, and next-generation nanophotonic devices.

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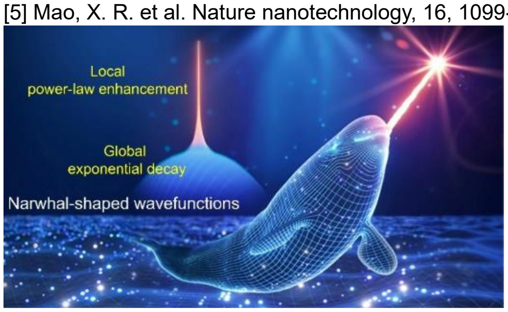

Fig.1 Narwhal-shaped wavefunctions

13.3 A scalable photonic quantum interconnect platform

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Many quantum networking applications require efficient photonic interfaces to quantum memories which can be produced at scale and with high yield. Synthetic diamond offers unique potential for the implementation of this technology as it hosts color centers which retain coherent optical interfaces and long spin coherence times in nanophotonic structures. Here, we report a technique enabling wafer-scale processing of thin-film diamond that combines ion implantation and membrane liftoff, high-quality overgrowth, targeted color center implantation, and serial, high-throughput thermocompression bonding with yields approaching unity. The deterministic deposition of thin diamond membranes onto semiconductor substrates facilitates consistent integration of photonic crystal cavities with silicon-vacancy (SiV) quantum memories. We demonstrate reliable, strong coupling of SiVs to photons with cooperativities approaching 100. Furthermore, we show that photonic crystal cavities can be reliably fabricated in parallel across membranes bonded to the same handling chip. Using suspended waveguide tapers, we couple our photonic crystal cavities off chip with passive packaging demonstrating sub-decibel insertion loss. Together these advances establish an approach to building scalable assembly of optically addressable quantum memory arrays which are a key building block for modular photonic quantum interconnects.

Optical Pathways in Distorted Photonic Crystals

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Abstract – We have studied the optical pathways in distorted photonic crystals, which enable beam steering without changing the refractive index. Here, we experimentally demonstrate meandering optical pathways in distorted photonic crystals consisting of adiabatically and spatially rotating elliptical air holes.

I. Introduction

A distorted photonic crystal (DPC) is a type of photonic crystal (PC) that exhibits an adiabatic change in lattice constants or lattice shape. We previously reported that the optical trajectory can bend in the direction opposite to the change in lattice constants, even when the averaged refractive index within each unit cell remains constant, and experimentally demonstrated this effect in a DPC designed for the terahertz (THz) electromagnetic region [1, 2]. This optical bending can be explained by the induction of anisotropic equi-frequency dispersion from an initially isotropic one. However, prior demonstrations were limited to low-frequency regions where the propagation dispersion lies below the light line in air, preventing light extraction from the in-plane of the DPC and resulting in only indirect observation. In this work, we demonstrate that a DPC consisting of adiabatically rotating elliptical lattice points can achieve on-chip beam trajectory meandering, and we experimentally visualize the corresponding optical pathways.

II. Methods and Results

Figure 1(a) shows a scanning electron microscope (SEM) image of the fabricated sample. The sample consists of both distorted photonic crystal (DPC) and photonic crystal (PC) regions, each with the same lattice constant of $a^{(0)}$ = 220 nm, consisting of elliptical air holes arranged in a square lattice. In the DPC region, each elliptical lattice point is gradually rotated along the y-axis, and the number of lattice points required to rotate 90-degree is defined as the parameter n_{90}. PbS quantum dots (QDs) were applied to the sample surface, and a laser beam with a wavelength of 1110 nm was coupled into the sample via a grating coupler. Figure 1(b) shows the images of radiated emissions from QDs. Since the PC region exhibits propagation dispersion along G-M direction, the optical pathways appear straight. In contrast, the DPC region exhibits bent pathways toward the +y direction, and the bending is more pronounced at n_{90} = 56.25 than at n_{90} =37.5. It can also be observed that the trajectory bends again toward the -y direction in the sample of n_{90} = 37.5. Moreover, the trajectories agree well with the simulation results, as shown in Fig. 1(c). Further details will be presented at the conference.

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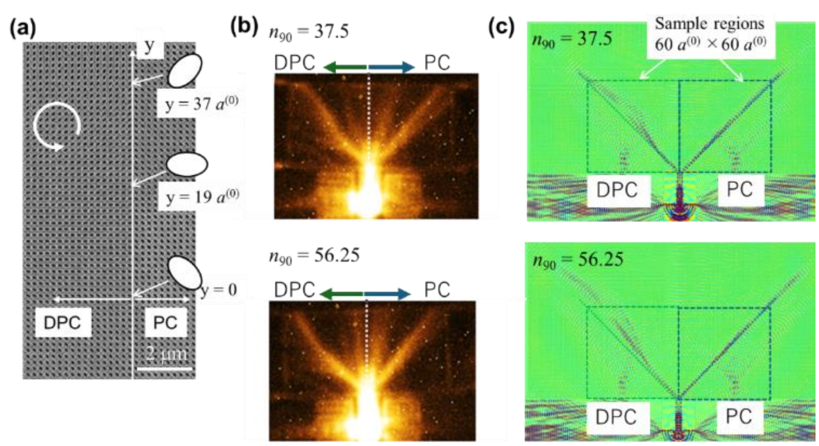

Fig.1 (a) SEM image of a sample, (b) Experimental results, (c) Simulation results.