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Characterisation of Photonic Crystal Surface Emitting Laser Devices and Materials



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Abstract

This thesis presents the detailed characterisation of photonic crystal surface emitting laser (PCSEL) devices and materials.

Initially, the multi-wavelength gain material (InGaAs/GaAs) for PCSEL arrays is achieved through selective area regrowth technology. The square masked region with widths in the range of 100-300 μm are presented to match the requirement of PCSEL. The details of the measurement apparatus and the system alignment process is presented before the sample characterization. Spatially resolved photoluminescence is used to measure the emission wavelength and white light interferometry is used to determine the thickness enhancement factor, which is combined with simulation. The results indicate that over 100 μm uniform emission area and total 86nm wavelength shift was achieved, and a thickness enhancement factor ranging from 1.19 to 2.23 at the centre of the masked region was obtained across all investigated patterns. Even for 300 x 300 μm masked region, the growth rate enhancement and wavelength variation is still observed due to the selective area regrowth effect. The result shows the potential of application of large area two-dimensional selective area growth technology for monolithically integrated multi-wavelength PCSEL arrays.

The detailed characteristics of the REPCSELs (and their associated PCSELs) are also presented. The reduction of threshold current and increased slope efficiency through surrounding the PCSEL with a DBR is demonstrated, with the REPCSEL device exhibiting a threshold of 324 mA (860 A/cm²), whereas no PCSEL device showed lasing operation up to 1.1A for 200 μm device. The effect of detuning with respect to the gain spectrum by change the PC and DBR period are presented. The minimum threshold current density is achieved when the lasing wavelength of the PCSEL is aligned with the peak material gain. The temperature dependent current power characteristics and spectral measurements are analysed. A wavelength selective enhancement through the resonator effect is demonstrated. This is followed by a detailed current dependent band structure analysis of PCSELs. The measurement results indicate that the in-plane loss parameters associated with the leaky and non-leaky modes are selectively modified by the perimeter DBR. The result demonstrates the potential to achieve a wavelength selectivity mechanism for lower threshold and high efficiency PCSELs.

Spatially resolved band structure for the quantitative analysis of PCSELs is presented. The details of measurement strategy for different methods before characterization is presented. The current dependent measurement at the zone centre about the influence of collected wavevector Δk on spectral linewidth is presented, and the reduction of linewidth for each mode is observed for a reduced collected wavevector Δk . Spatially resolved band structure allows the threshold gain to be estimated, and the role of inhomogeneity to be explored. The result indicated that the lasing mode with the lowest threshold had been observed and the estimated threshold gain is $\sim 110 \text{ cm}^{-1}$. Spectral

measurements of the PCSEL image plane indicate that the scale of inhomogeneous photonic crystal is smaller than 30 μm . The image plane mapping result elucidates how the PCSEL develops a spatially extended optical mode, formed through the coherent integration of numerous localized, would-be lasing regions with increasing current.

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Publications

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Chapter 1. Introduction

The first semiconductor laser was achieved in the 1960s [1], where GaAs based materials were used and operation under pulsed condition and low temperature was achieved. Then, in the 1970's, with the appearance of double heterojunction, which made room operation possible for semiconductor laser [2]. Then, around the 80s to 90s, with the development of epitaxial technology, the introduction of the quantum well further improved the efficiency of semiconductor laser [3][4].

Nowadays, etc. the semiconductor laser is the key element for optical fiber communication, which supports high speed data communication for the internet [5]. Additionally, Face id scans in smart phones, laser printer, barcode scanner, LiDAR [6], industrial metal cutting and welding [7], entertainment industry, medical treatment [8]. The development of laser diodes also resulted in research into photonic integrated circuits [2][9].

Traditional semiconductor lasers include edge emitting lasers and surface emitting lasers. Edge emitting lasers include Fabry Perot (FP) laser and distributed feedback (DFB) lasers. Surface emitting lasers include vertical cavity surface emitting lasers (VCSELs). Edge emitting lasers may suffer from multi-modal emission [10]. For the FP laser multiple wavelengths may be observed, depending upon the length of the cavity and the width of the pumped region. Even though DFB lasers can solve this multi-mode behaviour to a certain extent [10], multi-mode phenomena will occur when we try to increase the emission power by increasing its transverse dimension [11][12].

Single mode surface emission and symmetric far field can be obtained from VCSELs [13]. However, when trying to achieve power scaling through increasing the size of device, multi-mode behaviour still occurs [14]. At the same time, multi-layer DBRs in the vertical direction also can produce extra heat due to series resistance [15].

In recent years, photonic crystal surface emitting lasers (PCSELs) have become an active research topic and attracted much attention. The unique two-dimensional standing wave resonances within the 2D photonic crystal can achieve high power, high beam quality operation [16]. The concept of photonic crystal was proposed around 1987 [17][18] and in 1999, the first 2D PCSEL was independently demonstrated by the Meier and Noda groups [19][20]. Since then, by engineering the photonic crystal, numerous optical functions have been realized [22-30], and this type of new semiconductor laser has become a new research direction.

Compared with traditional edge emitting laser and VCSELs, PCSEL can offer advantages such as single mode high beam quality operation [21], manipulate the polarisation [22][23] and vary beam patterns [24][25], room temperature CW operation [26] and achieve beam scanning functionality [27], area scaling [28] laser array [29] and high speed modulation [30].

The first PCSEL laser was made from wafer bonding technology with emission power around the milliwatt level with circular atoms [31]. Then, the PCSEL laser was made from epitaxial growth technology with emission power at the watt class with triangular atoms [18], the emission power at the 10 Watt class with a double lattice [32] to recent CW operation at the 50 Watt class double lattice PCSEL with device size around 3 x 3 mm [28]. The potential of further increase in emission power can be achieved with laser arrays [29][33].

VCSELs need multi-layer DBRs with a high refractive index contrast to provide enough reflection in the vertical direction. This lattice constant mismatch between the two materials will introduce defects during the growth process, increase differential resistance, and damage electrical conductivity [34]. All of those limit the possible material that can be chosen for making VCSELs. For PCSELs, the emission wavelength can be determined by the lattice constant of the photonic crystal, this lattice constant can be flexibility adjusted in PCSEL. GaN at 0.43 μm [35], GaAs at 0.94 μm [32], InP at 1.3 μm [36] and 1.5 μm [37], GaSb at 2.34 μm [38] to 8.5 μm [31]. It gives a high freedom for material choice and hence emission wavelength.

For beam divergence, the narrow far field beam divergence $\sim 1^\circ$ to 2° can be achieved [26][39]. In recent years, the circular beam shape and divergence of 0.05° at 50 W single mode was achieved with 3 mm diameter emission area [28]. For edge emitting laser, the asymmetric beam profile and large beam divergence need extra lens systems to manipulate the beam shape which complicates the entire optic system and causes extra cost [40]. Table 1.1 presents a comparison of the performance characteristics of FP, DFB, VCSEL, and PCSEL lasers.

Overall, PCSELs are a potential candidate for the next generation of semiconductor lasers. The unique 2D dimension resonance with vertical emission and high beam quality, makes it an ideal laser source for next generation of LiDAR, sensing, high speed communications, and photonic integrated circuit [40][41].

Table. 1.1: Comparison of the performance among FP, DFB, VCSEL, and PCSEL lasers.

