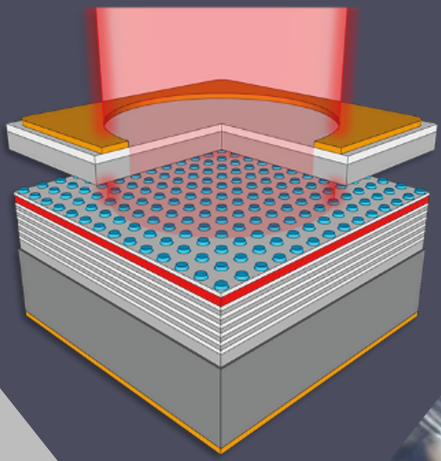

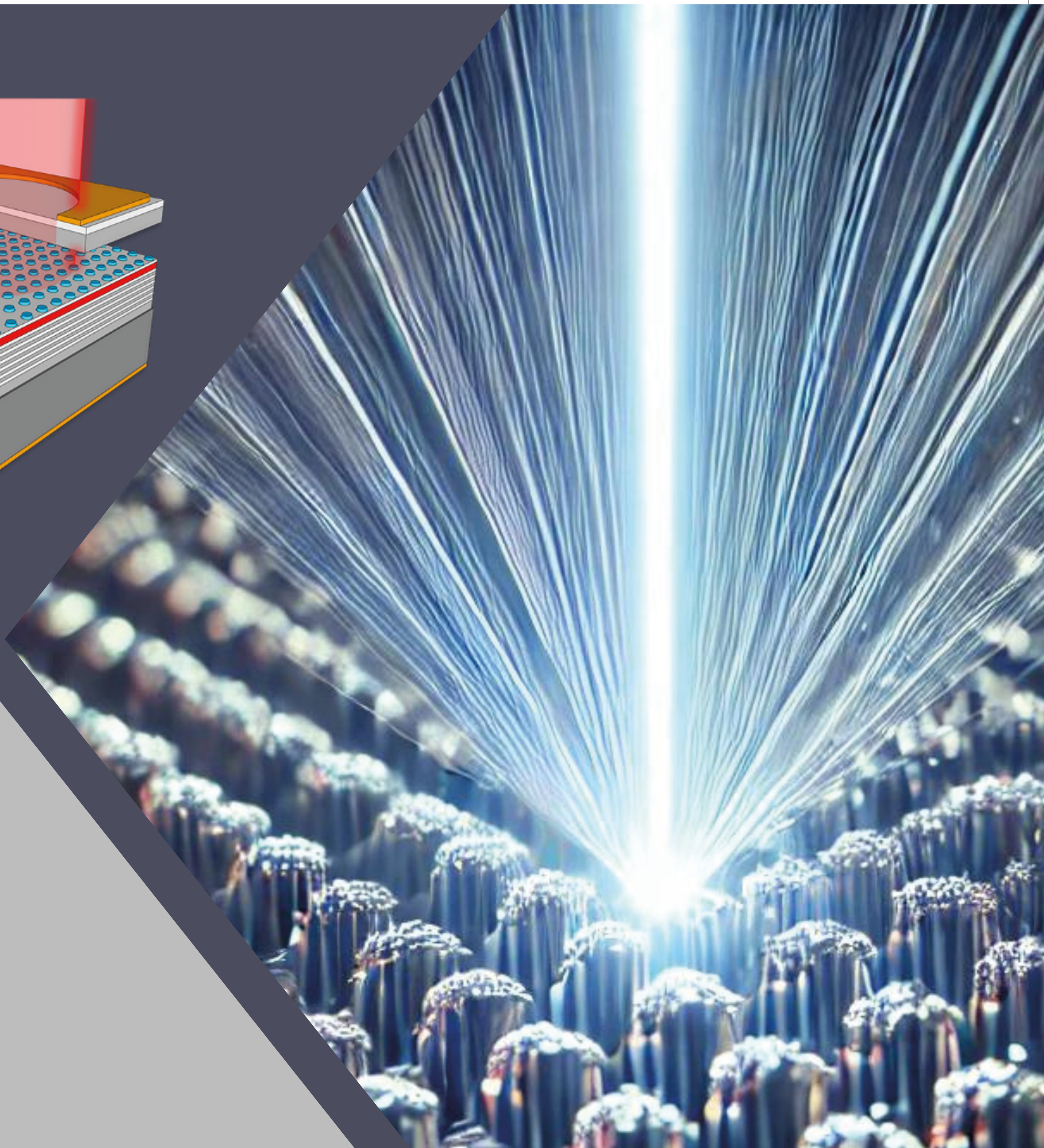

INTERNATIONAL WORKSHOP ON PCSELs 2024

University of Glasgow

VIA VERITAS VITA

Aston University

BIRMINGHAM UK

AIPT

Aston Institute of Photonic Technologies

Contents

Welcome

We are delighted to welcome you to Aston University, Institute for Photonic Technologies for the International Workshop on PCSELs 2024.

PCSEL 2024 is the first event of its kind dedicated to the latest advances in photonic crystal surface emitting lasers and related technologies, and builds on the success of two on-line meetings held during the COVID era. Since then, there has been a proliferation in the number of articles and groups focused on PCSEL research, and the time is right to bring the global research community together in-person for this two-day event.

We are honoured to welcome our keynote speaker, Professor Susumu Noda, to open and participate in the workshop. This year we celebrate 25 years of PCSEL research, and it is only fitting that Professor Noda can join us to reflect on the many advances that have been seen in his time as the pioneer of the field.

We would like to thank all of our invited and contributed presenters, from both academia and industry, for their enthusiastic participation in the workshop. Due to the international community's resounding response, we have been able to compile this booklet containing abstracts for all oral presentations, providing a unique snapshot of the state-of-the-art in PCSEL research in 2024. It is our opinion that every group active in the field has some representation at this event, which is a testament to the dedication of community to driving innovation.

Finally, we would like to thank all delegates for joining us for the next few days. We have attendees joining us from more than a dozen countries across three continents, making this a truly global event. We greatly appreciate your participation in making this workshop a success.

We look forward to an excellent workshop, and hope you enjoy your stay in Birmingham.

Professor Richard Hogg,
Aston University,
Workshop Chair

Dr Adam McKenzie,
University of Glasgow,
Programme Chair

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PHOSERTEK | OPTICA | HUAWEI | COMPOUND SEMICONDUCTOR | CATAPULT Compound Semiconductor Applications

Agenda: Thursday 7th November

Coffee Breaks & Poster Sessions:	Aston University, Main Building 406-408, B4 7ET
Talks & presentations:	Aston University, Main Building 417, B4 7ET
Lunch:	Conference Aston Restaurant, B4 7ER
Workshop Dinner:	The Bond, 180-182 Fazeley St, B5 5SE

09:00-10:00	**Registration (Aston Main Entrance) & Welcome Coffee (MB 406-408)**
10:00-10:10	**Welcome by Prof. Aleks Subic (Aston Vice-Chancellor & Chief Executive)**
10:10-11:00	**Keynote Session (Chair: Prof. Richard De La Rue)** Prof. Susumu Noda, Kyoto University, Japan *Recent Progress in High-Brightness and High-Functionality Photonic-Crystal Surface-Emitting Lasers*
11:00-12.30	**Session 1 (Chair: Prof. Richard De La Rue)** Prof. Kyoko Kitamura, Tohoku University, Japan *Generation of Optical Vortex Beams from Photonic Crystal Surface-Emitting Lasers* Prof. Leon Shterengas, Stony Brook University, USA *Photonic Crystal Surface Emitting GaSb-based Type I Quantum Well Diode Lasers* Karl Boylan, Huawei Technologies R&D, UK *Static and Dynamic Performance of InGaAlAs based Photonic Crystal Surface Emitting Lasers at 1.3 µm* Hai Huang, The Chinese University of Hong Kong, China *Topological Dirac-Vortex Surface-Emitting Laser*
12:30-14:00	**Lunch (Conference Aston)**
14:00-15:30	**Session 2 (Chair: Dr. Ben King)** Prof. Takashi Kuroda, National Institute for Materials Science (NIMS), Japan *Design and Performance of PC Resonators for Surface-Emitting Quantum Cascade Lasers* Dr. Lih-Ren Chen, National Yang Ming Chiao Tung University, Taiwan *Novel Designs of PCSELs Enabling New Applications* Prof. Ana Vukovic, University of Nottingham, UK *Laser PCSEL Model in Unstructured TLM Method* Ye Chen, Peking University, China *Vortex Microlaser Based on Collective Modes of Guided Mode Resonances*
15:30-16:00	**Coffee Break & Poster Session (MB 406-408)**
16:00-17:30	**Session 3 (Chair: Dr. Adam McKenzie)** Dr. Richard Taylor, Vector Photonics, UK *Vector Photonics: The Commercial Journey of PCSELs and Their Future Pathway* Prof. Åsa Haglund, Chalmers University of Technology, Sweden *Pushing Photonic Crystal Surface Emitting Lasers into the Deep-UV* Prof. Ling Lu, Chinese Academy of Sciences, China *Topological Cavity Surface Emitting Laser*
17:30-18:15	**Drinks Reception & Poster Session (MB 406-408)**
18:15	**Transportation to Dinner Venue (Meeting point: MB 406-408)**
19:00-21:30	**Workshop Dinner (The Bond)**

Agenda: Friday 8th November

Coffee Breaks & Poster Sessions:	Aston University, Main Building 402-404, B4 7ET
Talks & presentations:	Aston University, Main Building 417, B4 7ET
Lunch:	Conference Aston Restaurant, B4 7ER

09:00-10:30	**Session 4 (Chair: Prof. Thomas Krauss)** Prof. Boubacar Kanté, University of California, Berkeley, USA *New Physics in Photonic Crystals and Discovery of Scale-Invariant Lasers* Dr. Graham Berry, Huawei Technologies R&D, UK *Comparison of InP PCSELs and Other Traditional Lasers* Prof. Cunzhu Tong, Chinese Academy of Sciences, China *Triple-lattice Photonic Crystal Surface Emitting Lasers* Dr. Sang Soon Oh, Cardiff University, UK *Bound-State-in-the-Continuum Lasing Modes in InGaAs Nanowire Photonic Crystals*
10:30-11:00	**Coffee Break & Poster Session (MB 402-404)**
11:00-12.30	**Industry Round Table (Chair: Joe Gannicliffe)** Hosted by CSA Catapult
12:30-14:00	**Lunch (Conference Aston)**
14:00-15:30	**Session 6 (Chair: Prof. Richard Hogg)** Dr. Takuya Inoue, Kyoto University, Japan *Theoretical Analysis of Large-Area Photonic-Crystal Surface-Emitting Lasers* Dr. Ben King, Ferdinand-Braun-Institut, Germany *Design of High-Power GaAs PCSELs with an All-Semiconductor Photonic Crystal* Prof. Weidong Zhou, University of Texas, Arlington, USA *Laterally Confined PCSELs and Coherent PCSEL Arrays*
15:30-16:00	**Closing Remarks**

Keynote Speaker

Professor Susumu Noda

Recent Progress in High-Brightness and High-Functionality Photonic-Crystal Surface-Emitting Lasers

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Recommendation of further reading:

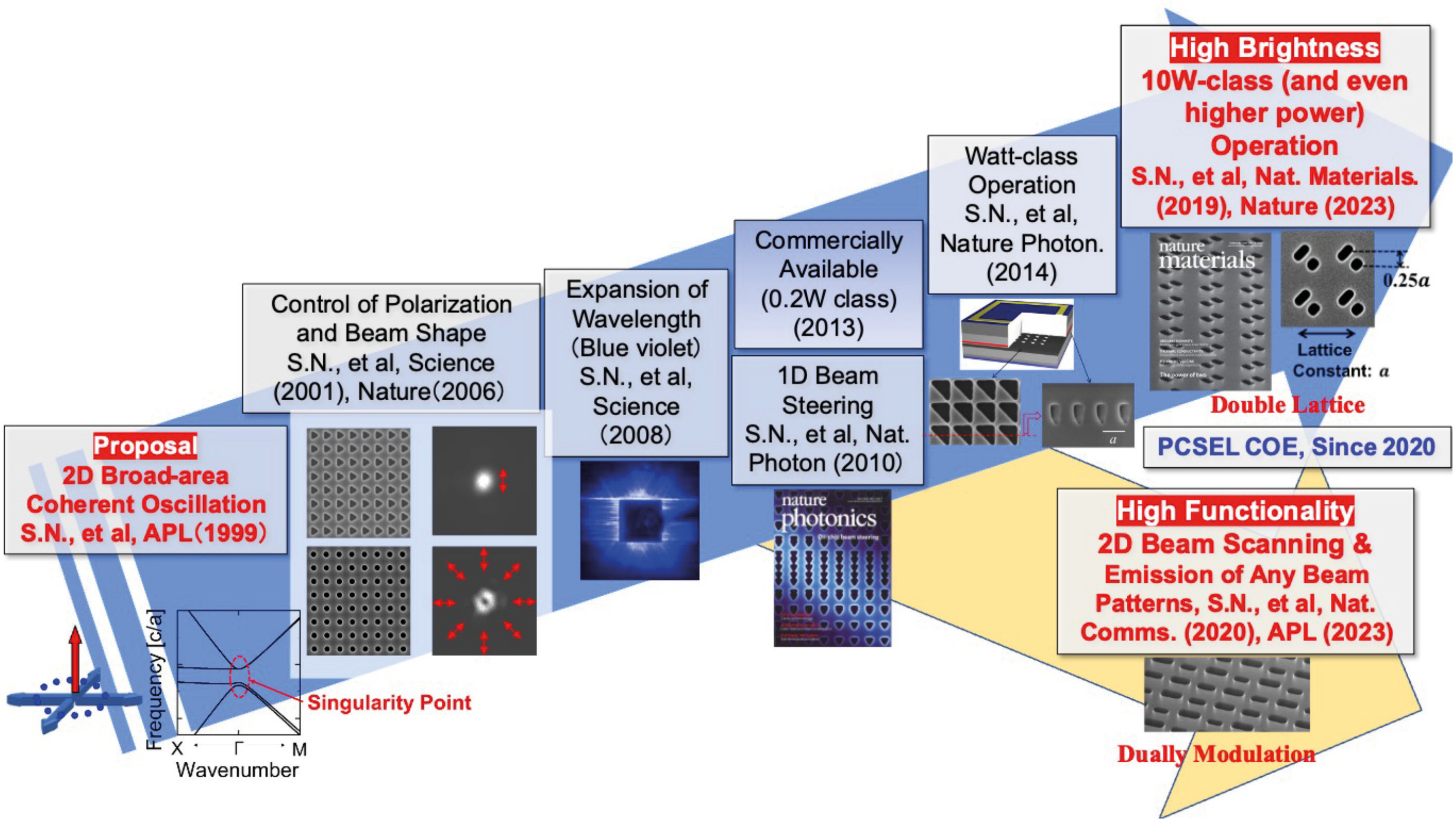
Tutorial Paper: S. Noda *et al,* "High-power and high-beam-quality photonic-crystal surface-emitting lasers, a tutorial" *Adv. Opt. Photon.* **15,** 977-1023 (2023).

Review Paper: S. Noda, *et al,* "Photonic-Crystal Surface-Emitting Lasers: Review", *Nature Review Electrical Engineering,* December Issue (2024) (in press).

Laser technology is one of the key technologies to realize a smart society, represented by smart mobility and smart manufacturing. However, existing lasers have individual issues that hinder their use in such emerging fields: For example, conventional semiconductor lasers have issues of low brightness and low functionality even though they have merits of compactness and high efficiency. These issues result in systems that are large and complicated, and whose application to direct material processing is difficult. Photonic-crystal surface-emitting lasers (PCSELs) boast both high brightness and high functionality while maintaining the merits of semiconductor lasers, and thus PCSELs are solutions to the issues of existing laser technologies. In this keynote talk, I will describe recent progress of PCSELs including their latest high-brightness and high-functionality operations. New trends such as short-pulse, short-wavelength, and optical communication wavelength operations also briefly discussed. In addition, the activities of the centre of excellence for PCSELs are also explained for social implementation.

Acknowledgements

This work was partially supported by the project of the Council for Science, Technology and Innovation; the Cross Ministerial Strategic Innovation Promotion Program (SIP) and Program for Bridging the Gap between R&D and the Ideal Society (Society 5.0) and Gathering Economic and Social Value (BRIDGE). The work was also supported by a Grant-in-Aid for Scientific Research (22H04915) of the Japan Society for the Promotion of Science, and by project JPNP22007 of the New Energy and Industrial Technology Development Organization (NEDO).



Generation of Optical Vortex Beams from Photonic-Crystal Surface-Emitting Lasers

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Abstract

Laser beams which possess cross-sectional polarization and phase distributions along azimuthal direction, called optical vortex beams (OVBs), have attracted much attention in the variety of fields. We here introduce photonic-crystal surface-emitting lasers (PCSELs) that enable us to a single-chip optical vortex beam generation.

Introduction

OVBs exhibit a spatial polarization or phase distribution along the azimuthal direction of the beam cross-section. Owing to the polarization or phase singular points, null intensity is observed at the beam centre, resulting in a doughnut-shaped optical intensity distribution. The mode of OVBs possessing phase distributions are expressed with Laguerre-Gaussian (LG) modes. The mode of OVBs possessing polarization distributions, so called vector beams, can be expressed by the superposition of right- and left-handed circularly polarized LG modes [1]. Therefore, both polarization and phase OVBs are connected by the integer of polarization or phase rotations; *l*.

In past two decades, many approaches to generate OVBs have been proposed. However, as far as the authors knowledge, all methods require external light sources or optical elements. Single-chip, high-power OVB generators must become universal light sources for many OVBs applications. We here introduce our progress of development of single-chip OVB generators based on PCSELs.

Optical *"polarization"* Vortex

Text Since 2006, in the early stages of the development of OVBs generators, we have reported that PCSELs can extract the vector beams that possess correspondent polarization distributions of the electro-magnetic fields of unit cell of the photonic crystal (PC) [2-3]. When the unit cell is consisted with point-symmetric shaped lattice such as circular air-holes, the internal electric fields of PC become also point-symmetric centred of the unit cell. As a consequence of this, the mode cannot radiate to the air if PCSEL is infinite structure, however, the mode can be obtained to the air with corresponding the symmetric electric fields because of the finite structure that is a vector beam. In this case, the possible polarization distributions are limited, due to the nature of the limited band-edge. In recent years, we have realized a novel single-chip vector beam generator that can generate arbitrary cylindrically polarized vector beams, that have an initial phase in their polarization, and that have higher-order polarization distributions by designing spatially modulated PCSELs [4]. In this case, we control differently between two-dimensional resonant and radiation effects with utilize the non-radiative band-edge of PCs [5-6]. Since the polarization and beam direction can be designed on demand with position modulation of each lattice of PC, arbitrary vector beams have been obtained.

Optical *"phase"* Vortex

Paying attention to other features of PCSELs that is "surface emission", we have freedom of integrate optics on the emission surface. It is worth to mention that the M^2 value of emitted beam is evaluated ~1 so that a PCSEL generate an ideal Gaussian beam that have great potential to integrate optics onto the emission surface. In 2019, we firstly demonstrated an OAM beam generation with $l = 1$ by integrating a quasi-spiral (8-segmented) spatial phase plate (q-SPP) on the top surface of a PCSEL. The PCSEL featured an injection current area of 50 μm in diameter and a PC layer comprising triangular air-holes arranged in a square lattice [7]. Very recently, with advancing of PCSELs high brightness, high beam quality operations, we have demonstrated OVBs generations with high-power (~5 W), and higher-order ($l \geq 1$) by q-SPP-integrated PCSELs featuring an injection current area of 500 μm in diameter, and a double lattice PC embedded to the structure with crystal regrowth technique [8]. The mode purity values are evaluated greater than 70% for $l = 1$-3, and the values are comparable with those of a pure Gaussian mode passing through an SPP.

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Photonic Crystal Surface Emitting GaSb-Based Type I Quantum Well Diode Lasers

Leon Shterengas[1*], Gela Kipshidze[1], Aaron Stein[2], Won Jae Lee[1], Ruyan Liu[1], Dmitri Zakharov[2], Kim Kisslinger[2] and Gregory Belenky[1]

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Abstract

The III-V-Sb buried voids photonic crystal surface emitting laser (PCSEL) technology has been developed and continuous wave room temperature operation of the devices operating near 2 μm was achieved. Increase of the number of the voids per unit cell in the buried photonic crystal layer led to enhanced laser efficiency.

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Introduction

The development of the epitaxially regrown PCSELs based on various material systems and active region architectures is actively explored to enable devices operation in wide range from visible to infrared. Monolithic PCSELs based on nitride, arsenide, and phosphide diode laser technologies operating in visible and near infrared telecom region of spectrum have been demonstrated [1]. The extension of the PCSEL technology to longer wavelength range above 4 μm was accomplished using quantum cascade laser design [2]. Our research group at Stony Brook University is involved in design and development of the GaSb-based PCSELs targeting operation at wavelength range from 2 to 4 μm. We have demonstrated air-pocket retaining epitaxial regrowth within antimonide material system and reported on diode and cascade diode PCSELs operating near 2 μm and 2.8 μm respectively [3]. 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 [4] and device output power was further enhanced in year 2024 [5].

Methods and Results

The key technological capability required for development of the efficient PCSELs is a capacity to seamlessly integrate high index contrast photonic crystal layer into laser heterostructure. Approach selected by our research group for the GaSb-based monolithic PCSELs fabrication, was in many aspects like the one developed by Kyoto University group for fabrication of their record-breaking GaAs-based PCSELs [1]. The process we adopted starts with the molecular beam epitaxial (MBE) growth of the n-cladding layer and n-side waveguide core layer, followed by the growth of the quantum well (QW) active region, which gets capped by p-side waveguide core layer. Then the incomplete laser heterostructure is removed from growth reactor, the square lattice of holes is etched in the p-side waveguide core layer, and nanopatterned incomplete laser heterostructure is reloaded back to MBE for regrowth of the p-cladding and p-contact layers. The regrowth regimes are optimized to form highly uniform array of buried voids. Increase of the PCSEL operating wavelength requites proportional increase of the period of the buried photonic crystal. However, the volume of the buried voids cannot be scaled up easily since it is affected by aspect ratio of the etched holes. Decrease of the relative size of the buried voids with respect to period of the photonic crystal (decrease of the void area fill-factor) can lead to reduction of the coupling coefficients controlling the strengths of in-plane feedback and surface emission. To obtain adequate area fill-factor of the void in the unit cell of the buried photonic crystal designed to operate at longer wavelength, several voids per unit cell can be used. Increased number of voids per unit cell helped to increase the device power and efficiency and PCSELs based on four-voids unit cell design demonstrated the highest power level so far.

Acknowledgements

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, through the Center for Functional Nanomaterials, Brookhaven National Laboratory, under Contract DE-SC0012704.

Design and Performance of PC Resonators for Surface-Emitting Quantum Cascade Lasers

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[2] Department of Applied Physics, University of Tsukuba, Tsukuba, Japan

* sakoda.kazuaki@nims.go.jp

Abstract

We report on the development of surface-emitting quantum cascade lasers with photonic-crystal resonators. Specifically, we describe the relation between the unit-cell structure and the laser performance including the resonance quality factor, extraction efficiency, output power, beam quality and far-field pattern.

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Introduction

Quantum cascade lasers (QCLs) are unique solid-state lasers that operate in the mid-infrared frequency range. They possess such good features as the wide tunability of the lasing frequency, compact device structures, and small power consumption. Their application to gas sensing is specifically promising, since the absorption lines of important gas molecules are covered by the QCLs. For the remote sensing of dangerous gases such as volcanic eruptions and for the extremely high-sensitivity gas analysis by a multiple laser-path configuration, high-quality laser beams with small divergence angles are needed because a long propagation length is required.

However, the conventional QCLs are of the edge emission type with small output apertures, so their divergence angles are generally large. The surface-emission device configuration, known as VCSEL (vertical-cavity surface-emission laser), improves this problem of the laser-beam quality. But because the emitted light from the active region of the QCLs, which utilizes the inter-subband transitions of multiple quantum wells (MQWs), are transverse magnetically (TM) polarized, so there is a mismatch with the cavity electromagnetic resonance modes, and the VCSEL configuration is not applicable to QCLs. PC (photonic crystal) resonators are used instead [1-5].

Methods and Results

In this presentation, we report on the development of the surface-emitting QCLs, which was carried out jointly by the National Institute for Materials Science, Toshiba Corporation, and Tokyo University of Technology [4,5], focusing on the relationship between the structure of the PC resonator and the laser performance. We compare three cases of the PC unit-cell shapes as shown in Fig. 1.

Acknowledgments

This study was supported by the Innovative Science and Technology Initiative for Security, Grant Number JPJ004596, ATLA, Japan.

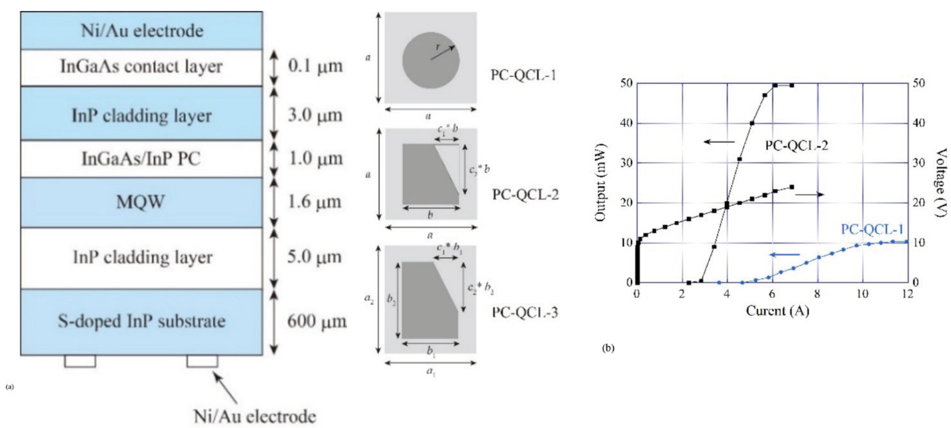

Figure 1. (a) Illustration of the side view of the device structure. (b) Left: top view of the unit cell composed of an InGaAs pillar (dark grey) buried with InP (light grey). Right: Peak output power of PC-QCL-1 and PC-QCL-2 with a pulsed excitation at 77 K. For PC-QCL-3, a peak output power more than 1 W was achieved.

Novel Designs of PCSELs Enabling New Applications

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Abstract

Photonic-crystal surface-emitting lasers (PCSELs) are renowned for their high-power output and single-mode emission capabilities, as well as beam steering capabilities. Through sophisticated design of photonic crystal lattices, researchers can unlock even more intriguing properties, enabling a wide range of versatile functionalities. This presentation will showcase our novel PCSEL designs.

References

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Introduction

Vortex beams have garnered significant interest for their applications in communication, quantum computing, and particle manipulation. We systematically studied the vortex vector beam generated from electrically driven PCSELs with hexagonal and honeycomb lattices. Their respective topological charges were investigated experimentally and theoretically and a dynamically topological charge switching mechanism was proposed. [1,2]

Reducing the threshold current (I_{th}) comparable to VCSELs and keep the low divergence angle, we propose a new method which applies reduced gain region by utilizing the selective quantum well intermixing (QWI) method to reduce the threshold current of PCSELs and perform a theoretical calculation to optimize the injection radius of the proposed structure. [3]

Methods and Results

Electrically driven PCSELs with honeycomb and hexagonal lattices were measured for the lasing characteristics such as L-I-V curves, far-field emission pattern and polarizations under varies current injections. Figure 1(a) presents the results of two lasing mode of PCSEL with honeycomb lattice. The simulated polarizations mapped in k-space align well with the experimental measurements, allowing for the determination of the topological charge. For the PCSEL with a hexagonal lattice, mode hopping and variations in topological charge were observed as a function of current pulses.

To achieve a threshold current comparable to VCSELs, we propose a structure that restricts the current injection gain region while maintaining a low divergence emission angle by extending the photonic crystal beyond the gain region, as illustrated in Figure 1(b). The absorption loss from quantum wells surrounding the gain region is minimized using a selective QWI method, enabling low I_{th} operation. The lower panel of Figure 1(b) shows the calculated divergence angles relative to the injection area.

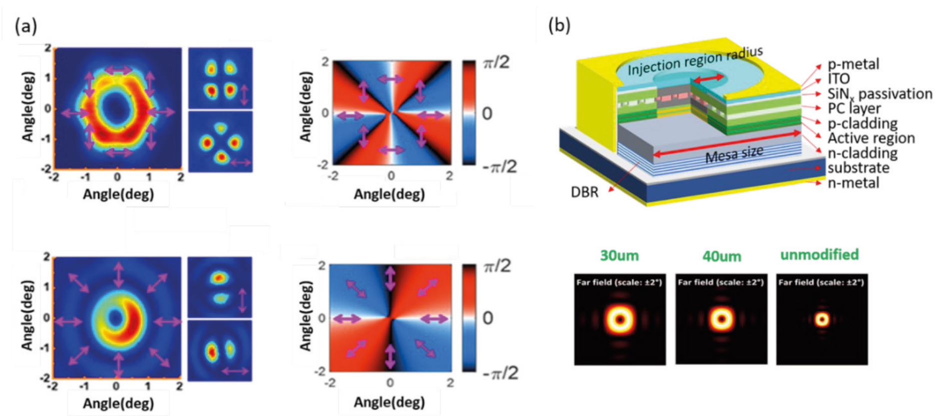

Figure 1. (a) The measured (left) far field pattern and calculated polarization (right) of honeycomb-PCSEL. (b) The illustrative schematic of PCSEL with MQW intermixing (upper) and simulated far-field pattern (lower).

Vector Photonics: The Commercial Journey of PCSELs and Their Future Pathway

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Abstract

Vector Photonics is a UK based company commercialising PCSEL technology across material systems, wavelengths, and applications spaces. In this talk we review the journey from inception to commercialisation and discuss the future roadmap to high power multimode and single mode devices and arrays.

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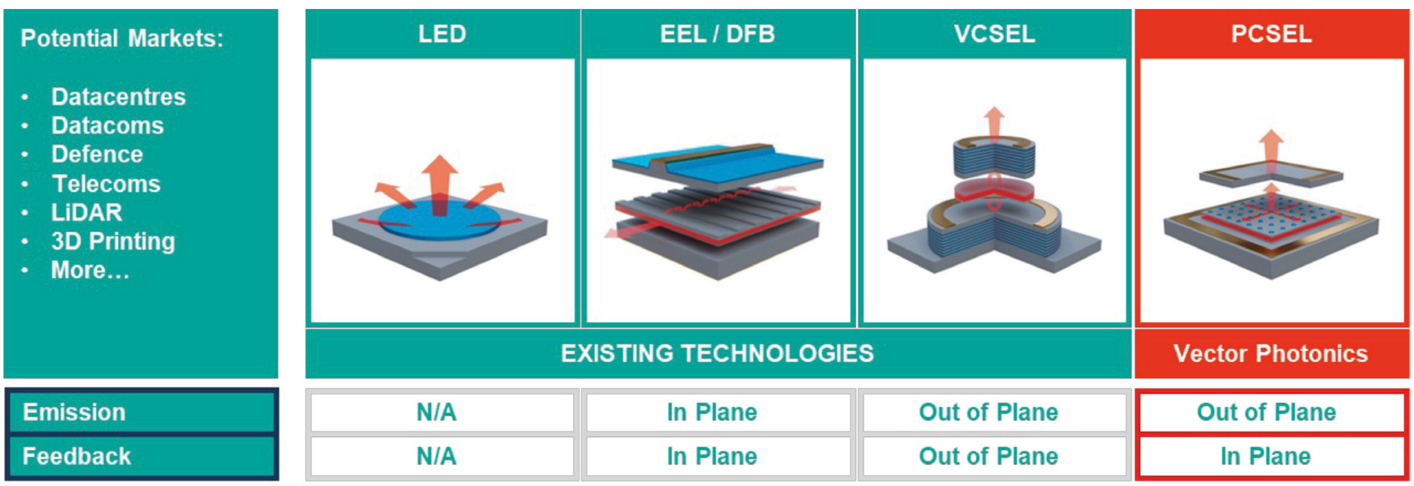
Introduction

Photonic Crystal Surface-Emitting Lasers (PCSELs) represent a significant advancement in semiconductor laser technology, integrating a two-dimensional photonic crystal layer within the laser structure. This innovation enables PCSELs to achieve high power, broad wavelength range, and robust performance, making them highly versatile for various applications. As such there has been significant recent interest in the development of these lasers [1] and in particular in their commercial potential.

The commercial potential of PCSELs is vast, spanning multiple high-growth markets. In data communications, PCSELs can significantly reduce power consumption in next-generation data centers, driven by the proliferation of mobile devices, the Internet of Things (IoT), and the rollout of 5G networks. Additionally, PCSELs are poised to revolutionize additive manufacturing, including metal and plastic printing, by providing high-power, efficient laser sources. Their application in LiDAR and optical sensing further underscores their importance in automotive, defence, and industrial sectors.

In this presentation we will review the development of all-semiconductor PCSELs from initial growth optimisation [2] to the development of coherently coupled arrays [3], we will consider the journey to commercialisation to date and the future prospects and challenges for this technology.



Pushing Photonic Crystal Surface Emitting Lasers into the Deep-UV

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Abstract

We demonstrate deep-ultraviolet (<280 nm) PCSELs under optical pumping. The photonic crystal was etched into the top cladding layer and a triangular lattice was used to promote 2D coupling. We verified lasing at a band edge with angular-resolved photoluminescence obtained low-divergent far-fields for a mid-range filling factor of 15%.

Introduction

Photonic crystal surface emitting lasers (PCSELs) have gained a lot of interest lately due to their ability to deliver high output power with a low beam divergence. At infrared wavelengths, an output power of 50 W with a beam divergence below <0.05° has been obtained [1]. The first blue PCSEL was demonstrated in 2008 [2], but it took until 2022 to reach Watt-level output powers [3] and green PCSELs have recently been achieved under pulsed operation [4]. Pushing the wavelength even shorter into the UV is challenging, due to 1) higher defect densities in AlGaN materials that can distort the photonic crystal symmetry, 2) the lower refractive index that makes it harder to obtain a 2D standing optical field and 3) the shorter wavelength that requires smaller photonic crystal feature sizes and can lead to higher scattering losses.

Methods and Results

Here we demonstrate deep-UV (λ<280 nm) PCSELs under optical pumping. The MOVPE grown epitaxial structure consists of three 2-nm-thick $Al_{0.40}Ga_{0.60}N$ quantum wells (QWs) surrounded by 30-nm-thick $Al_{0.70}Ga_{0.30}N$ waveguide on both sides with an AlN cladding. The photonic crystal is etched into the top AlN cladding layer leaving 65 nm to the top QW to prevent etch-induced damage. The triangular lattice promotes a stronger 2D coupling and ciruclar holes reduce the vertical loss and thereby the threshold. A lattice period of about 140 nm was used to set the lasing wavelength to the photoluminescence peak wavelength, and the hole diameter was varied to yield a hole filling factor (hole to unit cell area) between 10% and 22%.

Angular-resolved photoluminescence showed a kink in output power vs pump power and beam width and spectral narrowing around threshold. In addition, these measurements are important to prove that the laser operates as a PCSEL, i.e. to identify that it lases at a band edge in the bandstructure and in which mode. It is seen that a too low filling factor results in 1D lasing, and a too high filling factor results in an intricate emission pattern caused by secondary scattering of photons in the lasing mode to other bands in the photonic crystal. These undesired emission patterns can be supressed by a mid-range filling factor around 15%, which results in lasing in a mode with a 2D standing opical field that has low lateral loss, and a low-divergent far-field (< 1°) can be obtained.

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Topological-Cavity Surface-Emitting Laser

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*linglu@iphy.ac.cn

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Abstract

Contrary to the common belief that Nobel-winning topological physics lacks practical applications, we demonstrate that the textbook design of everyday semiconductor lasers, used in internet communications and cellphones, aligns with standard topological models in 1D. By advancing to the 2D vortex zero mode, we invent topological-cavity surface-emitting lasers (TCSELs) that significantly outperform their commercial counterparts. Furthermore, we demonstrate the monopole modes in 3D, proposed half-century ago by Jackiw and Rebbi, completing the kink-vortex-monopole trilogy of topological defect modes.