Feature	FP Laser	DFB Laser	VCSEL	PCSEL
Basic cavity	Fabry–Pérot edge cavity	Distributed feedback grating	Vertical DBR cavity	2D photonic crystal band edge cavity
Emission direction	Edge emission	Edge emission	Surface emission	Surface emission
Beam shape	Highly elliptical	Elliptical	Nearly circular	Circular / engineered
Beam divergence	Large and asymmetric	Large and asymmetric	Moderate	Extremely narrow
Single longitudinal mode	Poor	Excellent	Good	Excellent
Large area single mode scalability	Very difficult	Difficult	Difficult at high power	Excellent
High power operation	High power possible but poor beam quality	Moderate	Limited by multimode and thermal effects	Excellent potential
Modulation Bandwidth	MHz-GHz	GHz	GHz	GHz
Linewidth	MHz-GHz	kHz	MHz	kHz
Beam quality (M^2)	Poor at high power	Moderate	Moderate	Near diffraction limited
Brightness	Low-moderate	Moderate	Moderate	Up to $1 \text{ GW cm}^{-2} \text{ sr}^{-1}$
Coherent large area oscillation	No	No	Limited	Yes
Beam steering	Usually external optics required	Usually external optics required	Usually external optics required	Chip 2D steering demonstrated
Beam shaping	External optics needed	External optics needed	Limited	Direct beam engineering
Polarization control	Weak	Stronger than FP	Unstable	Strong design flexibility
Vector beam generation	Difficult	Difficult	Difficult	Naturally achievable
Thermal stability at high power	Poor	Moderate	Poor	Improved via PC engineering
Wafer scale array potential	Moderate	Moderate	Excellent	Excellent

1.1 Focus of this work

In this thesis, the characterization of the two-dimensional selective area regrowth (SAG) of InGaAs/GaAs quantum wells for a multiwavelength PCSEL array is introduced.

Chapter 2 starts with the basic explanation of what light is, how energy levels are formed within solid materials in a diode laser, and the basic photon generation mechanism in materials. It then moves to the introduction of the structure of active layers in semiconductor lasers. The double heterostructure (DH) and the optical transition process in quantum wells are introduced. The concept of resonant cavities and how to achieve mode selection are presented. The basic definition and coupling theory in photonic crystals is introduced, and the concept of photonic band structure is presented. Subsequently, the electromagnetic field distribution within photonic crystals and the definition of leaky and non-leaky modes are presented in addition to the loss mechanisms in photonic crystals. The mode profile distribution in PCSELs is then introduced. Finally, PC engineering is introduced.

Currently, most studies have concentrated on PCSEL devices with a single emission wavelength. The existing reports on multiwavelength PCSEL arrays were achieved by using a common active element and tuning the photonic crystal (PC) period. However, the emission wavelengths that can be achieved and the device efficiency by the use of a single active element are limited. Chapter 3 first demonstrates the possibility of applying very large two-dimensional SAG technology to fabricate multi-wavelength PCSEL arrays. The detailed characteristics of the InGaAs/GaAs quantum wells are introduced. Initially, the basic principle of selective area growth in one dimension is reviewed, and the extension of this to two dimensions is introduced. The sample preparation and the principle of photoluminescence are introduced. The details of the measurement apparatus are presented and the system alignment process is presented. Subsequently, sample characterization is discussed in detail. White light interferometry (WLI) measurement is used to measure the growth rate enhancement (GRE) factor. From the photoluminescence (PL) it is shown that a total wavelength shift of 86 nm and a uniform area size of over 100 μm is achieved. From the WLI measurement result, it is shown that the effect of anisotropy in the material growth kinetics is negligible throughout the growth process. This indicates the potential for the application of 2D SAG technology to PCSELs.

The characteristics of a resonator embedded PCSEL (REPCSEL) structure is also presented. The concepts and detailed procedures for fabrication and simulation have been reported by Bian [42]. Consequently, a detailed spectroscopic characterisation of the operating parameters of REPCSELs and their corresponding PCSELs is necessary. In Chapter 4, the band structure analysis of the REPCSEL as a function of injected current is described for the first time. Detailed characteristics of the operating parameters of REPCSELs (and their associated PCSELs) are presented in this chapter. Initially, nominally identical PCSELs and REPCSELs of different sizes are analyzed,

and the influence of the DBR on reducing threshold current and increasing slope efficiency is demonstrated. Then, the influence of variations in PC and DBR periods for $400\text{ }\mu\text{m} \times 400\text{ }\mu\text{m}$ REPCSELs is presented. The spectrum and near field of a $200\text{ }\mu\text{m} \times 200\text{ }\mu\text{m}$ REPCSEL are presented. The temperature dependent current power characteristics and spectrum measurements are subsequently detailed. The current dependent band structure measurement is presented. The spectrum at the zone center indicates that wavelength selective enhancement of the non-leaky mode through the resonator effect is achieved. The band structure analysis and simulation are presented. The careful alignment of the resonance peak envelope with the non-leaky mode and the trough with the leaky mode demonstrates that the perimeter DBR mitigates in-plane losses, with different loss responses observed for leaky and non-leaky modes.

The characterization of the band structure of PCSELs is then critically discussed. Band-structure measurements are commonly presented in PCSEL studies but their use for quantitative analysis has remained limited. In Chapter 5, spatially resolved band structure of a PCSEL over a range of currents is reported for the first time. Detailed characteristics of the band structure for the quantitative analysis of PCSELs is presented. Initially, different methods for PCSEL band structure measurement are introduced. The measurement apparatus and band structure below and above the threshold current of the PCSEL are presented. The current dependent measurement at the Gamma points with different k-vector resolutions is introduced. At low current, the result indicates that the lasing mode does not have the lowest linewidth and highest Q-factor. The spatially resolved band structure measurement apparatus is presented. The current dependent measurement at the Gamma point indicates that the lasing mode has the highest Q-factor at low current. Spatially resolved mapping reveals the influence of the inhomogeneity of the PCSEL. The spatially resolved band structure using a magnified image measurement apparatus is presented. The current dependent measurement at the Gamma point with MMF at 2- and 4-times magnification is presented. The result indicates that the characteristic length scale of PC inhomogeneity is less than $30\text{ }\mu\text{m}$. The mapping of the 4-times magnified image presents the influence of the inhomogeneity of the PCSEL. Finally, polarisation resolved band structure measurement apparatus is presented.

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Chapter 2. Background

2.1 The Basic Mechanisms of Emission and Absorption process in Semiconductors:

2.1.1 Light

Light, the most ubiquitous yet often overlooked phenomenon in everyday life, and is a fundamental component of the universe. The understanding of light's properties is usually explained using two different models. The wave model and the particle model, also known as wave-particle duality. In the wave model, light is considered as an electromagnetic wave that can be reflected, refracted, or diffracted [1]. From Maxwell's equations, light is an electromagnetic wave that can interact with the medium. The electric field vector of light will change the polarisation properties of the medium and move free charges, which will produce a time-dependent current. This current will act back on the speed, phase, and amplitude of the wave [2]. In the particle mode, light is made up of a stream of particles. Electromagnetic waves are composed of the smallest indivisible units of energy, called photons, and each photon has a specific quantum of energy [2].

$$E = h\nu \quad (2.1)$$

In this formula, h is Planck's constant, and ν is the frequency of light. Planck considered that the energy exchange between matter oscillators (like atoms or molecules) and electromagnetic radiation (like light) is discontinuous. Einstein proposed that light itself is not continuous, but has a particle nature, which is called a light quantum. This requires that light not only has wave properties but also particle properties.

2.1.2 The interaction between light and matter

For the electron distribution within covalently bonded solid materials in diode lasers, the electrons in each atom will occupy some particular quantized energy levels. These quantized energy levels can be found by solving the Schrödinger equation after adding the electronic potential according to quantum theory. The energy level of each atom in the crystal lattice is influenced by the surrounding atoms. The high energy levels of individual atoms broaden and overlap with each other to form a band of levels known as the conduction band. Low energy levels form the valence band in the solid [3]. The naming of the bands is mainly due to where the Fermi energy lies. The conduction band is usually the first partially or non-occupied band.

As can be seen in Fig. 2.1, when two atoms are close together, the electrons will arrange itself into a low energy bonding stated or high energy antibonding stated. This splitting of states is a classical phenomenon associated with solutions to the wave equation involving two coupled systems [3].

As more atoms are placed together, a similar process happens and the distribution of atoms is neither completely bonding nor antibonding, which finally forms the conduction band and valence band in a crystal. The distribution of those electrons energy states in their respective bands will influence the physical properties of the material.

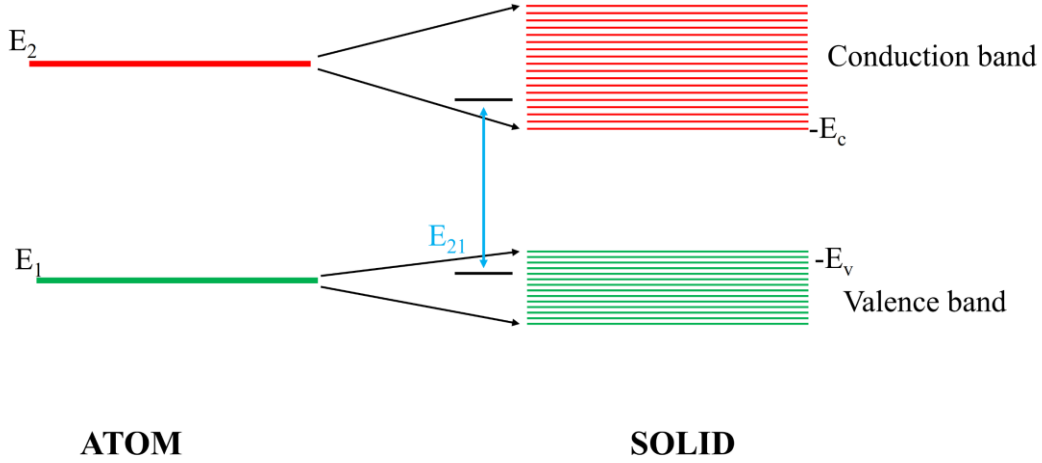


Fig. 2.1: Schematic illustration of how a single energy level of an atom forms an energy band in a crystal [3].

Light has specific quanta of energy but negligible momentum. The transition of electrons between different energy levels involves energy variation, which paves the way for interaction between photons and electrons. There are four basic electronic transitions involved in the interaction between photons and electrons when considering semiconductor lasers, as shown in Fig. 2.2.

Figure 2.2 presents the main electronic transition processes between the conduction band and valence bands [3]. In Fig. 2.2(a), R_{sp} is the spontaneous emission rate. An electron may spontaneously lose its energy in the conduction band, recombine with a hole in the valence band, which will generate a photon. Due to the emission time and direction being random, this incoherent emission will generate an incoherent field of radiation. Since spontaneous emission relies on the transition from a higher state to a lower state, the rate of spontaneous emission is proportional to the population of electrons in the conduction band and holes in the valence band where the constant of proportionality is the first Einstein coefficient, A_{21} .

In Fig. 2.2(b), R_{12} is the stimulated absorption rate. An electron can be promoted to the conduction band by absorbing the energy of an incident photon, leaving a hole in the valence band. This incident photon energy must be greater than the bandgap. In Fig. 2.3(c), R_{21} describes the stimulated emission rate. Here electrons and holes are already located in the conduction and valence bands, respectively. Here an incident photon stimulates the recombination of electrons in the conduction band with holes in the valence band. One important feature is that the new photons are coherent with the

incident photons. This transition forms the gain process necessary for laser operation. Fig. 2.2(d) represents nonradiative recombination processes, which means the recombination of electrons with holes will not generate a photon at the bandgap. The reasons for non-radiative recombination are complex and diverse, such as point defects, Auger recombination, and ionized impurities. Energy may be dissipated as heat and raises the temperature of the semiconductor crystal lattice, which is harmful to laser operation. This process can increase the threshold current and power consumption, cause multiple modes, and even damage to the laser. Light may be emitted through transition of an electron to the valence band through mid-gap states, but as this is parasitic to laser action at the bandgap it is considered “non-radiative”.