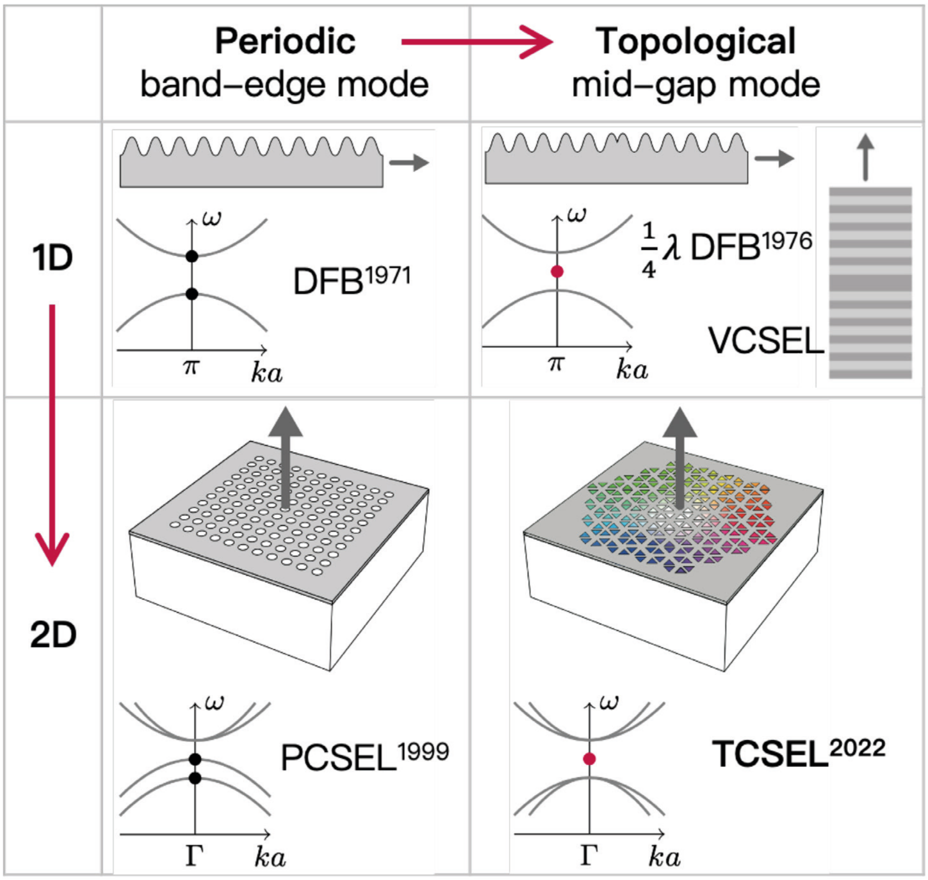

Figure 1. Comparison of the Dirac-vortex cavity and the three types of commercialized semiconductor laser cavities for single-mode operation. The cavities of uniform lattices, both 1D DFB and 2D PCSEL, have two competing high-Q band-edge modes. The cavities of topological defects, both the phase-shifted DFB, VCSEL and the Dirac-vortex cavities, have a single mid-gap mode. The years indicate when the device ideas were first proposed. ω, frequency; k, wavevector; a, lattice constant.

New Physics in Photonic Crystals and Discovery of Scale-Invariant Lasers

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Abstract

In this presentation, I will discuss our discovery of scale-invariant lasers. I will argue that a surface emitting laser that remains single mode irrespective of its size, a scale-invariant laser, should of necessity also waste light at the edge. This is a fundamental departure from the Schawlow-Townes two-mirror strategy that keeps light away from mirrors and edges to preserve gain and minimize loss. The strategy was implemented in the recent discovery of the Berkeley Surface Emitting Laser (BerkSEL).

Introduction

Lasers play a fundamental role in science and technology from quantum computing, to communications, manufacturing, defence, sensing, medicine, or imaging. However, scaling the power of lasers has always come at the cost of single mode operation, a scaling question that has been investigated, without success, since the invention of lasers in 1958.

Methods and Results

In the first part of the talk, I will propose an intriguing solution to this question and discuss a "scale-invariant" laser that remains single mode irrespective of its cavity size [1]. I will show that the discovered strategy goes beyond the Schawlow-Townes two-mirror strategy that is used by all existing lasers. I will conclude that mirrors are bad for the scaling of lasers [1-2]. We named the laser, Berkeley Surface Emitting Laser (BerkSEL or BKSEL). In the second part of this talk, I will briefly discuss our invention of functional topological lasers: integrable non-reciprocal coherent light sources as well as compact bound state in continuum sources [3-5].

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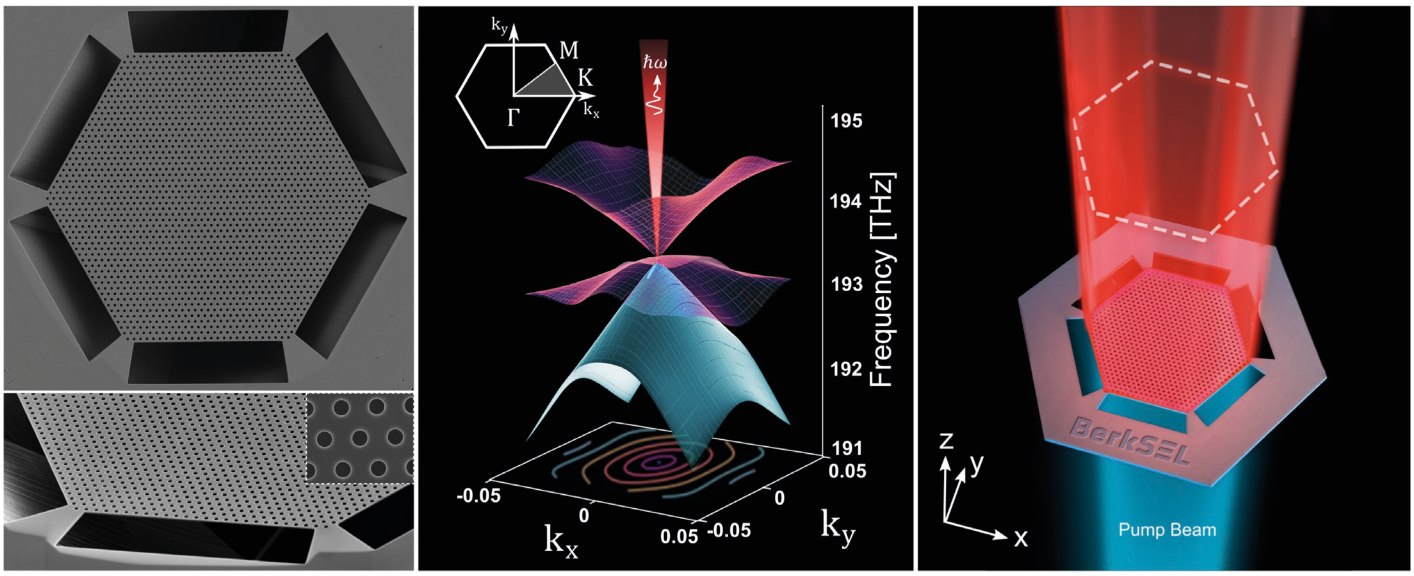

Figure 1. Top-view scanning electron micrograph of an open-Dirac electromagnetic cavity. (Middle) Dispersion of the structure showing a conical degeneracy. (Right) Schematic of a Berkeley surface-emitting laser (BerkSEL).

Comparison of InP PCSELs and Other Traditional Lasers

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Abstract

Photonic Crystal Surface Emitting lasers (PCSELs) are emerging as potential alternatives to traditional edge-emitting and vertical cavity surface emitting lasers. We will focus on the gap analysis for the PCSEL and show what is likely to be required to displace the incumbent technologies for a range of target applications such as Gas-sensing, CW light sources for Raman pump amplifiers and Silicon Photonics and also explore data transmission applications.

Introduction

In this talk we outline the development work we have undertaken with our InP-platform. We will present experimental measurements for key lasing parameters and compare with state-of-the-art results. Vertical cavity surface emitting and edge-emitting laser diodes are key mature component blocks used in the datacoms, telecoms and sensing application space. However, both these configurations have their limitations such as output power, non-ideal beam quality, poor back reflection stability and can also be difficult to manufacture using the InP toolset. With the invention of PCSEL and the demonstration of lasing by a number of groups using the InP material system some of these limitations can now be overcome [1, 2]. One such advantage of PCSELs is it can be designed to have single mode operation over a wide range of drive currents for a wide range of aperture diameter sizes i.e. small (~10um) to large high-power devices (> mm) as shown in [3]. With this knowledge and the demonstration of other key features such as narrow linewidth, low cost, ease of assembly (surface emission and high collimation) we can begin to assess the InP PCSEL for a range of applications in the wavelength regime (1.2–1.7 μm).

Methods and Results

The PCSELs in this work are based on a PIN structure with an air-void photonic crystal (PC) positioned on the N- side of the device. The lasers have InGaAlAs waveguide structure and MQW active regions based on our DFB lasers to aid the comparison.

We have fabricated a range of devices with differing contact window aperture diameter from 40um to 400um and a number of of photonic crystal designs to assess the maximum output power, efficiency and threshold current. We have also bonded the devices to various carriers to assess the thermal limitations of the PCSEL configuration.

We will present results to suggest, with further optimisation, it should be possible to fabricate small aperture devices with thresholds as low as 5mAs able to compete with the current InP VCSEL technology. We will also show, using the same basic platform, we should be able to realise larger aperture devices capable of output powers >1-2W to outperform the current set of high-power DFB and Grating Stabilised GS- FP lasers

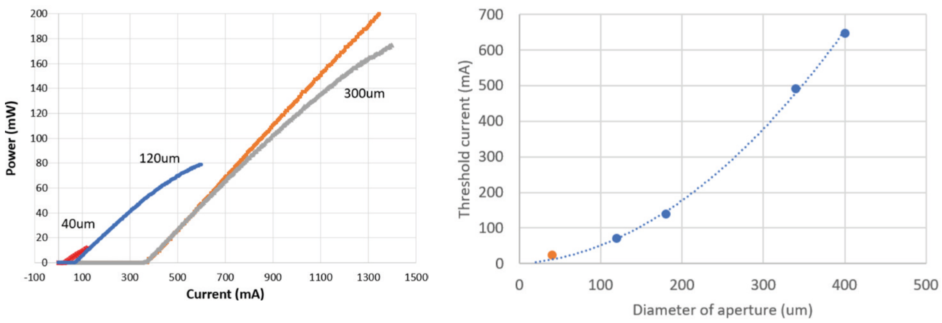

Figure 1. (a) LI plot for a various aperture size devices. (b) Threshold current dependence as a function of diameter.

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Theoretical Analysis of Large-area Photonic-Crystal Surface-Emitting Lasers

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Abstract

We review our recent progress in theoretical analysis of large-area photonic-crystal surface emitting lasers (PCSELs). Through transient simulations considering carrier-photon interactions inside large-area PCSELs, we reveal that the photon distribution spontaneously follows the injection current distribution owing to carrier-induced refractive-index change, suppressing spatial hole burning and enabling 100-W-to-1-kW-class single-mode operation.

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Acknowledgements

This work was partly carried out under the Programs for Bridging the gap between R&D and the Ideal Society and Generating Economic and Social Value (BRIDGE), Cabinet Office, Japan. This work was also partially supported by a Grant-in-Aid for Scientific Research (22H04915, 24H00430) from the Japan Society for the Promotion of Science (JSPS).

Introduction

Photonic-crystal surface-emitting lasers (PCSELs) enable high-power, coherent lasing oscillation in ultra-large emission areas owing to the two-dimensional standing-wave resonance induced at a singularity point (Γ point etc.) of the photonic band structure [1]. Recently, the size and output power of single-mode PCSELs have been rapidly increasing, and 50-W output power under continuous-wave (CW) operation in a 3-mm-diameter device was demonstrated in 2023 [2]. Along with such remarkable experimental progress, the development of theoretical analysis methods which enable accurate prediction of the lasing characteristics of large-area PCSELs is becoming increasingly important. In this talk, we review our recent progress in theoretical analysis of large-area PCSELs, especially focusing on the physics that allows single-mode oscillation over an ultra-large (3-10 mm) area even under high current injection [3,4].

First, we briefly review the theoretical analysis methods of large-area PCSELs. We especially focus on a time-dependent three-dimensional coupled-wave theory (3D-CWT) [3], wherein mutual optical couplings of waves inside photonic crystals as well as gain and refractive-index changes due to the carrier-photon interactions inside the active layer are fully considered. Using this method, the temporal and spatial evolution of both photon and carrier distributions in large-area PCSELs can be obtained, and various lasing characteristics such as current-light-output characteristics, near-field and far-field patterns, and lasing spectra can be predicted.

Second, we present the simulation results of lasing characteristics of ultra-large-area PCSELs [4,5]. By reducing the magnitude of the Hermitian and non-Hermitian coupling coefficients of the photonic crystal while maintaining their balance, both the frequency difference and the threshold gain difference between the fundamental mode and higher-order modes can be increased, enabling single-mode operation. Importantly, we reveal that the photon distributions inside large-area PCSELs spontaneously change from the initial unimodal distribution to a more uniform distribution following the injection current distribution as the injection current increases, owing to the carrier-induced refractive-index change and resultant band-edge frequency change. Therefore, by preparing a threshold gain difference large enough to suppress the lasing of the higher-order mode at the threshold current, single-mode lasing can be maintained even under high injection current levels because the spatial hole burning is spontaneously suppressed owing to the above-mentioned uniform photon distributions. In addition, by changing the lattice-point asymmetry (imaginary part of the Hermitian coefficient) as well as the current distribution density inside the device, one can flexibly change the near-field emission profile of the device, such as uniform, doughnut-like, and Gaussian distributions. We also investigate the influence of band-edge frequency non-uniformity that may be caused by various non-ideal factors in ultra-large-area PCSELs, and reveal that the robust single-mode (or few-mode) lasing oscillation can be maintained even when upward-convex band-edge frequency distributions or random frequency fluctuations exist.

Finally, we briefly review our recent studies on the transient analysis of short-pulse high-peak-power PCSELs [6]. We propose a "self-evolving" PCSEL with band-edge frequency gradation, which induces self-Q-switching operation without saturable absorbers owing to the carrier-induced transient change of the band-edge frequency distribution inside the photonic crystal. Based on the numerical design, we experimentally demonstrate self-pulsation with a peak power of several hundreds of watts and a pulse width of <30 ps.

Design of High-Power GaAs PCSELs with an All-Semiconductor Photonic Crystal

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Abstract

We present a design study on large area, high-power PCSELs with an GaAs/InGaP photonic crystal. Using coupled-wave-theory for PCSELs we show that a photonic crystal unit cell with an optimised triangular single-lattice feature is suitable for the realisation of PCSELs with very-large areas while maintaining large mode discrimination and high external efficiency.

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Introduction

Photonic crystal surface emitting lasers (PCSELs) are a class of semiconductor laser which incorporate a 2D photonic crystal in a semiconductor laser structure to provide large area 2D feedback and coupling to surface emission. It was recently demonstrated that by scaling the cavity diameter of a PCSEL to 3 mm an output power of 50 "W" could be achieved in continuous wave operation in a narrow circular beam [1], and an output power of up to 1.8 kW in pulsed operation using multiple active regions [2]. These devices utilise a high index contrast double-lattice photonic crystal, with contrast between semiconductor material and air-voids. In this paper we will present a design for an alternative approach to realising high-power GaAs-based PCSELs, based on an *all-semiconductor* (GaAs/InGaP) photonic crystal, emitting at λ=1070 nm.

Methods and Results

Using coupled-wave-theory for PCSELs and a newly realised design tool [3], we model infinite- and finite-size PCSEL cavities and show that all-semiconductor PCSELs have the potential to be realised with both large mode discrimination and high external efficiency for very-large device areas (1 mm<L<3 mm for a square cavity of size LxL) [4]. This is achieved by exploiting an optimised triangular single-lattice photonic crystal feature which reduces 1D coupling in the photonic crystal. We will discuss some of the design challenges in all-semiconductor PCSELs compared to void-containing devices, and provide an outlook on the manufacturability and potential benefits of these devices.

Acknowledgements

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Laterally Confined PCSELs and Coherent PCSEL Arrays

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Abstract

We report a novel design of coherent PCSEL array by passively coupling compact photonic crystal cavities in the lateral directions. Lateral confined heterostructure photonic crystal cavities offer flexibility in lateral coupling and mode confinement. Experimental characterization results show high beam quality and coherency from our fabricated laser array on InGaAs/GaAs multiple quantum well (MQW) platform.

Introduction

Monolithic PCSELs, also single PCSELs, have been demonstrated to possess high-power exceeding 50 W in continuous-wave (CW) operation and brightness of over 1 GW cm^{-2} sr^{-1} from a 3 mm diameter device aperture [1]. By designing the PC cavities, even higher output power can be achieved with larger cavity sizes. However, as the cavity size becomes larger, laser performance degrades due to the complex thermo-optical and electro-optical effects. At higher injection currents, the spatial hole burning effects create non-uniform gain distribution, thus reducing the lasing efficiency and distorting the mode profiles. High injection current induced thermal effects due to the produced high photon density at the cavity center also bring negative impacts and complexities for compensation design. On the other hand, semiconductor laser arrays are important to the applications of power scaling, which can be a promising solution to overcome the challenges in high-power PCSELs. PCSEL cavities are realized by the two-dimensional (2D) in-plane optical feedback by the PC modulation. Thus, the lateral coupling control between two PCSELs is achievable and such coupled PCSELs have been implemented by applying a waveguide connection in between for active coupling control using its optical gain/loss switching [2].

Methods and Results

In this paper, we investigate a compact design of coherent PCSEL arrays by placing PCSELs with suitable spacing to implement passive couplings (Figure 1). [3, 4] The PCSEL arrays are designed on an InGaAs/GaAs multiple quantum well (MQW) platform for lasing wavelength of 1040 nm. We fabricated single PCSELs and 2-by-2 PCSEL arrays under the same processing parameters and conditions for comparison. The sizes of PCSEL cavities are 100 μm by 100 μm for single PCSEL and individuals in the arrays. To test the coherent operation of PCSEL arrays, we characterize the spectral linewidth properties and measure the coherency in emitted laser beam by self-interference experiments. Linewidth of 0.22 nm from a 2-by-2 PCSEL array and 0.08 nm from a single PCSEL was observed, indicating feasible coherent beam combining with narrow peak wavelength splitting from different PCSELs. The self-interference experiments test the visibility of the interference fringes, showing strong coherency of the emitted beam from the PCSEL array that is similar with a single PCSEL.