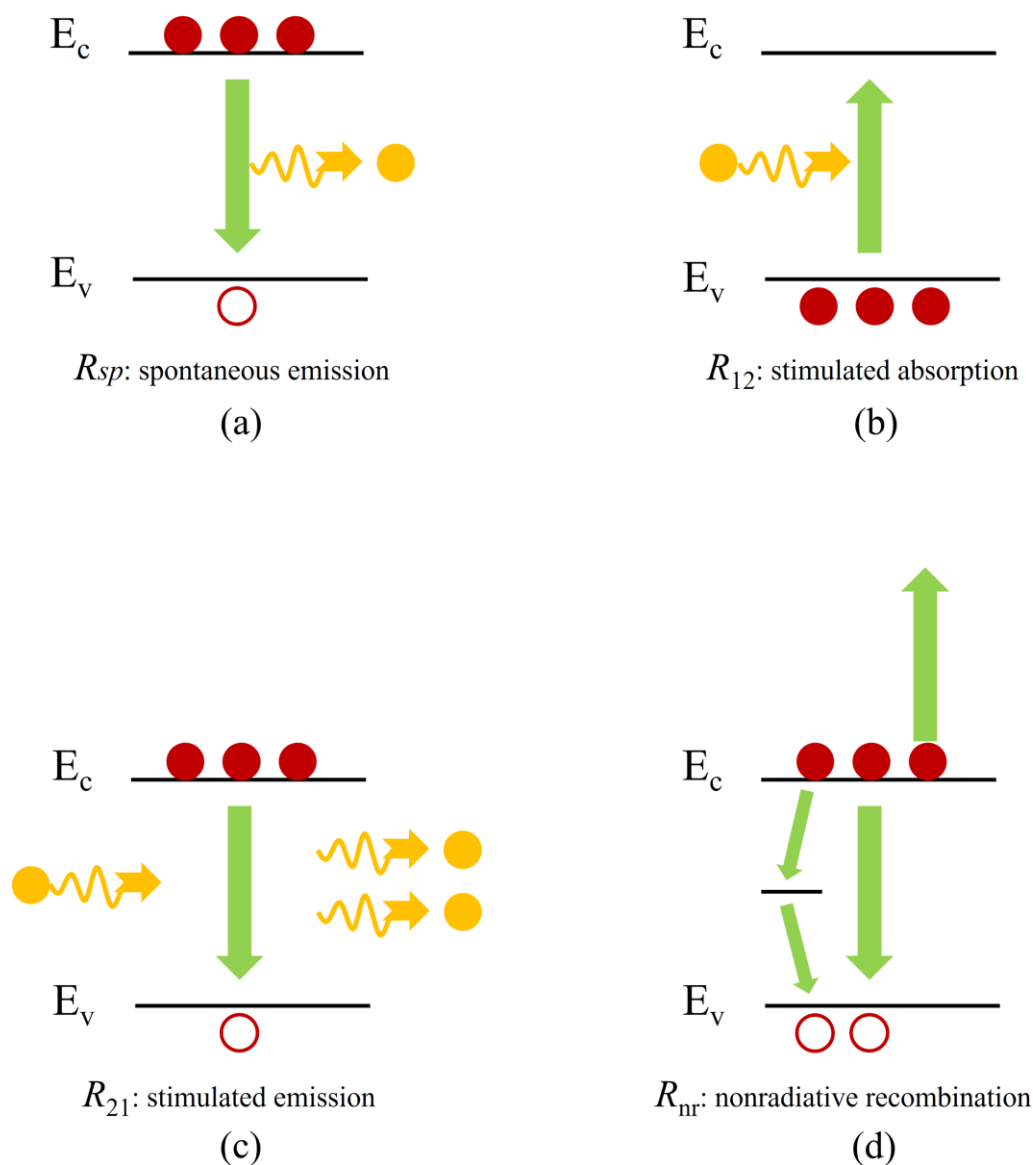


Fig. 2.2: The graph of four main transitions between the conduction and valence bands. The first three transitions are radiative transitions, and the last one is a nonradiative transition. The red solid circles represent filled states, the red open circles represent unfilled states, and the yellow solid circles represent photons [3].

In semiconductor crystals, the energy band structure is more complex, as shown in Fig. 2.3. Fig. 2.3 presents the energy band structures of Si and GaAs [4]. There is a forbidden energy range called the bandgap or energy gap E_g , which does not allow any states to exist in a perfect semiconductor. The minimum energy for an electron to transition from the valence band to the conduction band is equal to E_g . In GaAs, the movement of an electron from the highest energy of the valence band to the lowest energy of the conduction band does not involve a change in the wave vector and can occur directly as the photon has negligible momentum. This kind of material is called direct bandgap material. However, in Si, the movement of an electron from the highest energy of the valence band to the lowest energy of the conduction band not only requires the minimum energy E_g but also requires a change in the wave vector. This means it needs phonons (quantized lattice vibrations) to provide momentum [2]. This process reduces the recombination efficiency within the indirect bandgap material.

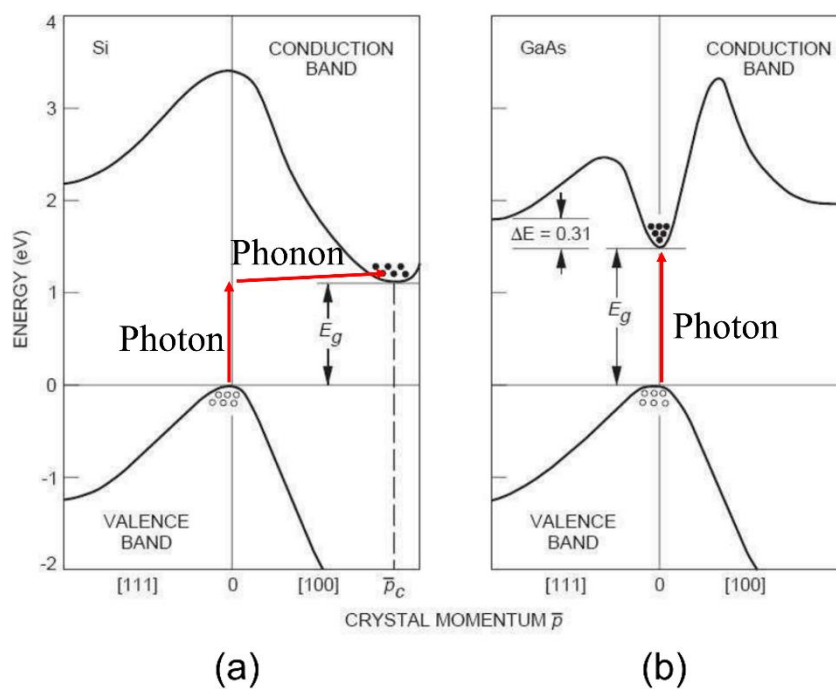


Fig. 2.3: Energy band structures of (a) Si and (b) GaAs, where E_g is the energy bandgap [4].

2.2 The Structure of The Active Layer

2.2.1 Quantum well active layer

The stimulated emission process is responsible for generating coherent light, and the key for stimulated emission process is to achieve population inversion. So, the double heterostructure (DH) structure has been adopted to achieve population inversion and improve generation efficiency [3]. Fig. 2.4 presents the energy diagram of a single DH structure. The DH is made from two different materials with different bandgaps. The lower energy bandgap of material 1 (E_{g0}) is surrounded by two barrier layers made of higher bandgap material 2 (E_{g1}). When electrons are injected from material 2 and fall

into the well formed by material 1, electrons in the well need extra energy to overcome the energy offset $\Delta E_{c\text{-offset}}$ between material 1 and material 2, which prevents them escaping. This enables the confinement of the injected carriers in a potential well and increases the population inversion in R_{21} (stimulated emission) process. It can improve the recombination efficiency of electrons and holes in material 1 and increase the current injection efficiency. The emission energy of photons will be greater than the energy gap (E_{g0}) in material 1. In this thesis, the ratio of $\Delta E_{c\text{-offset}}$ was assumed to be ~ 0.6 for the AlGaAs/GaAs system [85], ~ 0.4 for InGaAsP/InP [86], and ~ 0.75 for AlGaInAs/InP [87]. The InGaAs/AlGaAs/GaAs system is investigated in Chapter 3, the InGaAsP/AlGaInAs/InP system is discussed in Chapter 4. Chapter 5 focuses on the InGaAs/AlGaAs/GaAs system.

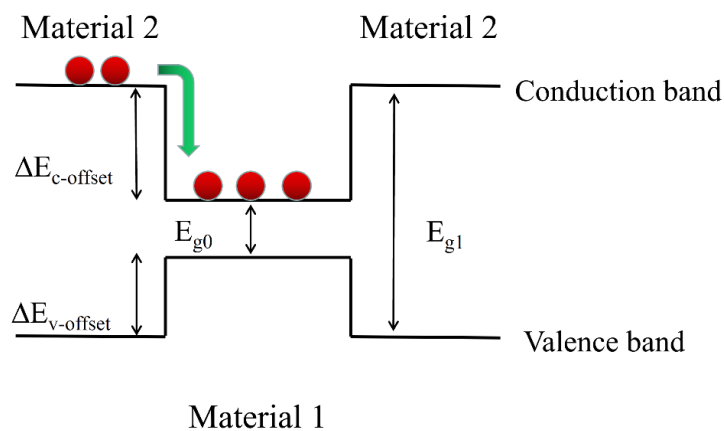


Fig. 2.4: Schematic illustration of the energy diagram of a single DH structure formed by material 1 sandwiched between materials 2 [3].