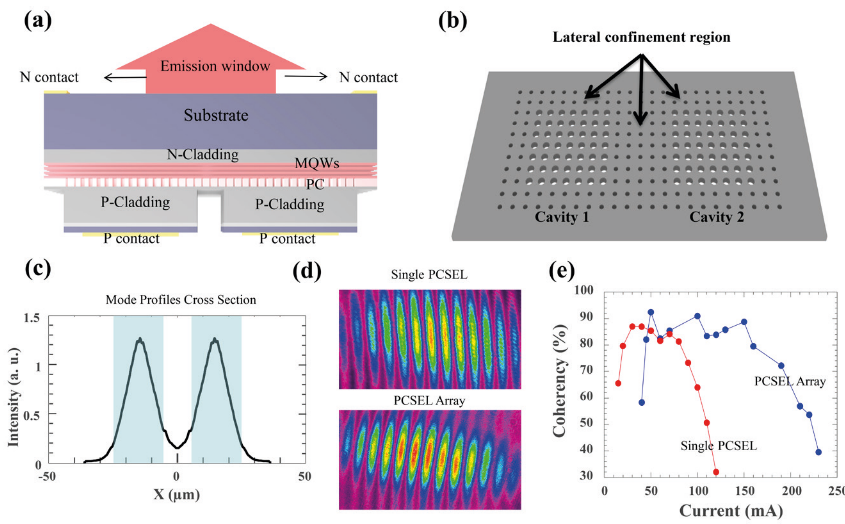

Figure 1. Coherent PCSEL arrays. (a) Cross section view of two coupled PCSELs; (b) Schematic of the PC layer. Cavity 1 and cavity 2 are confined by lateral PC structure; (c) Simulated electric field intensity distribution in the cross section; (d) Far field images of beam self-interference; and (e) Coherency percentage as indicated by the visibility of interference fringes.

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Static and Dynamic Performance of InGaAlAs based Photonic Crystal Surface Emitting Lasers at 1.3 μm

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Abstract

We demonstrate a high power, high wall plug efficiency, single mode InGaAlAs based PCSEL operating up to 85°C. It exhibits high output power ~330mW with a wall plug efficiency of 15% at 25°C. Smaller devices show an average RIN of -152dB/Hz and S21 3dB bandwidth of 5.5GHz.

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Introduction

Edge emitting laser diodes are ubiquitous within datacoms and telecoms. The motivation behind this research is to find a disruptor that can challenge the incumbents in performance and cost as core elements of next generation networks and also in different applications such as lidar, healthcare, and sensing [1]

Methods and Results

The PCSEL in this work consists of a photonic crystal (PC) patterned on the N side of a PIN structure. The InGaAlAs active was chosen as the large conduction band offset can improve over temperature performance. The P metal is used as an electrical contact and a mirror.

The key variables investigated included: fill factor, PC composition, PC thickness, spacer thickness, single lattice and double lattice geometry, hole spacing and hole depth. These experiments were run to understand the design space that had been reported in literature [2,3] and validate the models developed by our partners[2].

The results from Figure1 show the light current (LI) curve over temperature in CW up to 2A for a 500μm^2 double circle PC with a 330μm contact window diameter and fill factor of 17%. The SMSR up to 2A is > 50dB and the lasing mode is on the long side of the stopband. The slope efficiency at 25°C is 0.23W/A with a WPE of 15% thanks to a differential resistance of < 0.1Ω. The output power is > 300mW at 2A with no rollover observed.

PCSELs from the same wafer, with a contact window of 40μm are measured for dynamic performance. The measured average relative intensity noise (RIN) spectrum is -152dB/Hz and the relaxation oscillation frequency is 6.6GHz. The 3dB small signal bandwidth is measured to be 5.5GHz and is limited by the capacitance.

While these results are encouraging we believe that a number of parameters in the design and fabrication can be further optimised to further improve the prospects of using PCSELs in a range of applications [1,3].

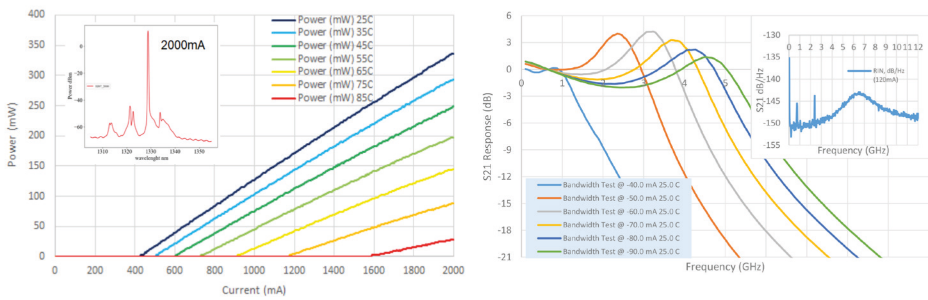

Figure 1. (a) LI plot over temperature (25°C-85°C) up to a bias of 2A. Inset is a plot of PCSEL spectra at 2A and 25°C, (b) Dynamic S21 response plot as a function of bias. Inset is the spectral RIN plot.

Topological Dirac-Vortex Surface-Emitting Laser

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Abstract

We demonstrate stable, room-temperature, continuous-wave Dirac-vortex topological lasers on silicon, achieving linearly polarized vertical surface emission. These lasers offer robust wavelength stability and larger free spectral range, advancing next-generation on-chip light sources.

Introduction

Topological cavity surface-emitting lasers (TCSELs), a novel robust light source technology, while maintaining high beam quality, the emitting beams usually carrying orbital angular momentum (OAM) from these lasers demonstrate unique advantages in enhancing the channel capacity of optical communication systems[1,2].

Methods and Results

The laser utilizes a hexagonal lattice photonic crystal structure [3]. The unit cell of this photonic crystal consists of triangular holes arranged in a specific pattern to break the translational and inversion symmetries. This design allows for the creation of Dirac-vortex states, which are topologically protected and exhibit unique optical properties (Fig. a).

We achieved linearly polarized Dirac-vortex lasers (Fig. b). In the experiments, by increasing the radius R_0 of the central region, the laser linewidth gradually narrowed, indicating a higher quality factor. However, this also led to a reduction in the free spectral range, resulting in a decrease in side-mode suppression ratio, single-mode performance, and a gradually decreasing divergence angle (Fig. 3a). These observations are consistent with the simulations. Besides, Dirac-vortex cavity lasers follow a relationship of $FSR \propto V^{-1/2}$, resulting in a larger FSR for a given modal volume ("V"). This is due to the Dirac-vortex cavity resonance being topologically pinned to the Dirac point, which has a zero density of states, unlike the nonzero density of states in conventional structures.

Our research on silicon-based monolithically integrated InAs/GaAs quantum dot Dirac-vortex topological lasers has achieved stable linearly polarized vertical surface emission through continuous pumping at room temperature. We have also confirmed the robustness of the Dirac-vortex topological laser's wavelength to changes in cavity size, breaking the conventional inverse scaling law of free spectral range with cavity size, providing new insights for next-generation on-chip light sources.

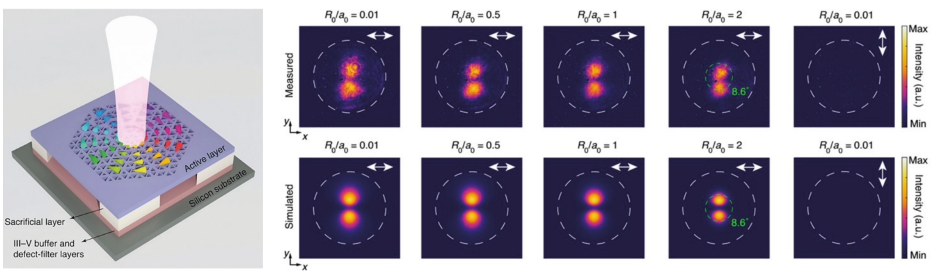

Figure 1. (a) Topological Dirac Vortex Laser on silicon. The photonic crystal is in active layer by partially remove sacrificial layer. (b) Linear polarized far-field emission patterns from the Dirac-vortex lasers in measurement and simulation.

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Laser PCSEL Model in Unstructured TLM Method

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Abstract

We present the latest advances in modelling PCSEL performance using a numerical 3D Transmission Line Modelling (TLM) method based on unstructured grid. The laser rate equations are combined with the Maxwell's equation to provide a realistic model of laser gain. The simulated and experimental results are compared and shown excellent agreement.

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Introduction

The time domain numerical TLM modelling method based on unstructured grid [1] presents an ideal platform for inclusion of the realistic laser gain model. This is achieved by using the polarisation vector to relate carrier dynamics in the lasing media with the macroscopic Maxwell's equations. The physics of lasing media is fully described using polarisation equations for each radiating transition *n* driven by a product of the external electric field *E(t)* and instantaneous population inversion, ΔN_n,

$$\left(\frac{d^2}{dt^2} + 2\varsigma\omega_n \frac{d}{dt} + \omega_n^2\right) P_n(t) = -\kappa \Delta N_n(t) E(t)$$

where *Pn (t)* is time-dependent material polarization for the n^{th} transition, κ is the scaling factor denoting "strength" of the field-atom coupling, ς is the bandwidth of the Lorentizan material response and ω_n is the oscillation frequency of the n^{th} transition. The macroscopic Maxwell's equations are combined with the electron population densities using either the two- or four-level rate equations [2].

Methods and Results

The unit cell if the double lattice InP PCSEL is shown in Fig.1a) showing the cross section of the meshed photonic crystal double lattice region and vertical epitaxy comprising of the reflective cavity, Multi-Quantum Well (MQW) region, photonic crystal (PC) region and top epitaxial layer. The fully reflective mirror is placed at the bottom of the unit cell and the top boundary is matched with the material refractive index. Periodic boundary conditions are placed on the lateral sides to simulate infinite periodicity. The spectrum of the light coming out of PCSEL in the wavelength window 1300-1350nm assuming no gain in MQW (cold cavity) and with frequency dependant gain (hot cavity) is given in Fig.2. It can be seen that in the case of no gain the PCSEL supports 4 distinct modes in the wavelength region. However, when the gain is included in the model one mode is able to combat the losses of the cavity and achieve lasing at 1332nm. The experimental measurements show lasing at 1329nm – the small discrepancy is explained by the assumption of infinite periodicity, lower losses and neglecting thermal expansion in a practical device. Full details will be given in the presentation.

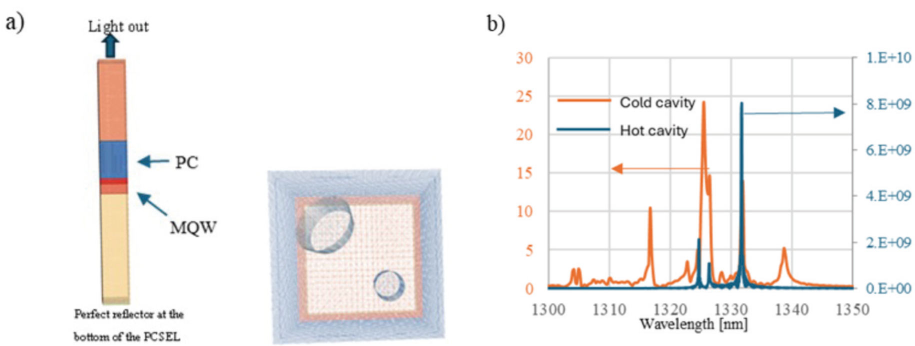

Figure 1. Unit cell vertical profile and meshed double photonic crystal lattice profile. (b) PCSEL spectra in 1300-1350nm region in the case of cold cavity (no gain) and hot cavity (with laser gain model).

Vortex Microlaser Based on Collective Modes of Guided Mode Resonances

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Abstract

Vortex microlasers have emerged as promising optical sources for micromanipulation and quantum communication recently. Here, we propose a photonic crystal (PhC)-based vortex microlaser utilizing the collective modes formed by the guided mode resonances (GMRs). We demonstrate single-mode chiral emission with a low optical-pumping threshold of 18 kW/cm^2 at room temperature.

Introduction

Optical vortices traveling with a helical phase wavefront, carry the orbital angular momentum and have wide applications due to the spatial singularities, such as micromanipulation and quantum communication. Traditional vortex microlasers are mostly based on microring resonator [1] and have phase singularities in real space, suffering significant scattering loss. Momentum-space vortex lasers based on PhC slabs [2] have low lasing threshold by leveraging bound states in the continuum (BICs); however, they have challenges in generating high-order vortices.

In this work, we propose and demonstrate a vortex microlaser utilizing collective modes of GMRs omnidirectionally hybridized within PhC slabs. Inspired by collective modes of Mie resonators [3], we designed square latticed PhC on a InGaAsP membrane with a circular lateral boundary to hybridize GMRs. Hence, single-mode chiral emission was realized with an optical-pumping threshold of 18 kW/cm^2 at room temperature.

Methods and Results

Figure 1a shows our vortex microlaser, which is formed by square latticed air holes and has a heterogeneous structure that the central region A is surrounded by region B. The interface between region A and B offers a circular boundary of photonic bandgap for lateral confinement. Therefore, the GMRs on the iso-frequency contour of region A couple with each other due to scatterings and then collectively oscillate in the form of Bessel functions.

We fabricate samples on an InP-based InGaAsP MQWs wafer and remove the sacrificial layer underneath the MQWs. Our vortex microlaser has a footprint of 26.8×26.8 μm^2 and is optically pumped by a 1064 nm pulsed laser. The lasing threshold is of 18 kW/cm^2 at room temperature as shown in Figure 1b and single-mode lasing is observed as shown in Figure 1c. To verify the characteristics of chiral emission, we measure the polarization distribution and the self-interference pattern of vortex beam as shown in Figure 1d and 1e. A pair of fork fringes with opposite orientations is observed, confirming the phase singularity with the quantum number of $|m|=1$.

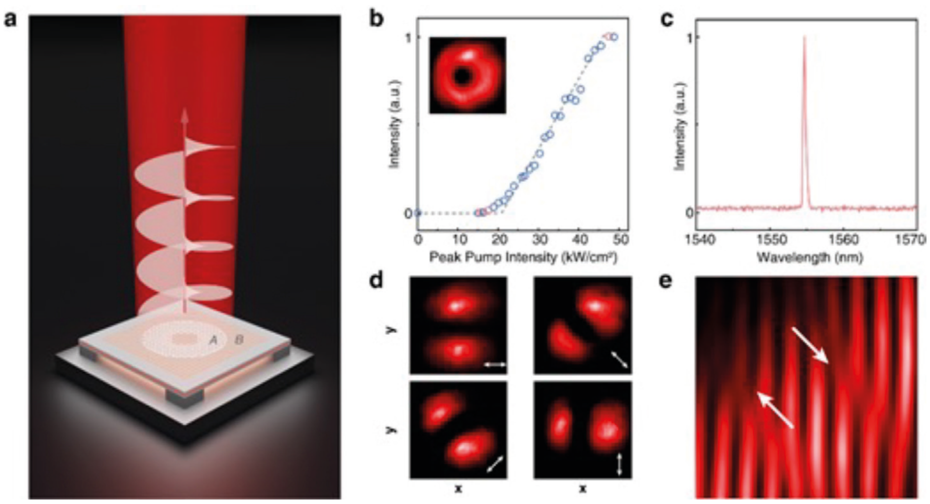

Figure 1. Schematic and experiment results of the vortex microlaser. (a) Schematic of the vortex microlaser. (b) Measured power curve showing a threshold of 18 kW/cm^2. (c) Measured above-threshold PL spectrum. (d) Polarization distribution of the vortex beam. (e) Self-interference pattern of the vortex beam.

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Triple-lattice Photonic Crystal Surface Emitting Lasers

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Abstract

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

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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.

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 905nm, 940nm InGaAs/GaAs quantum wells (QWs), 1.246μm InAs/GaAs quantum dot (QD) and 1.55μm InP based QW material [2-6]. The low threshold current ~ 35.6mA was realized in 940nm PCSEL, which is compared with traditional DFB lasers. The continuous wave (CW) operation of 1.246μm InAs/GaAs QD and 1.55μm 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.

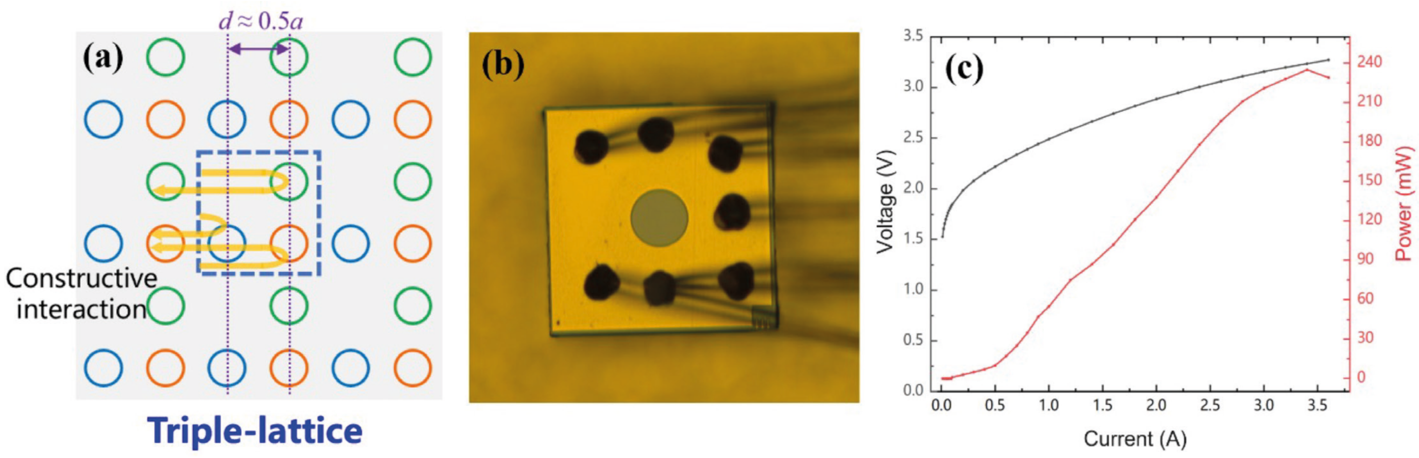

Figure 1. (a) Principle of triple-lattice PCSELs, (b) image of the PCSEL chip bonded on a heat-sink with p-side down, (c) L-I-V performance of 940nm PCSEL fabricated by nano-imprint.

Bound-State-in-the-Continuum Lasing Modes in InGaAs Nanowire Photonic Crystals

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Abstract

We report experimentally observed bound-state in the continuum lasing modes from deformed honeycomb lattice nanowire photonic crystals. Additionally, we show the angular distribution of the intensity which depends on the pump area and determine the topological charges from the distribution of local polarization.

Introduction

Topological photonics allows for new designs for topological edge mode lasing, e.g., valley-Hall photonic crystal lasers [1]. Alternatively, these new designs can be used for vertically emitting lasers based on semiconductor nanowires, e.g., a deformed honeycomb lattices [2]. Bound-states-in-the-continuum (BICs) can be used for enhancing non-linear effects with enhanced Q factors [3]. Interestingly, the quadrupolar modes in a deformed honeycomb lattice are BIC modes and show a singular point with a topological charge in the far-field radiation pattern.

II. Methods and Results

Using numerical simulations, we design the nanowire lasers by deforming the hexagons in honeycomb lattices of InGaAs nanowires. The undeformed honeycomb lattice has the periodicity a = 640 nm and the centre-to-centre distance $R = a/3$ = 213 nm. For extended and compressed honeycomb structures, we set R = 230 nm and R = 190 nm respectively. To fabricate the laser, we use the selective area epitaxy method which employs a 20 nm SiN mask with an array of air holes with the diameter of 30 to 50 nm to define the location of the InGaAs nanowires. The SEM images of the fabricated nanowires are shown in Fig. 1(a).

The extended honeycomb lattice has a band gap at Γ-point as per Fig. 1(b). As reported in Ref. [4], the two band edges have different symmetries where *p*-orbital (*d*-orbital)-like are at the top (bottom) band edge. The doubly degenerate d-orbital like band edge mode is a quadrupolar mode and, importantly, is a BIC mode with a high *Q*-factor. The radiation pattern was measured using the back-focal plane measurement. Optically pumped lasing from the compressed honeycomb lattice generates a circular radiation pattern whereas the extended one has a doughnut-shape radiation pattern.

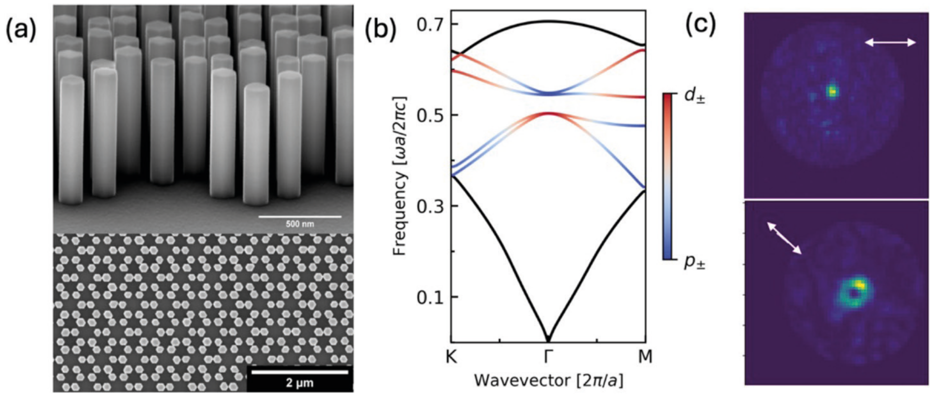

Figure 1. (a) SEM image of InGaAs nanowire photonic crystal laser with an extended honeycomb lattice. (b) Photonic band structure with band inversion. (c) Far-field pattern of the lasing modes for the compressed (top) and extended (bottom) honeycomb lattices.

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First electrically-driven plasmonic crystal laser

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Abstract

Electrically-driven plasmonic crystal lasers (PCLs) have been demonstrated for the first time. The 1-D InGaAs/GaAs PCLs are consisted of SiNx grating covered by Ti/Pt/Au. The measured lasing threshold current, slope efficiency, and linewidth are 1.08 A, 12.7 mW/A, and 1.1 nm, respectively, at room temperature.

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Introduction

Similar to photonic-crystal surface-emitting lasers (PCSELs), plasmonic crystal laser (PCL) receives growing attention due to its small divergence angle, narrow linewidth, and, particularly, great potential for ultra-high-speed operation [1-3]. Room-temperature operation with optical pumping exhibited excellent device performance [3,4] but there is no successful electrically-injected laser diodes (LD) up to date. Inspired by the fabrication process and success of PCSELs, in this work, the first electrically-driven PCLs working at room temperature have been demonstrated. The epi-structure, lasing characteristics and device performance will be presented.

II. Methods and Results

Figure 1a shows the epitaxy structure and measured photoluminescence (PL) of our sample. The six InGaAs quantum wells are placed very near the surface to enhance plasmonic coupling [3]. Figure 1b illustrates the bird-viewed device structure of our back-side emitting PCL. The 150-nm-thick PECVD SiNx gratings were formed by e-beam lithography and dry etching, then covered by p-type ohmic metal Ti/Pt/Au (2/5/200 nm). The process was finished with n-side polishing and n-ohmic metalization. The grating size is 350x350 µm2 with the respective period and width of 279 nm and ~50 nm. Figure 1c shows the typical top- and bird-view SEM images. Performed at pulse condition with pulse width of 0.35 •s and duty cycle of 0.035 %, Fig. 1d plots the measured L-I-V characteristics at 10 oC, resulting threshold current density of 0.88 kA/cm2 and slope efficiency of 12.7 mW/A. The linewidth is 1.1 nm and the redshift rate in 10 - 30 oC is 0.088 nm/K, as shown in Fig. 1e. The line-shape far-field pattern in Fig. 1f indicates the divergence angle in x- and y-direction are 1.4o and 14.7o, respectively.

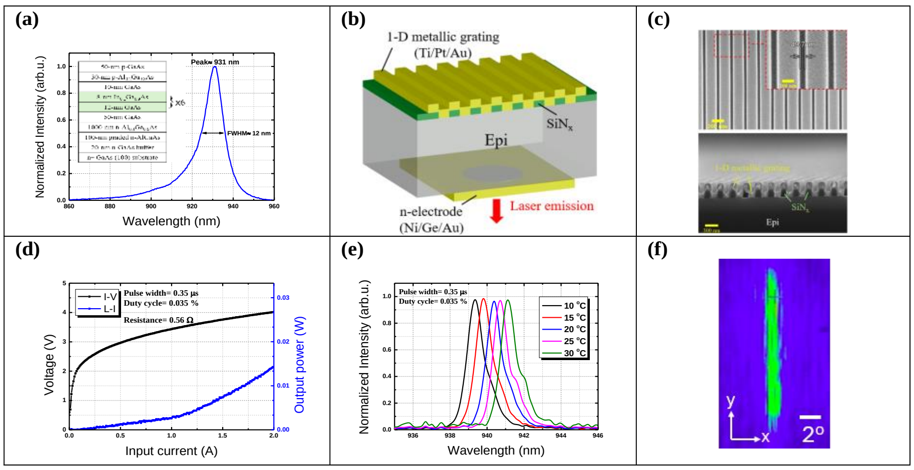

Figure 1. (a) Epitaxy structure and PL spectra. (b) Schematic of device structure. (c) SEM images. (d) L-I-V at 10 oC. (e) Temperature-dependent lasing spectra. (f) Far-field pattern.

Characterizations of Topological-Cavity Surface-Emitting Laser

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Abstract

In this study, we measured the near-field and the far-field of the topological-cavity surface-emitting laser of 500 μm in diameter, verifying their single-mode and vector-beam nature. This is consistent with the highly-symmetric design of TCSEL having C3v point-group symmetry.

Introduction

The topological-cavity surface-emitting laser (TCSEL) is one of the most promising applications of topological photonics [1]. As a new type of surface emitting laser, TCSEL with its outstanding single-mode performance, high power, and low divergence angle, are expected to potentially useful [2]. The measurement of the near-field and the far-field of TCSEL, like their lasing spectrum, is the crucial mean of verifying the topological nature of the topological mode. Here, we measured the near-field and the far-field of TCSEL, as well as the lasing spectrum.

II. Methods and Results

The amorphous Si film deposits on the MQW epi-structure via chemical vapor deposition, and then processed into a Dirac-vortex cavity structure using electron beam lithography (EBL) and dry etching, as shown in Figure 1(a). We characterized the lasing spectrum and the optical field of this sample under 1064 nm pump laser (pulse width = 4 ns and pulse rate = 250 kHz). These results are shown in Figure 1.

In the experiment, we used optical spectral analyzer and power meter to measure the lasering spectrum. The designed lasing wavelength of TCSEL is 1554 nm which performs outstanding single-mode behavior, as shown in Figure 1(b). To further verify its vector-beam nature, we tested the near-field and the far-field of this mode, the results show in Figure 1(c). Due to the different optical confinement factors and the out of plane coefficients around the cavity, the near and the far field output spot exhibits a three-lobed pattern. The polarization of the near field and the far field is the radial polarization.

References

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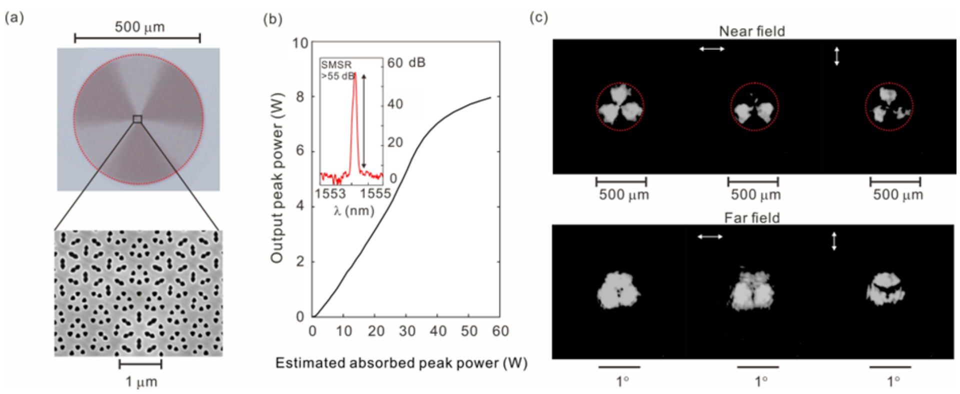

Figure 1. The experimental characterization results of TCSEL. (a) The optical microscope and SEM image of TCSEL. (b)The lasing spectrum of TCSEL. (c) The near and the far field of TCSEL.

Coupled-wave theory for topological cavity surface-emitting lasers

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Abstract

We study the topological-cavity surface-emitting laser (TCSEL) based on the three-dimensional coupled-wave theory (3D CWT) which has been successfully applied to photonic-crystal surface-emitting lasers (PCSEL). With this quasi-analytical approach, we explain the mode selection mechanism and lasing performance of TCSEL.

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Introduction

Recently, the topological-cavity surface-emitting laser1,2 has been proposed as a promising way for high-performance surface-emitting semiconductor laser. However, it is not computationally feasible to model the entire TCSEL with full-wave simulations, whose device size is thousands of periods of non-periodic lattices in a slab waveguide. We extend the 3D CWT to model a TCSEL by introducing spatially non-uniform coupling matrices. Furthermore, we demonstrate that TCSEL has a large threshold margin with large area, which is important for achieving large-area single-mode semiconductor lasers.

II. Methods and Results

In the framework of 3D CWT with a triangular lattice, the electric fields at the Γ point are mainly composed of six fundamental propagating plane waves (R_1, 〖S_1,R〗_2,S_2,R_3,S_3). The coupling of these waves is described by a coupling matrix, which can be approximated via Fourier coefficients of the refractive index distribution of the periodic structure or rigorously extracted from the full-wave simulated band structure. The radiation field could also be calculated using an out-of-plane coupling matrix and the far field is obtained through the Fourier transform of the radiation field.

For a finite-size PCSEL, after discretizing the entire cavity, the coupling matrices are uniformly distributed at each node of the differential grid. In the case of a TCSEL, where the structure is non-periodic, we use different coupling matrices that are specifically calculated based on the local periodicity approximation at different nodes. Base on the staggered-grid difference method, the resonance wavelengths, corresponding thresholds and mode distributions can be obtained by solving the eigenproblem on the differential grid with such non-uniformly distributed coupling matrices with open boundary conditions. Similarly, the radiation field can be derived using non-uniformly distributed out-of-plane coupling matrices and the mode distribution of the topological mode. The staggered grid is set up with a precision of 30×30 to achieve converged solutions shown in Figure 1.

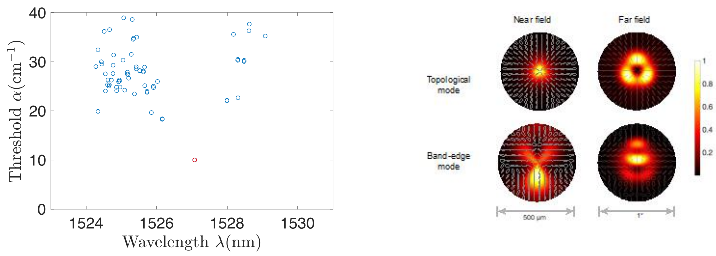

Figure 1. (a) Calculated eigenmodes in a finite-size TCSEL with diameter L=500μm. The topological mode (red circle) located in the band gap has the lowest threshold. (b) Near field and far field of the topological mode and the band-edge mode with the lowest threshold.

Resonator Embedded Photonic Crystal Surface Emitting Lasers

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Abstract

Resonator-embedded photonic crystal surface-emitting lasers (REPCSELs) utilize an external resonator effect formed by using unsaturated DBR reflectivity. This design offers wavelength-selective modification of photon lifetime due to selective in-plane loss modification for particular modes, resulting in a selective increase in out-of-plane scattering.

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Introduction

Lateral optical confinement has been explored in various systems using band-edge resonances of 2D photonic crystal (PhC) slabs. Finite 2D PhC structures act as lossy resonators, with losses increasing as lateral size decreases[1]. However, adding boundary mirrors can make a finite 2D PhC behave like an infinite PhC. These effects have been demonstrated in optically pumped laser structures using PhC heterostructures [2] or DBR pairs [1], and confirmed through cold cavity band-structure analysis, where boundary mirrors reduce in-plane optical loss. In this work, we present results on all-semiconductor REPCSEL devices with embedded DBR structures surrounding the PCSEL region, specifically targeting the key optical communication wavelengths of 1310 nm and 1550 nm.

Methods and Results

The inset of Fig. 1(a) shows a schematic of the REPCSEL with an emission wavelength of 1.3µm, where the PC and DBR regions are defined by the 2nd and 1st order Bragg conditions, respectively. The gap between PCSEL and DBR is designed to have a zero-phase shift for reflected light. The PhC region consists of 500×500 PhC atoms and mirrors with 100 DBR periods on each side. It was found that REPCSEL can achieve a threshold current of 324mA under pulse condition, while none of the PCSEL can lase up to 1.2A. A slope efficiency of 0.04 W/A and a power conversion efficiency (PCE) of 2% at 1 A were observed.

Figure 1(b) shows the measured band structure of the REPCSELs with an emission wavelength of 1.5 µm. The dotted lines represent are from simulation. Three different DBR target wavelengths (λ1 =1550nm, λ2 =1542nm & λ3 =1534nm) were used. The calculated internal resonance enhancement factor (IREF) shows the various modifications of the modes at the Γ point when shifting the DBR target wavelength.

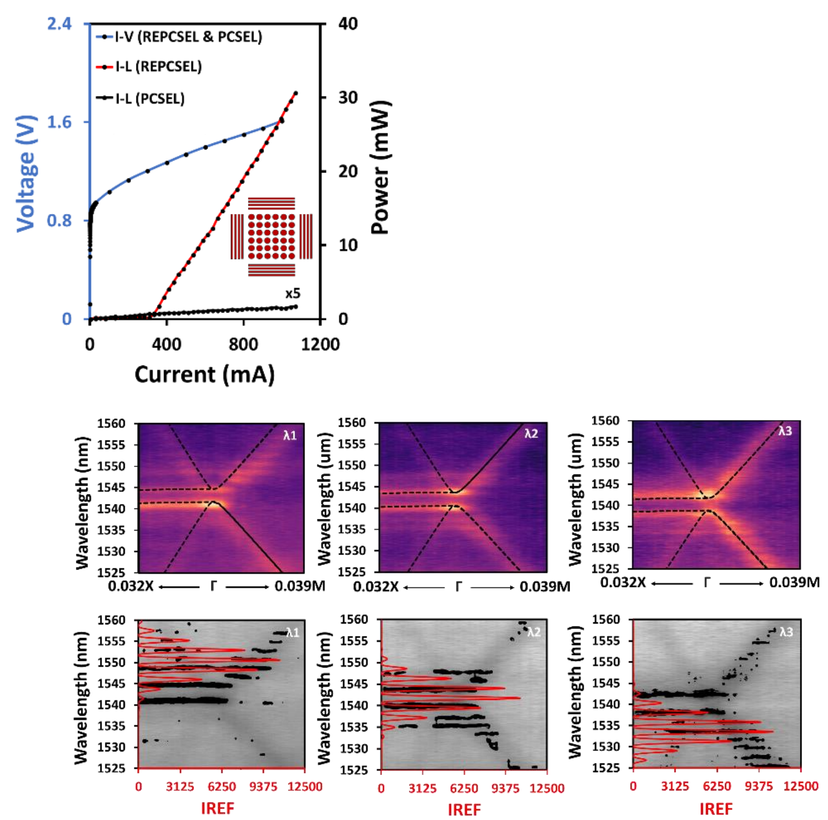

Figure 1. (a) The LIV results of PCSELs and REPCSELs at 1.3 µm emission wavelength. (b) Visualisation of band-structure of REPCSEL at 1.5 µm emission wavelength; DBR periods targeting at λ1 =1550nm, λ2 =1542nm & λ3 =1534nm. Greyscale with thresholds selected to highlight peaks in the band-structure image.

A Novel Technique for PCSEL Photonic Bandstructure Measurement

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Abstract

Resonator-embedded photonic crystal surface-emitting lasers (REPCSELs) utilize an external resonator effect formed by using unsaturated DBR reflectivity. This design offers wavelength-selective modification of photon lifetime due to selective in-plane loss modification for particular modes, resulting in a selective increase in out-of-plane scattering.

Introductions

In Photonic Crystal Surface Emitting Lasers (PCSELs), a two-dimensional (2D) photonic crystal (PC) is incorporated to support 2D coherent lasing. Experimentally probing the bandstructure affords us insight into the photonic properties of the device and allows us to measure the frequencies and quality factors (Q-factors) of the PCSEL's band-edge modes, as well as explore its symmetry.

Methods and Results

The n-side-emitting, 1.3µm InP PCSEL is bonded p-side-down for measurement. A lens is mounted above the device at the lens's focal length, which collimates light emitted with a polar angle, $\theta \lesssim 20°$. A single-mode fibre is positioned above the lens to measure the angularly-dependent spectra - its lateral position is controlled by two perpendicularly oriented linear stages. The in-plane wavevector, k, is related to θ [1], and is accessed by manoeuvring the fibre in the xy-plane. Two sets of reciprocal space coordinates, or 'paths', are devised: the first is a circular path around the Γ-point at θ= 3°, which checks the alignment to the Γ-point and rotation of the device in the xy-plane, in addition to probing the rotational symmetry of the bandstructure. The second is a 'XΓM' path, which measures the bandstructure along the conventional high-symmetry directions of a square-lattice PC (X→Γ, then Γ→M), with θ≤ 5°.