Then, with the development of nanofabrication technology, at the end of the 1960s and early 1970, A. Y. Cho and J. R. Arthur successfully implemented molecular beam epitaxy (MBE) to grow epitaxial interface structures down to the atomic level for the first time [5]. Known as quantum wells (QWs), Esaki and Tsu proposed minibands and minigaps to describe the electronic states in this artificial two-dimensional structure and the transport characteristics of this artificial structure [6]. In DH bulk material, the narrow bandgap active layer is thick, which means the well width in the corresponding well model is wide. The electrons are free to move in the three orthogonal directions in bulk material, thus having three degrees of freedom. However, when the width of the QW is less than the mean free path and the De Broglie wavelength of the electron, the movement of electrons in the direction perpendicular to the well (growth direction) is limited and the carrier energy is quantised in this direction [7]. Only two degrees of freedom remain in the well plane for the carriers to gain kinetic energy, which produces a set of discrete energy levels due to quantum effects. So QW materials are called two-dimensional quantum materials [8].

Figure 2.5 presents the interband and intersubband transitions process in a QW. For the interband transition process, the strength of interaction is related to the wavefunction

of electron states. It leads to the K-selection rule (or phase matching condition) in the interband transition process, which only happens with electron states that have the same quantum number, where $n_c = n_v$, (momentum conservation with propagation along the same direction). Any transition process between different quantum numbers is not allowed in an infinite quantum well. However, the conduction band and valence band have different effective masses and barrier heights, and barrier height is finite. There still exists a very low probability for transition processes to occur between different quantum numbers in the real situation owing to the penetration of the carrier wavefunctions into the barriers [3] [9]. The transition energy of interband transitions is equal to the energy gap of the confinement energies of the electrons in the conduction band and the holes in the valence band [3].

For the intersubband transition process, any elastic or inelastic transition that can provide the correct momentum exchange will allow the transition to occur between the higher state and the lower state. The transition energy of the intersubband process is equal to the energy difference between the two confinement energies of the individual electronic states in the conduction band (or hole in valence band). It is easier to control the energy difference by adjusting the width of the well. Compared with the interband transition process, the same material based on the intersubband transition process can cover a wider emission frequency range [9]. The lifetime of electrons in the two processes is also different. In the interband transition process, radiative transitions dominate the recombination process, and the lifetime is longer. However, in the intersubband transition, the radiative emission of photons is not the dominant transition mechanism, any elastic or inelastic transition like spontaneous emission, phonon scattering, impurity or interface defect scattering, or electron-electron scattering mainly occurs. These dominant non-radiative processes can reduce the electron lifetime even in the most perfect material [9]. The basic characteristics of interband and intersubband transitions are also different because the joint density of electronic states for optical transitions is different in QW.

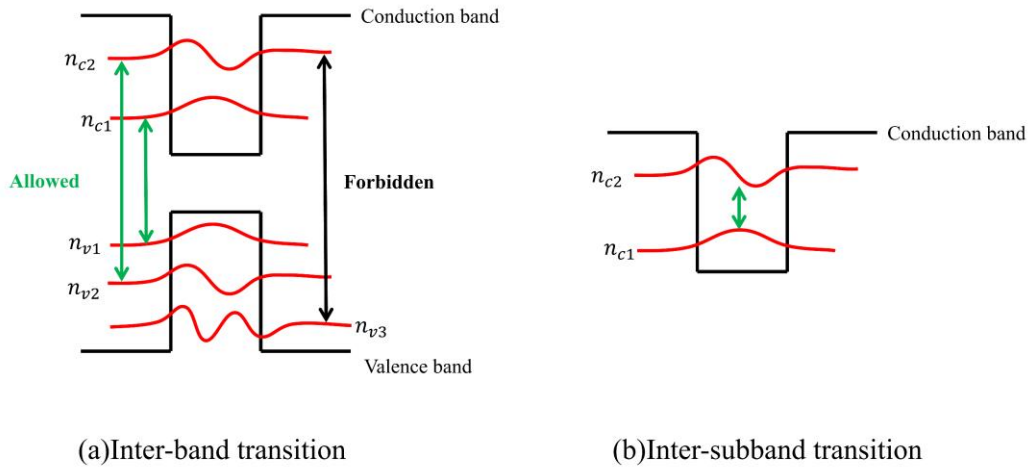


Fig. 2.5: Schematic illustration of the simplified band structure of (a)interband and (b)intersubband transitions [9].

Figure 2.6 presents the interband and intersubband transition processes in a QW. The joint density of states in intersubband transitions has an atomic like shape and is peaked at E_{21} , and this atomic like system results in a narrow optical gain linewidth. The gain and absorption lines, broadened by scattering, become transparent and symmetrical around E_{21} . In contrast, the joint density of states in the interband is constant and step like at E_{21} , which results in a broadened gain spectrum due to the distribution of electrons in the conduction band and holes in the valence band [8].

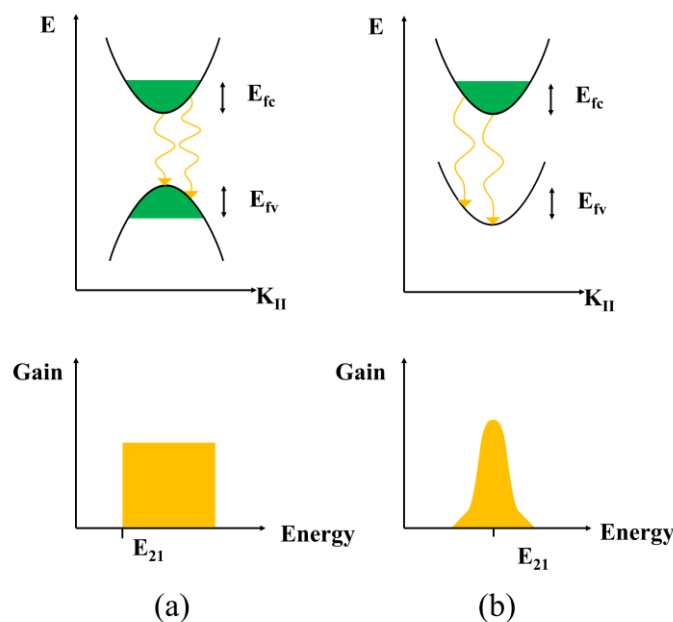


Fig. 2.6: Schematic illustration of (a) interband transition, (b) intersubband transition in a QW [8] [9].

2.3 Fabry-Perot (FP) Laser

As mentioned above, the R_{12} stimulated emission process generates coherent photons. Stimulated emission becomes significant when achieving population inversion and its proportional to the photon density. However, all four carrier transition processes may happen at the same time. Absorption and spontaneous emission are the dominant effects under normal circumstances. In an infinite block of laser material with a broad emission spectrum and consisting of all emission phases, spontaneous emission triggers stimulated emission, but the phases of the photons generated by spontaneous emission are not coherent.

The laser is a device which incorporates optical feedback and stimulated emission. Under a high level of electrical injection, when the population of electrons at the band edge of the conduction band is larger than the population at the band edge of the valence band, making the absorption and stimulated emission rates equal, the transparency condition can be reached. Further increase in the population of electrons in the conduction band can achieve population inversion, and amplification of stimulated photons dominates absorption [10]. Optical gain is combined with some form of

feedback to set a phase condition for the laser. An optical resonator can provide this phase condition, and can be made by cleaving along the semiconductor crystal planes, leaving optical gain medium between two mirrors, which is known as an FP laser. As shown in Fig. 2.7.