Fig.1 shows the experimentally measured bandstructure along the (a) circular (b) and XΓM paths, where the drive current is 125mA (the threshold current is 207mA). The four characteristic bandedge modes are observed at the Γ-point (c) and their Q-factors are extracted from their frequencies and spectral widths according to Q=ω/FWHM; the Q-factors are 1900, 3000, 2600 and 2000 for the A, B, C and D modes respectively. From the circular bandstructure, the pattern appears symmetrical and well aligned with the high-symmetry directions, suggesting that the alignment procedure was successful and that there is minimal rotational offset between the basis vectors of the PC lattice and the directions of the linear stages. In addition, it is clear that although the PC-lattice has four-fold rotational symmetry, the circular bandstructure does not. This is because the PC unit cell - a design similar to [2] - does not share the same anisotropy of the lattice, so the four Γ→X and Γ→M directions are not all equivalent. We are exploring these techniques draw further links between the bandstructure and device performance.

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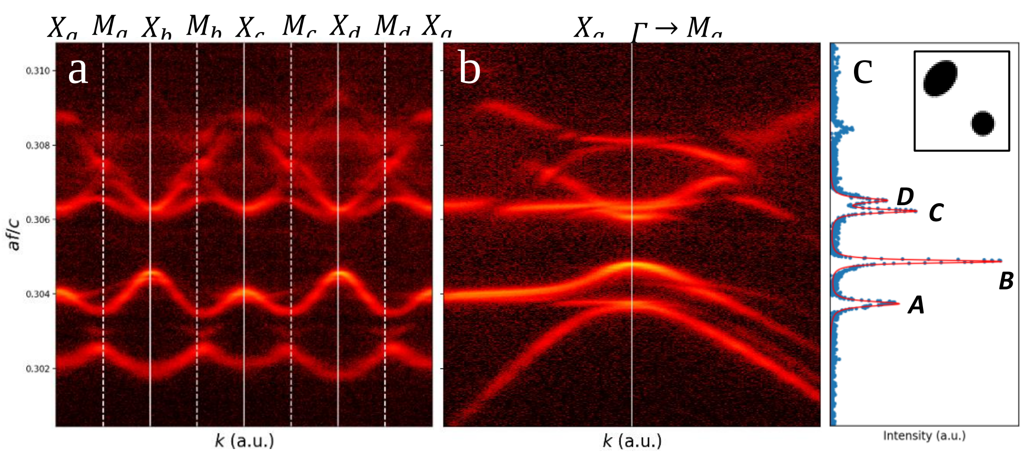

Fig. 1: Experimentally measured photonic band structure along a circular (a) and XΓM (b) path. The spectrum at the Γ-point is plotted (c) and the four band-edge modes are identified; the PC-unit cell is shown in the inset, with air indicated by the black regions.

Ultralow-threshold 1.3 µm single-mode quantum-dot laser based on bound-states in the continuum

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Abstract

On-chip vortex beam lasers are key components of ultra-compact integrated communication systems with high-data-capacity transmission. Here, we demonstrate an ultralow threshold (7.5 µW) vortex beam laser based on optical bound states in continuum (BICs), comprising an InAs/GaAs quantum dot active region and lasing at ~1.3 µm at room temperature. This work shows an energy-efficient single-mode BIC laser, offers great potential to on-chip communication systems.

Introduction

Currently, miniaturised III-V based on-chip lasers-including defect cavity lasers, nanoscale coaxial lasers, micro-disk lasers-attract enormous attention, owing to their compactable, low power consumption and wide emission range. However, only BIC lasers have the capability of delivering vortex beams[1-3]. On-chip BIC laser is developed based on the concept of BIC mode with OAM referred to a none-zero topological charge, which has no radiation loss owing to the perfect localised field, leading to an infinity quality factor, Q. Moreover, BIC lasers constructed by photonic crystal (PhC), a 2D fundamental topological object that has a compactable planar structure, is demanded in photonic integrated circuits. The employed symmetry-protected BIC localised at Γ point manifests a helical polarisation state, observed as OAM associated with different topological charges.

Methods and Results

Here, we developed a 1.3 µm QD BIC laser (shown in Fig. 1a) on III-V material platform, which exhibits a single mode 1.3 µm vortex beam generation. This on-chip BIC laser possesses a lasing at 1254 nm with ultralow threshold power of 7.5 µW (0.038 W/cm²) at room temperature (shown in Fig. 1b), which is, to the best of our knowledge, the lowest threshold BIC reported in the literature[1-3]. The performances of this nano-laser that are examined with optical set-ups well match with the simulated results. As designed, a vortex beam with a doughnut shape beam pattern is generated by this QD BIC laser. This vortex beam has been examined by comparing measured far-field patterns and simulated far-field patterns associated with different polarisation conditions. The BIC laser performs as an ultralow threshold vortex beam laser.

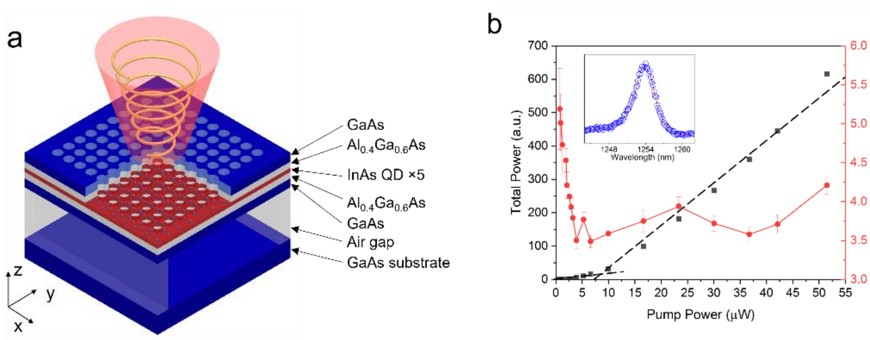

Figure 1. a Schematic of the fabricated BIC laser. The device is designed with a square lattice that supports a TE polarized BIC mode emitting at Γ-point. A vortex beam (red) generated vertically through the BIC cavity that is suspended on the GaAs substrate. This suspending structure is utilized to confine the beam vertically by delivering a refractive index contrast. It is constructed through a membrane that consists of an active region formed by 5 layers InAs/GaAs QDs, two waveguiding layers of Al0.4 Ga0.6As and a caping layer of GaAs. b. Integrated light intensity as a function of pumping power (light-light curve) for the entire spectrum from 1100 nm to 1400 nm. A lasing threshold of 7.5 µW is identified from the linear fitting dash lines (blue). The black round dots corresponding to y-axis at left are the measurement data. An orange line represents the linewidth of the Lorentzian fitted spectrum associated with different pumping power. An inset depicts a spectrum measured at a pumping power of 9.9 µW with a measured linewidth of 3.5 nm.

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Switchable Tamm Cavities Using Phase Change Materials

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Abstract

Silicon-silica Distributed Bragg Reflector(DBR) stacks are combined with thin layers of Ge2-Sb2-Te5 phase change material to create switchable Tamm resonant cavities in the 1300-1600nm wavelength range. Finite Difference Time Domain modelling is used to optimise the stack design and reflectance measurements for the silicon-silica DBR have been completed.

Introduction

Tamm resonant cavities are a combination of a conventional DBR with a thin conducting upper layer which form a resonant cavity which can be tuned by adjusting the thickness of the conducting layer and a spacer layer above the DBR. These are showing great promise for laser applications where the cost associated with growing an upper DBR layer in a Vertical Cavity Surface Emitting Laser (VCSEL) can be removed[1,2]. They also lend themselves to being combined with various metasurface designs for controlling beamshape, modal behaviour and reflectivity. This paper explores the replacement of the conducting layer with a switchable phase change material, in this case GST225, a chalcogenide glass which can be rapidly switched in a non-volatile way between its amorphous and crystalline states which have radically different refractive indices[3]. This could open up a range of new applications in LIDAR, remote sensing and optical beam-steering.

Methods and Results

Figure 1a shows the Tamm structure we are studying and the DBR structure that has been fabricated, all layers are quarter wavelength at 1550nm apart from the GST and final silicon spacer layers. Figure 1b shows the predicted switching behaviour at 1550nm for different GST thicknesses, showing excellent switching performance at ~45nm thickness. The DBR has been fabricated and characterised and the next step is to add the GST layer and test the final structure. Future directions include patterning the GST layer to allow metasurface designs to be incorporated.

(a)

(b)

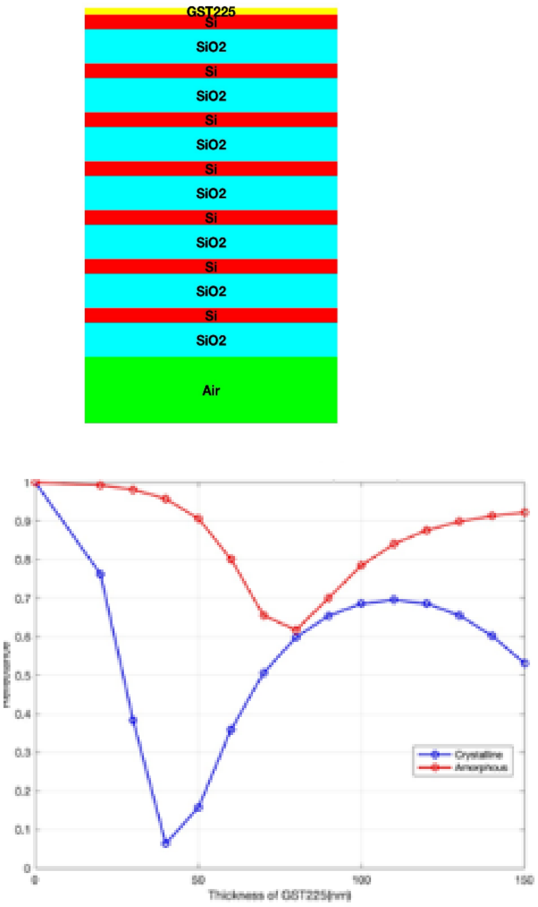

Figure 1. (a) Tamm structure (b) Lumerical Finite Difference Time Domain results for switching between amorphous and crystalline states of GST. Measured ellipsometry data is used for real and imaginary refractive indices of the GST layer.

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Towards TAMSELs - Tamm Assisted Meta Surface Emitting Lasers

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Abstract

We have designed and fabricated a metasurface combined with a Tamm optical state to shape the far field, and in doing so pave the way for Tamm MetaSurface lasers, an analogue of the PCSEL

Introduction

Tamm Optical States (TOS), sometimes called "Tamm plasmons", are the photonic analogue of the well known Tamm electronic states that are formed at the termination of a crystal lattice[1]. They are formed by the termination of a dielectric semiconductor distributed Bragg reflector with a thin (>10s of nanometers). These confine light between the metal and the DBR. They offer advantages over conventional surface plasmons: they coupled vertically to TE and TM light without the need for momentum matching, and they are much lower loss as the peak of the electric field lies in the dielectric rather than at the metasurface. We report the design and fabrication of a Tamm metasurface, designed like a circular Bragg grating to achieve a wide Tamm mode but with shaped emission.

II. Methods and Results

We have designed a Tamm structure that is close to the technologically important telecommunications O band[2]. By depositing a layer of gold we form a Tamm states, and have used a focused ion beam to write a range of metasurfaces into the gold. Fourier microscopy of the sample illustrates the possibility to shape the far field emission by coupling of the Tamm state to this extended 2D metasurface, allowing the shaping of the fair field. This raises the intriguing possibly of other forms of Tamm photonic crystals with gain, to form a TAMSEL. The freedom[3] to form arbitrary metasurfaces provides the opportunity intriguing, readily manufacturable devices.

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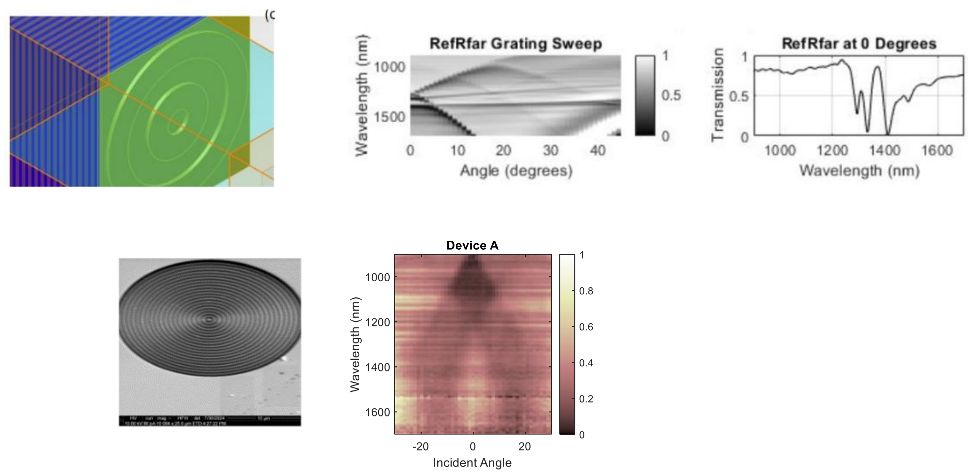

Figure 1. (a) A simulated and fabricated metasurface consisting of a gold Circular Bragg Grating on top of a suitable designed Distributed Bragg Reflector (b) Fair field calculations of shaped emission of the Tamm metasurface

Void-Retaining Epitaxy for Photonic Crystal Surface Emitting Lasers

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Abstract

This work outlines recent advances in void-retaining epitaxial regrowth and void engineering in photonic crystal surface emitting lasers.

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Introduction

Metalorganic vapour phase epitaxy (MOVPE)-based regrowth has been one of the key technologies driving the progress of photonic crystal surface emitting lasers (PCSELs) in the last decade, enabling beyond-Watt-class operation, and opening new degrees of freedom to PCSEL design, allowing for both all-semiconductor and void-containing photonic crystal (PC) structures to be realised [1]. The latter case, void-retaining epitaxy (VRE), can be considered as a distinct paradigm of crystal growth, and an understanding of void engineering in this regime is crucial for optimised device performance. However, to date, few studies have been conducted focusing explicitly on VRE, and our understanding of the full potential of this technique is still limited. In this work, key aspects of the VRE regrowth process and void formation, including the effects of mass-transport (MT) [3], and adatom kinetics and crystallographic anisotropy [4], are reviewed and illustrated for GaAs-based photonic crystal structures.

II. Methods and Results

PC test structures consisting of square-lattice arrays of circular grating pits were fabricated on (100)-oriented GaAs substrates by electron-beam lithography and reactive ion etching. To investigate the effects of pre-growth MT in this system, two samples were subjected to nominally identical regrowth process, differing only in the temperature ramp time prior to deposition - in both cases, MT was quenched by the growth of an AlAs/GaAs superlattice structure designed to illustrate the evolving growth front. Cross-section scanning transmission electron microscopy (STEM) imaging, reveals that longer ramp times lead to significant MT and deformation of the grating pit, and the resulting high-order crystal planes (and their associated higher growth rates) result in the formation of much smaller voids than in those where MT is minimised. Following this, the roll of intrinsic adatom mobility on void formation was explored through three samples for which the aluminium composition of the infill layer was varied. As shown in Figure 1b, an increase in low-mobility aluminium species during deposition favours reduced infilling of the grating pit, leading to significantly larger voids with more complex geometries. Additionally, it is shown that an in-plane asymmetries in void shape arise due to the natural growth rate anisotropies associated with high-index crystal planes long orthogonal axes of the semiconductor crystal. These findings point towards new routes for the engineering and optimisation of complex void geometries in buried PC systems, unlocking further degrees of freedom for future device design.

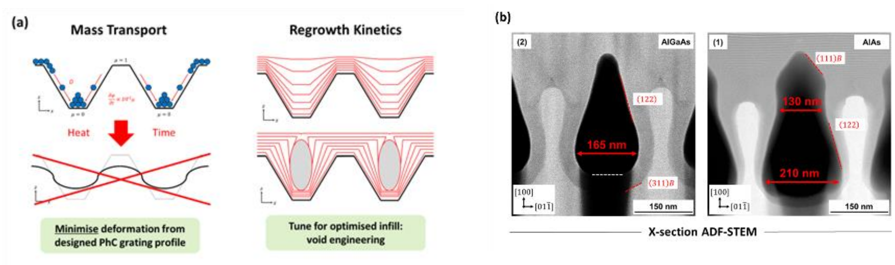

Figure 1. (a) Schematic diagrams highlighting the main considerations for VRE, namely control of mass-transport and tuning of adatom kinetics during regrowth. (b) Cross-sectional STEM images illustrating how complex void geometries can emerge by exploiting the intrinsic adatom mobility of different (Al)(Ga)As alloys.

Probabilistic Markov Chain Modelling of PCSEL Losses

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Abstract

We extend our work on probabilistic Markov chain modelling of PCSELs to consider devices with a pumped and un-pumped PC region, including self-absorption in the un-pumped QWs. The interdependence of parasitic losses, and impact on internal loss is highlighted.

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Introduction

The determination of the link between microscopic scatting coefficients (κ1D, κ2D & κrad) and device level optical losses is of critical importance to PCSEL engineering and development. The experimental determination of device level optical losses remains difficult [1]. The development of simulation methods to assess the device level optical losses as a function of chip design and PC scattering coefficients is therefore timely. This paper reviews and extends our work to consider a PCSEL with a pumped and un-pumped region, that is commonly used to maximise slope efficiency through the elimination of in-plane loss. We incorporate and analyse the effect of self-absorption of the active element.

II. Methods and Results

The probabilistic Markov chain (PMC) model transforms the scattering coefficients into probabilities of light scattered to specific directions and calculates the device level losses of PCSEL devices. In our PMC method, each matrix element is a PC atom, and the time unit, is defined as the time of one photon travelling from one PC atom to the closest neighbour [2,3]. Input parameters are κ1D, κ2D, κrad, and internal loss (κi).

We consider a square PCSEL [4], that we previously used to validate the model [2] with the electrical contact defining the pumped, gain region of side length S. This is bound by a region of width W, consisting of an un-pumped active element and PC. This is surrounded by a perfectly absorbing region. See Fig. 1. We show that when self-absorption is included, αi no longer has a unique value, but is a function of scattering coefficients, number of QWs in the active element, operating wavelength, pumped region size S, and un-pumped width W. For modest un-pumped PC width, we show the interdependence of α// and αi. The importance of this is PCSEL characterisation will be discussed.