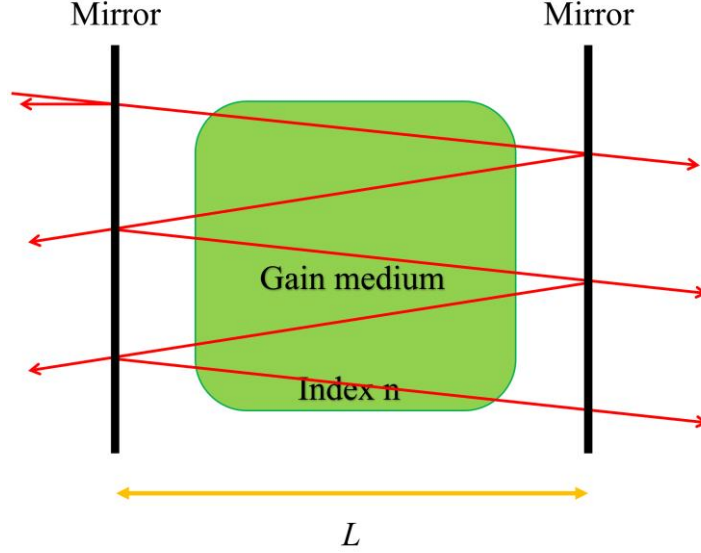


Fig. 2.7: The basic structure of a FP interferometer [11].

A basic laser cavity is formed by an FP interferometer. The incident radiation will undergo multiple reflections between two FP mirrors, and the gain medium is placed between these two FP mirrors. The gain process needs to overcome the loss during each round trip to achieve lasing. Usually, a high reflection (HR) coating is deposited on one mirror to increase the efficiency of the emission from the other side. The wavelengths of the longitudinal modes need to satisfy the phase condition of the FP cavity in the equation below [12].

$$L = m \frac{\lambda}{2n_g} \quad m \in N \quad (2.2)$$

L represents the length of the cavity, n_g is the group effective refractive index of the cavity, m is an integer and represents the numerical order of the cavity mode, the longitudinal mode spacing is given by the equation below [12].

$$\Delta\lambda_m = \lambda_m - \lambda_{m+1} \approx \frac{2n_g L}{m^2} \quad (2.3)$$

After substituting Eq. 2.2 into Eq. 2.3,

$$\Delta\lambda_m = \frac{\lambda_0^2}{2n_g L} \quad (2.4)$$

λ_0 represents the centre wavelength. Wavelengths that do not satisfy the phase condition of the FP cavity are cancelled during the resonance process and monochromatic emission may be obtained. Fig. 2.8, shows the longitudinal FP cavity modes [12].

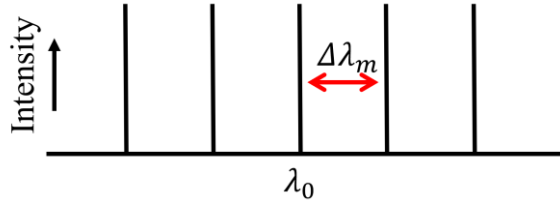


Fig. 2.8: Schematic of the FP modes that satisfy the phase-matching condition of Eq 2.2.

Figure 2.9(a) presents the gain spectrum in a QW and Fig. 2.9(b) presents the lasing spectrum after the influence of the gain spectrum. For the strained InGaAs/GaAs and AlInGaAs/InP quantum well structures used in this thesis, the TE gain is dominant over the TM gain. This is mainly because the dominant optical transition occurs between the first conduction subband(e_1) and the first heavy hole subband (hh_1) [3][88]. As a consequence of the selection rules, TE is dominant.

Due to the broad distribution of carriers in their respective bands, a broadened gain spectrum is realised as shown in Fig. 2.9(a). This broadening includes the effects of the energy uncertainty of the electron states, electron-phonon and electron-electron interactions. In addition, thickness variations during the growth process contribute to inhomogeneous broadening.

The Fabry–Pérot (FP) cavity supports multiple longitudinal cavity modes due to the phase-matching condition inside the laser cavity. If the gain within the cavity can achieve the cavity loss for one of these phase-matched longitudinal modes (the mode closest to the gain peak), then lasing is achieved. Due to incomplete gain clamping, an FP laser may exhibit an emission spectrum composed of a handful of FP modes, with the spectrum generally being more single-mode-like at higher currents [13].

The dominant mode λ_0 has side modes, λ_1 or λ_{-1} that are amplified during the resonance process. If the mode separation is small as compared to the gain spectrum width, mode selection may be weak and multimode behaviour may occur, reducing the performance of the laser if monochromaticity is required. This kind of spectrum means that it can be hard to achieve an FP laser with single mode operation.

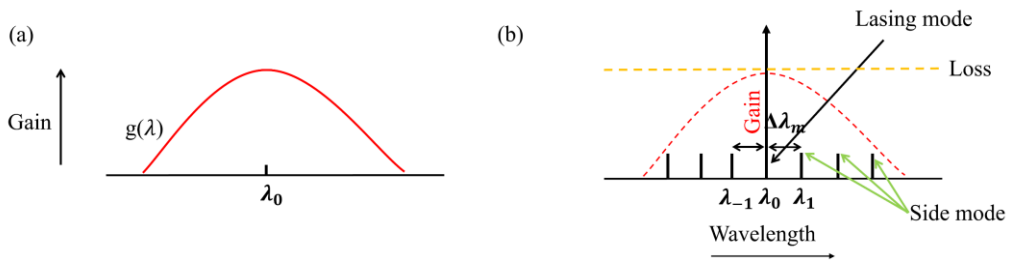


Fig. 2.9: (a) The gain spectrum of MQW. (b) The laser spectrum of a FP laser [13].

2.4 Distribute Bragg Reflector (DBR)

The FP laser utilizes mirrors that have a uniform reflectivity with wavelength. A Bragg reflector, made up of multi-layer stacks of material can have a wavelength selective reflectivity that may help in achieving single mode operation. Fig. 2.10 schematically presents the basic structure of a Bragg reflector. Two kinds of materials with different refractive indices form a periodic structure. The grating period is Λ and the index discontinuity is given by the refractive index Δn . The red arrows represent the coupling of forward and backward waves [8].

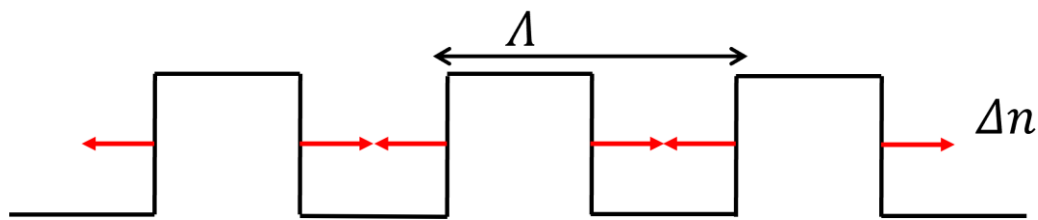


Fig. 2.10: The simplified structure of the Bragg reflector [8].