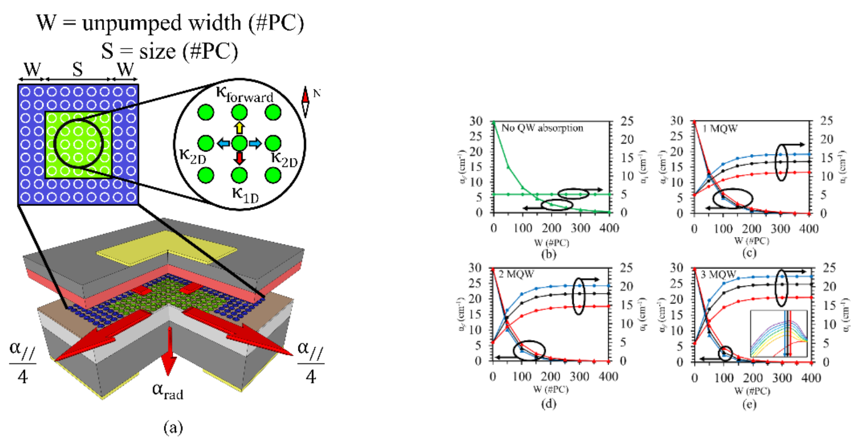

Figure 1. (a) Schematic of the PCSEL simulated, showing pumped and un-pumped regions. In-plane loss and internal loss as a function of un-pumped PC region width, W, for a PCSEL of S=700x700 for (b) no self-absorption, (c) 1 QW, (d) 2 QW, (e) 3 QW. The inset to (e) shows the PCSEL wavelength-gain detuning used.

Towards Void Containing Quantum Cascade Mid-IR PCSELs

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Abstract

Key building blocks for the development of quantum cascade photonic crystal surface emitting lasers are discussed. These include opportunities for optical lithography of the photonic crystal pattern, void retaining epitaxial regrowth, and the simulation of key parameters. We show that photolithography can readily be applied to unique unit cell photonic crystals with periods above 2100nm, and that void retaining epitaxy can be successfully applied to test structures.

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Introduction

The determination of the link between microscopic scatting coefficients (κ1D, κ2D & κrad) and device level optical losses is of critical importance to PCSEL engineering and development. The experimental determination of device level optical losses remains difficult [1]. The development of simulation methods to assess the device level optical losses as a function of chip design and PC scattering coefficients is therefore timely. This paper reviews and extends our work to consider a PCSEL with a pumped and un-pumped region, that is commonly used to maximise slope efficiency through the elimination of in-plane loss. We incorporate and analyse the effect of self-absorption of the active element.

II. Methods and Results

The probabilistic Markov chain (PMC) model transforms the scattering coefficients into probabilities of light scattered to specific directions and calculates the device level losses of PCSEL devices. In our PMC method, each matrix element is a PC atom, and the time unit, is defined as the time of one photon travelling from one PC atom to the closest neighbour [2,3]. Input parameters are κ1D, κ2D, κrad, and internal loss (κi).

We consider a square PCSEL [4], that we previously used to validate the model [2] with the electrical contact defining the pumped, gain region of side length S. This is bound by a region of width W, consisting of an un-pumped active element and PC. This is surrounded by a perfectly absorbing region. See Fig. 1. We show that when self-absorption is included, αi no longer has a unique value, but is a function of scattering coefficients, number of QWs in the active element, operating wavelength, pumped region size S, and un-pumped width W. For modest un-pumped PC width, we show the interdependence of α// and αi. The importance of this is PCSEL characterisation will be discussed.

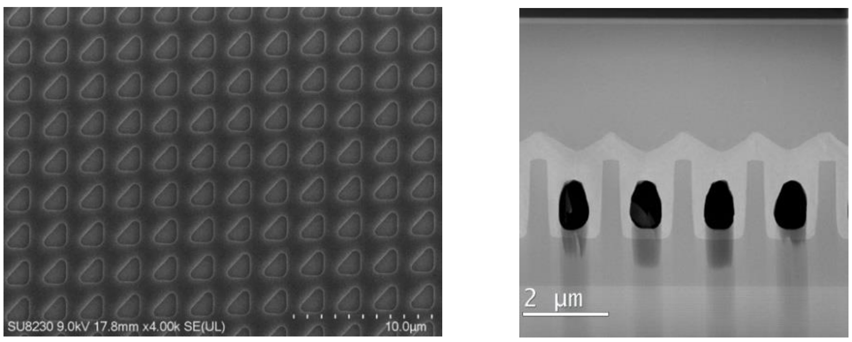

Figure 1. (L) Top down Scanning Electron Microscope (SEM) image of triangular 2.7um period PC pattern achieved with Karl Suss MA6 mask aligner in S1805 resist. (R) High-Angle Annular Dark Field Scanning Transmission Electron microscope Image of QC-PCSEL void retaining structure.

Coupled Wave Theory for Triangular Lattice TM-Polarised Photonic Crystal Surface Emitting Lasers

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Abstract

A coupled-wave analysis of triangular-lattice photonic crystal surface emitting lasers with transverse magnetic polarization is presented. An enhancement in 2D coupling is confirmed when switching from TE square lattice to TM triangular lattice. Finite device calculations are used to distinguish the theoretical lasing mode for specific device parameters.

Introduction

The majority of experimental reports have focused on material systems and heterostructures that predominantly produce transverse electric (TE) gain. However, there has been relatively little activity on PCSELs that use TM-polarized gain media, which this work addresses. Furthermore, most PCSEL structures reported to date have used a square PC lattice symmetry. Coupled wave theory (CWT) was originally developed for 1D structures and is extensively used in the design of distributed feedback lasers. It was later extended to 2D square lattices using an eight-wave model, describing optical coupling through Bloch waves. 2D CWT has been applied to square lattices for TE and TM waves, as well as triangular lattices for TE waves [1,2,3]. CWT has since matured into a full 3D description, allowing for modelling of finite multi-layer devices [4]. On the way to a 3D CWT description, this paper presents a 2D CWT method for the case of a triangular lattice under TM polarization. Using CWT, it has been shown that TM waves exhibit direct 2D orthogonal in-plane coupling for square lattices. For TE waves, moving from a square to triangular lattice symmetry provides higher in-plane scattering [5]. Therefore, it is both interesting and timely to apply CWT to TM waves in a triangular symmetry PC medium.

II. Methods and Results

To solve the coupled wave equations, a staggered grid finite difference method is employed, treating the problem as a generalized eigenvalue problem which can generate solutions for finite device systems. The finite device simulations predict lasing characteristics of specific device structures such as the lasing mode (Fig. 1). This work presents a series of calculations for the as yet unexplored TM polarised triangular lattice PCSEL. This includes the mode frequency and radiative constant against in-plane wave-vector, the in-plane EM field profiles, coupling strength parameter sweeps for fill factor, and finite device calculations. Fourier transforms of different unit cells will be shown and the relation to coupling will be explored.

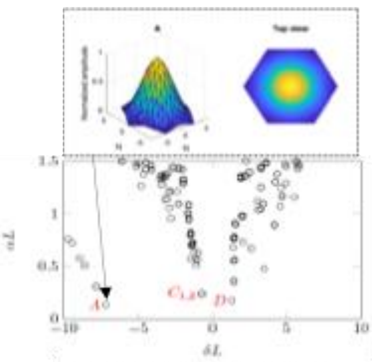

Fig. 1 : Eigenvalue solutions (bottom) and corresponding eigenvectors (top) for TM triangular lattice PCSEL lasing modes.

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Large-Area 2D Selective Area Growth for PCSEL

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Abstract

Large-area selective area growth of InGaAs/GaAs quantum wells by metalorganic vapour phase epitaxy is reported. A total wavelength tuning range of 86 nm was observed by micro-photoluminescence measurements at the central point of each of the masked regions. This opens new routes for future applications in monolithically integrated multi-wavelength photonic crystal surface emitting laser arrays.

Introduction

Photonic-crystal surface-emitting lasers (PCSELs) have been wildly studied around the world due to their excellent performance. Compared with conventional semiconductor lasers, PCSELs can achieve narrow linewidth, high brightness, small divergence angle, and are promising candidates for high-power arrays [1][2]. Selective area growth (SAG) of multi-quantum well (MQW) structures is an important technique for realizing laser arrays, and tens-of-nm wavelength variation can be achieved on wafer scale [3] However, the large 2D emission area (>100 µm2) [4] makes it incompatible with current SAG technologies which current focus on small-area ridge-waveguide devices. [5]

II. Methods and Results

In this work, we present an investigation of large area 2D SAG of InGaAs/GaAs MQW structures. The MQW structure containing three 6 nm-thick InGaAs wells with 30 nm-thick GaAs barriers, and composition of the InGaAs well was tuned to emit at 945 nm in the field far from the SAG region. The SAG features are growth on
(100) orientated GaAs substrates with SiO2 as the mask material from 100 to 300um (Figure 1(a)). Photoluminescence (PL) spectroscopy reveal that the peak wavelength variation > 70 nm is achieved at the centre of each SAG features (Figure 1(b)). Overall, the PL peak wavelength tends to increase with mask width and reduce as the SAG window area increases. A similar tend is also found for the growth rate enhancement and indium incorporation associated with group-III diffusion. 2D Micro-PL mapping (Figure 1(c)) shows that flat wavelength distributions across areas with dimensions around 110 x 110 µm2, which can have future application in multi-channel PCSEL arrays. solve the coupled wave equations, a staggered grid finite difference method is employed, treating the problem as a generalized eigenvalue problem which can generate solutions for finite device systems. The finite device simulations predict lasing characteristics of specific device structures such as the lasing mode (Fig. 1). This work presents a series of calculations for the as yet unexplored TM polarised triangular lattice PCSEL. This includes the mode frequency and radiative constant against in-plane wave-vector, the in-plane EM field profiles, coupling strength parameter sweeps for fill factor, and finite device calculations. Fourier transforms of different unit cells will be shown and the relation to coupling will be explored.

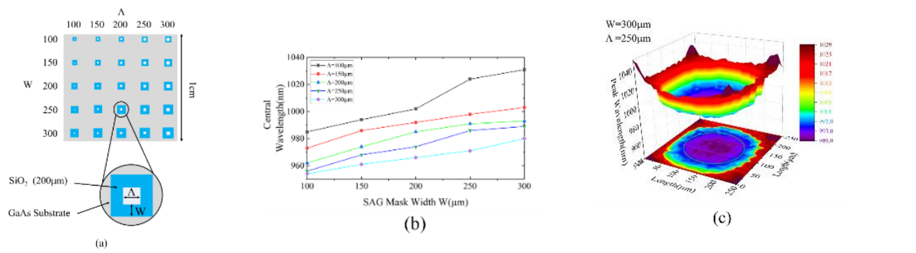

Figure 1. (a) Dimensions of SAG region and mask widths. (b) Peak PL wavelength from center of each SAG region, showing >70 nm wavelength tuning. (c) PL wavelength map for sample with W = 300 µm, Λ= 250 µm showing a flat distribution within a central 110 x 110 µm2 area.

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SOI Photonic Crystals for Heterogeneously Integrated Surface Emitting Lasers

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Abstract

This work illustrates the design, simulation, and fabrication of silicon-based photonic crystals (PhCs) for the development of heterogeneously integrated III-V-silicon PCSELs. The design of the PhC patterns were optimised to achieve high Q factors at a wavelength of 1550 nm.

Introduction

PCSELs have emerged as promising candidates for next-generation optical sources owing to their unique properties such as high-speed operation, high power, and beam control/steering [1]. This study aims at the development of PCSELs by heterogeneous integration of InP-active material on silicon-on-insulators (SOI) photonic crystals (PhCs). Decoupling the design of the III-V gain medium from that of the PhC optical cavity offers larger design flexibility as well as a cheap route for large volume manufacturing through mature CMOS technology [2]. The study outlines the initial steps of this development by reporting results on the design, fabrication, and characterization of SOI PhCs.

Using the finite difference time domain (FDTD) method, the lattice constants and hole/pillar sizes of the PhCs were first optimized to maximise the Q-factor and achieve the desired emission wavelength of 1550 nm. A diversity of design variations such as square, triangular and honeycomb lattices, as well as circular, triangular and elliptic PhC atom shape arrangements were explored [3]. The most promising PhC designs were fabricated using electron beam lithography (EBL) and dry etching on a standard SOI material platform.

II. Methods and Results

The devices were characterised by top illumination of the PhC devices with a tunable laser and by measuring the intensity of the reflected light as a function of the wavelength over the range 1500-1600 nm. The setup also contained beam polarisation controllers, a set of lenses to adjust the size of the beam on the devices and a microscope to facilitate the alignment. The measurements confirmed an excellent agreement with the simulations (see Fig.1 a and b), with the best results in terms of Q-factors achieved with a square lattice with circular atom shapes (see Fig.1 c and d).In this abstract, we discussed the design and fabrication of PhCs in SOI with high Q-factors at 1550 nm, which is the first step towards the development of a heterogeneous integrated PCSEL. The following step includes the transfer and bonding of an InP epilayer membrane onto the SOI PhC layer to provide the optical gain. These heterogeneously integrated devices have the potential to offer higher design flexibility and lower manufacturing cost than monolithical PCSEL devices.

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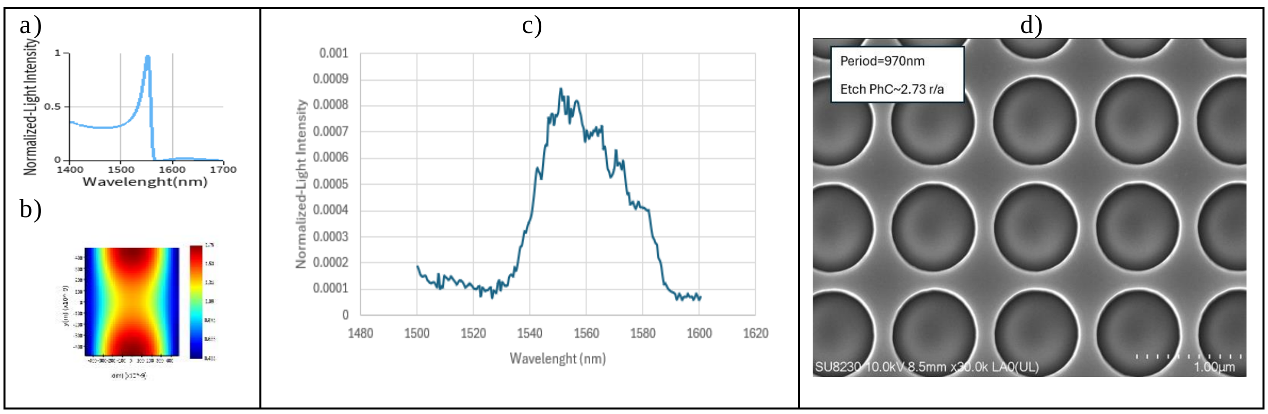
Figure 1. Simulation and experimental results of square lattice hole-based SOI-PhC. (a) Simulation result of normalized-reflected light emission peak. (b) Electric field intensity in xy planes. (c) Experimental result of normalized-light emission peak. (d) SEM image of fabricated PhC.



Fabrication of Electrically Pumped 1550 nm InP Topological Surface Photonic Crystal Laser

Xiao Sun[1*], Yupei Wang[1], Zhibo Li[1], and Lianping Hou[1]

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Abstract

We present a fabrication process for a 1550 nm topological photonic crystal laser on an InP platform, highlighting the challenges of achieving nanoscale precision for C-band topological lasers and introducing a meticulously engineered epitaxial structure.

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Introduction

Topological physics has been a central focus of fundamental research since the groundbreaking discovery of the quantum Hall effect [1]. This discovery reveals that certain physical properties can remain stable despite continuous changes in system parameters. This phenomenon holds significant promise for improving the stability and performance of practical devices. However, translating these robust topological phenomena into concrete applications has been challenging. Recently, a notable advancement has been made with the implementation of a topological photonic crystal (T-PhC) cavity in electrically pumped terahertz topological lasers [2][3]. Despite this progress, the fabrication of topological lasers operating at the C-band on the nanoscale remains a significant hurdle. In this work, we present a novel fabrication process for an electrically pumped 1550 nm InP topological surface photonic crystal laser, tackling a critical challenge in developing practical topological devices.

II. Methods and Results

This epitaxial structure consists of a 250 nm thick 1.1Q PhC layer placed above a 210 nm multi-quantum well (MQW) layer on an InP substrate, forming the topological cavity. Above the PhC layer is a 1900 nm InP cladding layer, which also fills the PhC holes. The photonic crystal layer, featuring a Dirac-vortex pattern, is carefully selected to ensure sufficient modal overlap (coupling strength), eliminating the need to etch the MQWs. The Dirac-vortex pattern features a honeycomb PhC lattice with a generalized Kekulé modulation within each supercell. This modulation encompasses parameters such as the radial distance 'R', the correlated phase 'φ', the distance between sub-lattices, and the side length of the triangle PhC to achieve a topological interface state mode as shown in Fig.1(a). Figure 1(b) shows the results of the ICP dry etching process applied to the topological photonic crystal, using an optimized etching recipe on the Oxford PlasmaPro system. Fabrication of the device is still ongoing.

Figure 1. (a) Simulated mode of the topological interface state. (b) SEM images of the topological photonic crystal, fabricated using the optimized ICP dry etching process.

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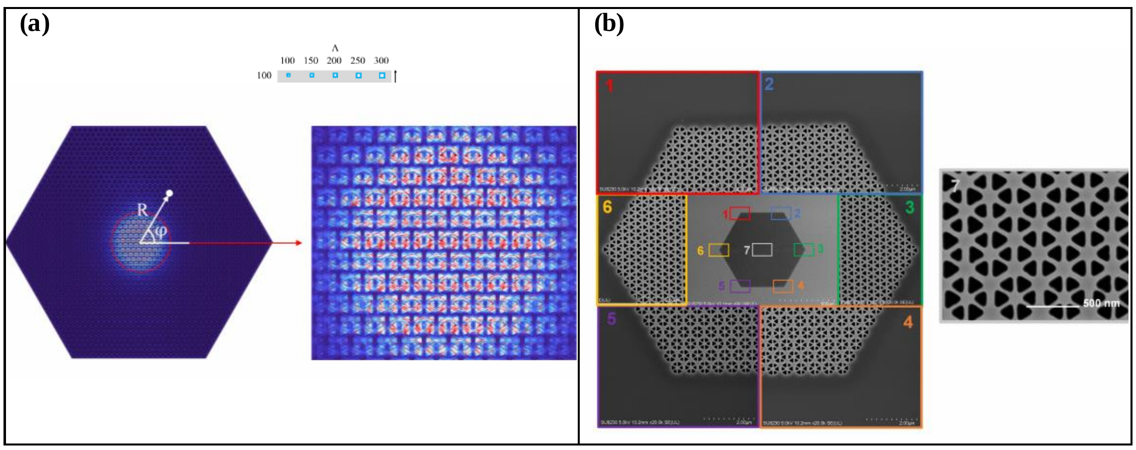

Comprehensive Three-dimensional Modelling Methods for Photonic Crystal Surface Emitting Lasers

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Abstract

Photonic Crystal Surface Emitting Lasers (PCSELs) are a promising technology offering high-power, high-beam-quality emission. We present a comprehensive three-dimensional (3D) modelling approach using Plane-Wave Expansion (PWE), Finite Element Method (FEM), and Finite-Difference Time-Domain (FDTD) method to study photonic band structure, quality factor, and emission efficiency of PCSELs. These techniques provide accurate lasing mode validation, optimising performance in both infinite and finite PCSEL structures.