Figure 2.11 presents the SEM image of DBR grating after fabrication [14]. By using two different types of dielectric layers with alternating refractive index, the forward wave will be reflected at each refractive index discontinuity interface. The grating period is chosen for a suitable Bragg wavelength (λ_0). This wavelength selective reflector, as opposed to a broadband reflector allows lasing wavelength selection as shown schematically in Fig 2.12. In laser diode technology, if the DBR forms a mirror at the end of the cavity (active element) it is called a DBR laser. If the DBR is continuous and above or to the side of the active element it is termed a Distributed Feedback Laser (DFB). In practice, a deliberate phase shift is introduced in the grating to ensure single mode operation. See Fig 2.13.

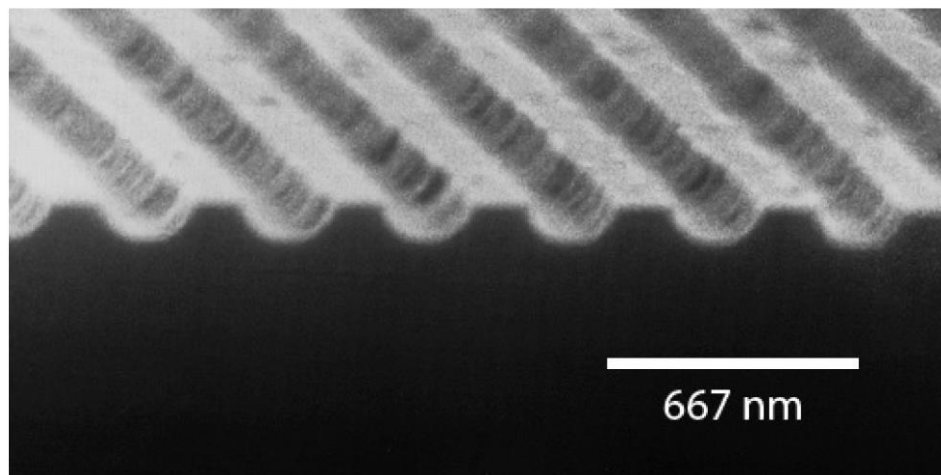


Fig. 2.11: SEM photograph of a roughly rectangular diffraction grating etched into GaAs [14].

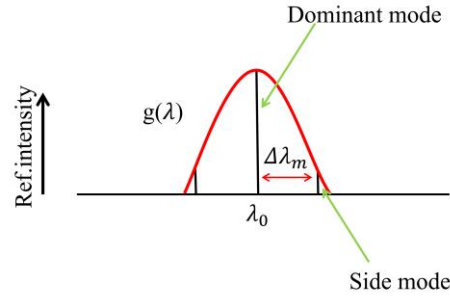


Fig. 2.12: A series of wavelength windows with strong Bragg reflection [15].

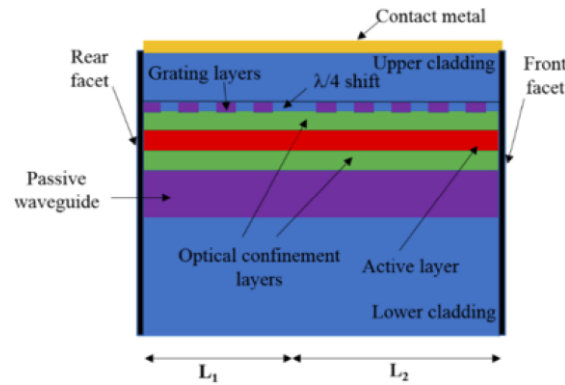


Fig. 2.13: An example of a DFB laser diode [89].

2.5 Vertical Cavity Surface Emitting Laser (VCSEL)

Vertical cavity surface emitting lasers (VCSELs), compared with edge emitting semiconductor lasers like FP or DBR lasers, have emission in the vertical direction to the wafer plane. Fig. 2.14 schematically presents a VCSEL structure. The DBR region (typically GaAs/AlAs, or Al_{Low}GaAs/Al_{High}GaAs depending on emission wavelength) is located at the top and bottom of the active layer in the vertical direction, so the resonance occurs in the vertical direction, which enables vertical emission. The active layer is typically an InGaAs/(Al)GaAs multi-quantum well placed at the anti-node of the resonance. The emission power can be scaled by the emission area [16].

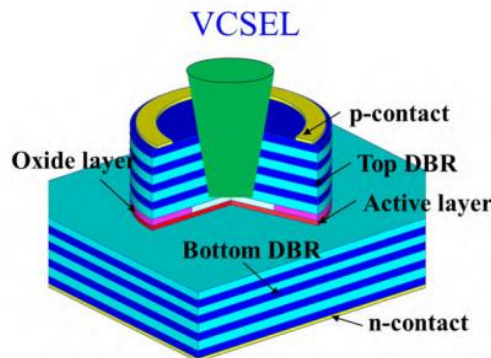


Fig. 2.14: The structure of the VCSEL includes the DBR region, which is located at the top and bottom part [17].

2.6 The Drawbacks of Conventional Lasers

In general, most semiconductor lasers can be divided into edge emitting lasers and VCSEL, and the details of their design will be based on different applications. However, traditional semiconductor lasers find it hard to meet all application requirements as societal and research needs continue to grow [18]. For edge emitting lasers, catastrophic optical damage to their facets can be an issue when operating at high power [19]. The far field pattern is also not suitable for many applications because the divergence angle in the transverse direction is too small compared with that in the longitudinal direction [20][21][22]. This astigmatism requires complex and costly coupling optics [20][21].

For VCSELs, even though symmetrical beam can be maintained, a large emission area may cause transverse multimode behaviour which degrades the beam quality and limits single mode output [23]. Single mode operation is limited to several milliwatts [23] and multimode behaviour will happen when the lasing diameter is larger than several μm for high power operation [24]. To provide enough feedback in the vertical direction and achieve single mode selection, the number of DBR layers in the vertical direction will increase, which not only adds manufacturing difficulty but also increases the resistance, leading to a large RC time constant that limits the bandwidth [12][24]. Oxide confined structures and increased number of layers also cause poor thermal conductivity, which may affect the performance of the device. Even though the VCSEL arrays have been reported to achieve high output power, coherent lasing action has not been effectively demonstrated as coupling between neighbouring devices is difficult due to the vertical light confinement of the structure [12].

In 1999, Noda group and Meier group independently and simultaneously proposed a concept for using a two-dimensional photonic crystal as the laser cavity of a semiconductor laser [25][26]. Subsequently, photonic crystal surface emitting lasers (PCSELs) have been widely studied around the world due to their unique properties.

Compared with conventional edge emitting semiconductor lasers (e.g., Fabry–Pérot lasers), PCSELs can achieve narrow linewidth [23] [27] [28], high brightness [23] [27] [28] [29] [30], and small divergence angles [23] [27] [31]. While certain advanced semiconductor lasers, such as distributed feedback (DFB) lasers, can also provide narrow linewidth and controlled beam polarisation, PCSELs uniquely enable simultaneous control of multiple beam properties within a single chip-scale device. These include beam polarisation [32], emission pattern [33], and beam direction [34], as well as the ability to generate vector beams [35].

These advantages of PCSELs can be employed across a wide range of wavelengths and semiconductor platforms, all without the need for external optical elements [36] [37] [38] [39]. This has propelled the PCSEL forward as a new technology, addressing current limitations and unlocking new opportunities for semiconductor laser applications [18] [20] [21] [40] [41].