Introduction

Photonic crystal surface emitting lasers (PCSELs) can emit coherent light with high beam quality and minimal divergence over a large area, opening up new possibilities for scalable, energy-efficient laser devices [1-3]. However, the complex photonic crystal structure inside PCSELs presents design challenges, including modelling finite PCSELs with stable mode, optimising emission efficiency, and quantitative study on laser performance. Both accurate passive and active modelling of these devices is essential to overcoming these challenges, as it provides a detailed understanding of the interaction between the photonic crystal design and laser performance.

Several methods have been developed for PCSEL modelling, each with unique advantages. Finite Element Method (FEM) excels in simulating complex 3D structures, allowing detailed analysis of eigenmode profiles, quality (Q) factors, and field confinement in both infinite and finite PCSELs. Plane-Wave Expansion (PWE) efficiently calculates photonic band structures for periodic lattices but struggles with complex, non-periodic structures. The Finite-Difference Time-Domain (FDTD) method is effective for determining resonant wavelengths in both passive and active devices but requires more computational resources for complex PCSEL structures. A combined approach utilizing PWE for band structure, FEM for Q factor and mode analysis, and FDTD for dynamic emission studies offers a comprehensive framework for PCSEL modelling.

II. Methods and Results

In this work, we present a comprehensive three-dimensional (3D) modelling approach for InP-based two-dimensional (2D) PCSELs using a combination of PWE, FEM, and FDTD. These tools are employed to accurately study and validate the photonic band structure, lasing modes, and emission properties of PCSELs composed of both square and hexagonal lattices with varying atom shapes and sizes. CrystalWave, based on the PWE method, efficiently calculates the photonic band structure, showing excellent agreement with FEM results. COMSOL Multiphysics, based on 3D-FEM, focuses on analysing a unit cell of the PCSEL to calculate the band structure and Q factor, which are key for identifying lasing modes and understanding field confinement at the Gamma point. 3D-FDTD method from Ansys Lumerical further models both infinite and finite PCSEL structures, providing resonance wavelengths in the emission spectrum. The Q factor obtained from both FEM and FDTD is used to calculate the radiation constant, a crucial parameter for optimizing the top emission efficiency. Our results show that the calculated radiation constants for different atom sizes and shapes agrees well with existing literature [3], validating the models. The lattice with different shapes exhibits the same resonance wavelength, while the PCSEL with asymmetric atom demonstrates relatively larger radiation constant. Together, these techniques offer a robust framework for optimizing PCSEL performance, particularly in complex 3D structures, enabling the realization of optimal PCSEL designs.

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Epitaxially Regrown Quantum Dot Photonic Crystal Surface Emitting Laser

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Abstract

Quantum dot based epitaxially regrown photonic crystal surface-emitting lasers (PCSELs) are demonstrated at room temperature. The GaAs based devices exhibit ground-state lasing at ~1230 nm and excited-state lasing at ~1140 nm with threshold current densities of 0.69 kAcm-2 and 1.05 kAcm-2, respectively.

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[3] Y. Liang, C. Peng, K. Sakai, S. Iwahashi, and S. Noda, Phys. Rev. B 84, 195119 (2011)

Introduction

Quantum dot (QD) active media offer a number of advantages over quantum well active elements. They offer extended wavelength of operation as compared to QWs (e.g., 1.3 µm lasers on GaAs substrates), temperature-insensitive operation, low threshold current density, and feedback insensitivity. Additionally, the ability to utilize both the ground-state (GS) and excited-state (ES) of the QDs allows multiple emission wavelengths from one heterostructure. Optically and electrically pumped QD-based PCSELs have been demonstrated utilizing deep etching and the use of transparent contact layers. Here we describe epitaxially regrown QD-based PCSELs. We show that choice of the grating period allows emission at the GS or ES of the QDs, 90nm apart in wavelength.

II. Methods and Results

Figure 1 (a) and (b) shows a plan view SEM of the PC prior to regrowth and TEM image of void containing regrown PC respectively. Figure 1(c) shows the light output power-current (LI) curve with photonic crystal periods of 338 nm (GS) and 368 nm (ES) under quasi-CW conditions (10 µs pulse width, 1% duty cycle) at room temperature. Due to absorption in the full thickness substrate and reflection at the semiconductor/air interface, the device power is expected to be underestimated by a factor of around 3. The power loss due to substrate absorption and reflection at the substrate/air interface can be reduced by thinning the substrate and introducing anti-reflection coatings. GS lasing is obtained at a threshold current density of 0.69 kAcm-2 and output power of ~12 mW is measured at 1.25 kAcm-2. The slope efficiency of the laser is ~ 9.5 mW/A. The threshold current density for ES lasing emission is at 1.05 kAcm-2, which is higher than that of GS because of the higher degeneracy of the ES, and the need to saturate the GS gain to achieve ES lasing. An output power of ~15 mW is achieved at 2 kAcm-2 for ES and the slope efficiency is ~ 9.5 mW/A. The inset of figure 1(c) shows the sub-threshold electroluminescence spectrum showing the GS and ES emission. The blue line indicates the GS lasing peak at lasing wavelength of ~ 1230 nm and the red line indicates the ES lasing peak at lasing wavelength of ~ 1141 nm. Both lasing spectra are obtained at current density of 1.25 kAcm-2 under quasi-CW conditions at room temperature.

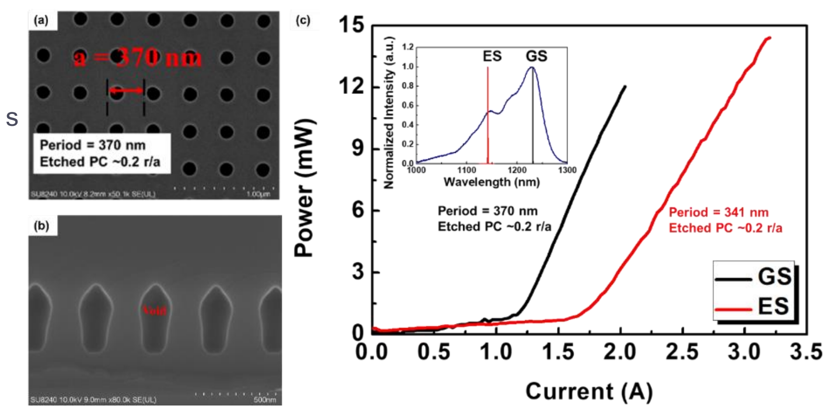

Figure 1. (a) Plan view SEM image of a photonic crystal with circular air holes with a period of 370 nm aiming GS lasing (b) cross-sectional TEM image of void containing regrown PC layer following overgrowth (c) LI characteristics of the GS (black) and ES (red) devices.

Coupled Mode Theory with a Back-Reflector

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Abstract

In a PCSEL the photonic crystal scatters light in both vertical directions (up and down). Recent studies have shown that the inclusion of a backside reflector [1] can help collect this light and improve the efficiency. The reflector influences the local density of states, changing both the Q-factor and the light proportion that is ultimately radiated in a useful direction. Both effects were studied using a directional Green's function that was incorporated into Coupled Mode Theory (CMT). In addition to the expected physics we find a curious interference effect, where, for some parameter choices, PCSEL lasing switches from the long-wavelength A and B modes to the shorter C and D modes, with a resulting drop in performance. This switching is possible only when the device contains holes of differing heights, and a backside reflector.

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Introduction

The inclusion of a back-reflector in a PCSEL reduces the amount of light that is radiated in a useless direction. Reducing the radiative Q-factor of a PCSEL is often desirable, which is also achieved with a reflector. The reflector can either be a Distributed Bragg Reflector (DBR) or the simpler option of exploiting the metallic electrical contact which the device already possesses.

II. Methods and Results

To direction-resolve the emission a directional Green's function of the form G(x,y) D(y,y) G(y,x) is calculated, where G is the ordinary 1D slab Green's function and D defines a wave exciting the structure in the useful direction. This allows calculation of two radiative matrices in CMT [2], one for total emission, and one for useful emission, together giving the efficiency of each mode. The round-trip phase to a back reflector (here a DBR) from the crystal layer controls the emission strength, as compared to experiment in Fig.1(a).
An unexpected result (not shown) is an abrupt (step-like) switch in parameter space where the C and D modes (usually low Q and non-lasing) increase in Q-factor and take over. This interference effect is possible only due to the combined interaction of multiple photonic crystal layers (IE holes of different depths) and the back-reflector, Fig.1(b).

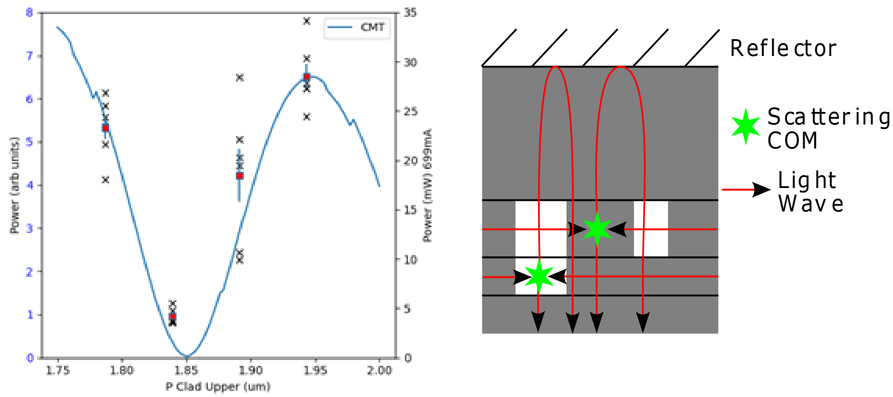

Figure 1. (a) The round trip distance between the photonic crystal layer and DBR is varied both in the model (lines, left axis) and in a real sample (x's ,right axis). Red boxes are averages, error bars standard errors. (b) Schematic of two crystal layers with different hole centres of mass in-plane, and different round trips to the mirror, leading to interference and an increase in mode C and D Q-factors.

Van der Waals materials for surface-emitting lasers

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Abstract

Nanophotonics has witnessed significant advancements through the development of nano-scale resonators and waveguides based on noble metals, dielectrics, and III-V semiconductors. While these materials offer a rich platform for research and applications, the emergence of two-dimensional (2D) materials presents new opportunities. This work explores the integration of light-emitting 2D materials into both conventional and "all-2D-material" photonic structures, to realise novel surface-emitting laser devices.

Introduction

Nanophotonic structures enable a range of applications including optical waveguiding, Purcell enhancement of light emission and low-threshold lasing. Many research fields and technologies have benefited from nano-scale resonators and waveguides realised by noble metals or dielectrics such as silicon, and III-V materials. While these offer a large range of opportunities for both research and technology, van der Waals (vdW) materials may expand the possibilities of nanophotonics in the visible and near-infrared due to high refractive indices (n>4), low absorption in visible wavelength range, and compatibility with a wide range of substrates due to their weak vdW attraction [1]. The layer-dependent material properties of 2D materials, combined with their flexibility for placement on arbitrary substrates, introduce additional degrees of freedom in device engineering. For instance, combining direct-bandgap semiconductor monolayers with dimers and metasurfaces, fabricated in high-index thicker-layer vdW materials, offers new possibilities for light-matter interaction.

II. Methods and Results

Here, we will present how to fabricate metasurfaces in multilayer vdW materials (with thicknesses ranging from 50 to 100 nm) in a variety of geometries for a range of photonic applications Our investigations revealed a rich variety of photonic resonances, as well as strong coupling between the excitonic features and anapole modes/plasmonic modes in the vdW nanostructures placed on different substrates [2-3]. We successfully fabricated high Quality-factor photonic crystal resonances on both conventional dielectric substrates (e.g. silicon nitride) and the aforementioned multilayer vdW materials, supporting guided resonances (GMRs) and bound states in the continuum (BICs), By integrating monolayer of tungsten disulphide (1L WS_2, which is a direct bandgap emitter, 2.15 eV) as the gain material, combining it with the photonic crystal resonators, we observed absorption enhancement and Purcell enhancement of photoluminescence. By carefully engineering the resonances and the device architecture, we achieved optically pumped, room temperature, ultra-low threshold lasing with a single atomic layer of gain material [4]. Two types of lasing modes were observed, the GMR mode and the symmetry-protected BIC mode, which exhibit similar threshold values and far-field emission patterns. We provide a thorough study of the laser performance, paying special attention to directionality, output power, and spatial coherence. Notably, our lasers demonstrated a coherence length of over 30 µm, which is several times greater than what has been reported for 2D material lasers so far. More recently, we demonstrated the formation of single photon emitters in monolayer tungsten diselenide (1L WSe_2, bandgap = 1.6 eV) with optimised excitation, emission, and collection, with enhanced quantum efficiencies [5], showcasing the potential of vdW materials for a diverse range of optoelectronic devices beyond surface-emitting lasers, such as quantum light sources.

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High-Q nano-pillar metasurface in the near-visible regime

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Abstract

Despite great interest in high-Q metasurfaces, experimental demonstrations in the near-visible have been limited to typical Q-factors of a few hundred. Here, we address this issue by introducing a dual pillar design with an etchless fabrication process to demonstrate Q-factors greater than 3000 and an amplitude>0.5 in the near-visible region.

Introduction

All dielectric metasurfaces have witnessed widespread interest in recent years due to their capabilities of acting as high Quality-Factor (high-Q) cavities coupled to free-space, with applications in biosensing, lasing, nonlinear and quantum optics [1]. One largely employed strategy is to design structures that support Bound States in the Continuum (BICs), which are discrete non-radiative modes embedded in the radiation continuum of the photonic crystal's band structure. Despite theoretically extending to infinity, the BIC Q-factor is limited by scattering losses and material absorption. To avoid these problems, the demonstrations of BIC supporting metasurfaces with Q-factors of 1000 or more are typically limited to the near infrared regime (around 1500 nm), where crystalline silicon exhibits a high index, low absorption coefficient and the lithography fabrication process is well optimized [2]. Moreover, the nature of the BIC approach suffers from very low resonance amplitudes, so only little energy can be coupled into and out of the resonance, resulting in e.g. very low output power lasers. Alternative solutions involve breaking the symmetry of the structure to create a "quasi-BIC", which supports a guided mode resonance that exhibits much higher resonance amplitude but a correspondingly lower Q-factor of a few hundred at best best in the near visible region [3]. Here, we show that a design based on coupled nanopillars achieves both high Q-factor (>3000) and high resonance amplitude (A=0.5). Furthermore, we show that using the ALD-based Damascene process for fabrication produces even higher quality structures.

II. Methods and Results

The photonic crystal consists of an array of 150 nm thick Titania (TiO_2) dimer pillars, arranged in a rectangular unit cell, as shown in Fig. 1a and the inset of Fig. 1b. Using a dimer offers an additional, very important degree of freedom. While the period controls the resonance wavelength λ_0, the distance g between the pillars controls the Fourier components and thereby the radiative properties of the mode, that is, the Q-factor [4]. We note that a single pillar structure does not offer this degree of freedom and achieves a correspondingly much lower Q-factor (<100) (not shown here). We fabricated the dimer structure using ebeam lithography and dry etching and achieved a Q-factor of 1000, with good resonance amplitude. We then used the etchless Damascene process [3] as an alternative, because it achieves higher quality structures (Fig. 1c). As a result, we were able to record a Q-factor of 3200 and similarly good resonance amplitude (A=0.5), as shown in Fig. 1d, indicating good power coupling efficiency. We note in addition that the field distribution of the resonant mode carries a large component outside the pillars (not shown here), which suggests that our approach offers an ideal platform for both lasing and biosensing applications.

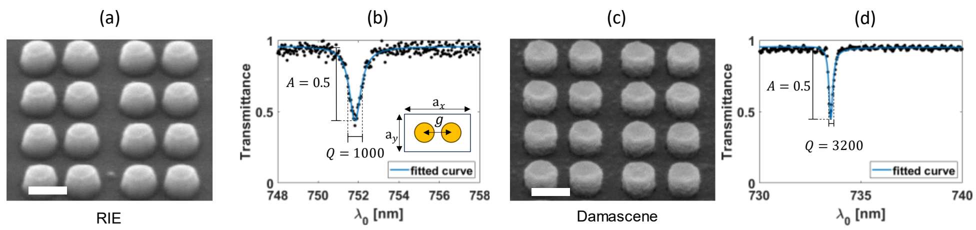

Figure 1. SEM micrograph (a) and transmittance (b) of the RIE based TiO_2 dimer pillars. (c) and (d) show the SEM and transmittance of the ALD-based Damascene TiO_2 dimer pillars. The spectra show the fitted curve used for the Q-factor calculations. The scale bars in (a) and (c) are 200 nm.

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Poster Session

First electrically-driven plasmonic crystal laser
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Characterizations of Topological-Cavity Surface-Emitting Laser
Yan Li
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Coupled-wave theory for topological-cavity surface-emitting lasers
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Resonator Embedded Photonic Crystal Surface Emitting Lasers
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A Novel Technique for PCSEL Photonic Bandstructure Measurement
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Ultralow-threshold 1.3 µm single-mode quantum-dot laser based on bound-states in the continuum
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Switchable Tamm Cavities Using Phase Change Materials
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Towards TAMSELs – Tamm Assisted MetaSurface Emitting Lasers
Petros Androvitsaneas
Quantum Engineering Technology Laboratories,

Void-Retaining Epitaxy for Photonic Crystal Surface Emitting Lasers
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Probabilistic Markov Chain Modelling of PCSEL Losses
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Towards Void Containing Quantum Cascade Mid-IR PCSELs
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Coupled Wave Theory for Triangular Lattice TM-Polarised Photonic Crystal Surface Emitting Lasers

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Large-Area 2D Selective Area Growth for PCSEL

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SOI Photonic Crystals for Heterogeneously Integrated Surface Emitting Lasers

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Fabrication of Electrically Pumped 1550 nm InP Topological Surface Photonic Crystal Laser

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High-Q nano-pillar metasurface in the near-visible regime

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