2.7 Photonic Crystals

2.7.1 Photonic crystal (PC)

A photonic crystal is a structure where the variation of refractive index of material is periodic. As shown in Fig. 2.15, a one-dimensional variation in refractive index, can be used in DBR, DFB and VCSEL lasers. For PCSEL in this thesis, the PC layer was made by two-dimensional variation in refractive index. For a three-dimensional variation in refractive index, it provides more flexibility for manipulating light properties, but the structure is difficult to fabricate [42][43].

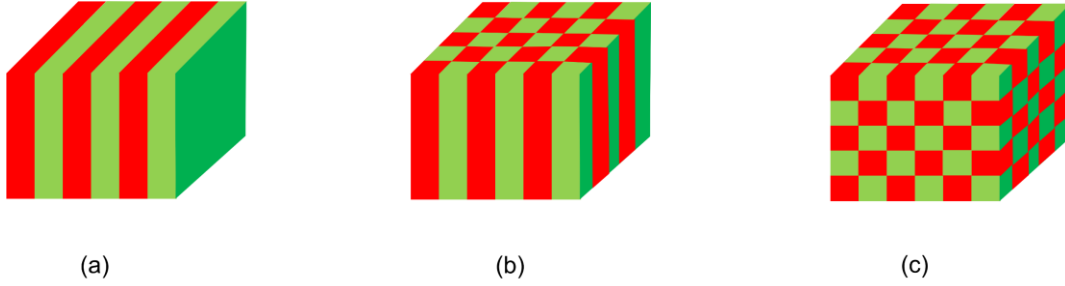


Fig. 2.15: PCs with periodic changes in a) one-dimensional, b) two-dimensional, and c) three-dimensional structures [44].

2.7.2 Key definitions in PC

Figure 2.16 presents the basic definition of a single unit cell in a PC [45], which represents the smallest repeatable unit. The period, a , is defined as the distance which the unit cell repeats. The filling factor, ff , is defined as the ratio of one material to the other in the PC. For an all semiconductor PCSEL, if the refractive index of the atom material A is lower than the field material, B, it is defined as type I. If the refractive index of material A is higher than material B, defined as type II [44].

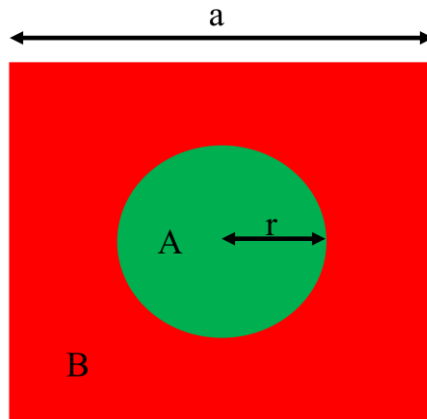


Fig. 2.16: Schematic illustration of one single unit cell of PC [45].

Figure 2.17 presents a reciprocal lattice of a square lattice, where the pitch equals $2\pi/a$, and the square represents the first Brillouin zone. Because of the high symmetry of the

square, the irreducible Brillouin zone can be represented by a triangle constructed by the Γ , X, and M points. The Γ point represents the centre of the Brillouin zone, and X and M represent other points of high symmetry. The points X' are equivalent to X [44].

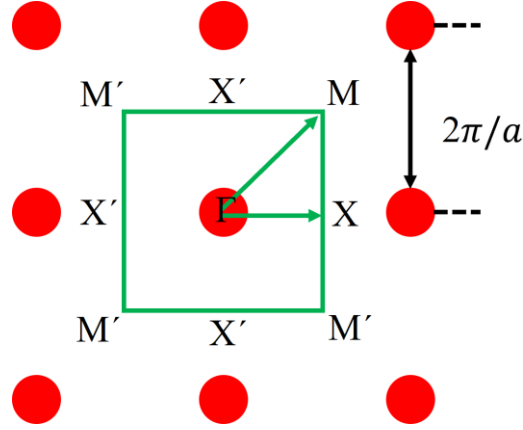


Fig. 2.17: Reciprocal square lattice and Brillouin zone. The green arrows indicate the reciprocal lattice vectors along the Γ -X and Γ -M directions, with Γ (0,0), X ($\pi/a, 0$), and M ($\pi/a, \pi/a$) [44].

2.7.3 Coupling theory in a PC

For light coupling in PCs, an example is shown in Fig. 2.18. The optical coupling coefficients κ_1 , κ_2 , and κ_3 are used to describe the in-plane feedback behaviour. The coupling coefficient κ_1 is one-dimensional distributed feedback where the first-order diffraction occurs ($\kappa_1 = k + G_{1,0}$), it describes the intensity of the coupling of the fundamental wave in the oblique direction. The coupling coefficient κ_2 is a two-dimensional resonance caused by the first-order diffraction, in which the diffracted waves couple with each other at the orthogonal directions ($\kappa_2 = k + G_{1,0} + G_{0,1}$), it describes the intensity of the coupling of the plane waves perpendicular to each other. Coupling coefficient κ_3 is one-dimensional distributed feedback where second-order diffraction occurs ($\kappa_3 = k + G_{2,0}$), it describes the intensity of the coupling of forward and backward propagating waves [46] [47]. κ_1 , κ_2 , κ_3 can be calculated by using the 2D coupled wave theory in K. Sakai *et al* [48]. The vertical emissions will occur due to first-order Bragg diffraction, which causes out of plane coupling between the fundamental wave and radiative wave (green circle) and contributes to surface emission. For a square lattice with TE polarisation, κ_2 is equal to zero due to the electric fields of two propagating waves being orthogonal to each other and the overlap integral will vanish [47]. The strengths of κ_1 , κ_2 , and κ_3 depend on a PC structure [49], filling factor [47], the refractive index [47], and the overlap of the in-plane mode with the PC [45] [49] [50].

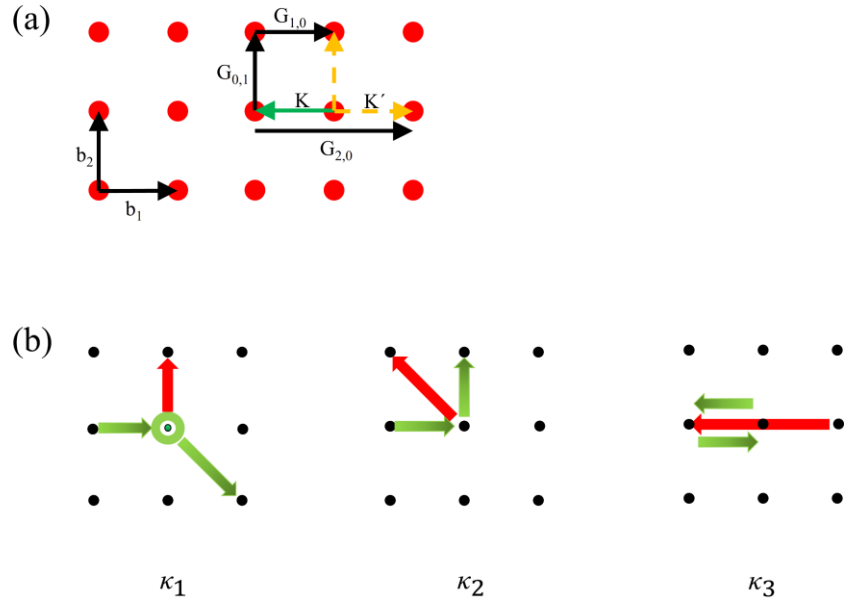


Fig. 2.18: (a) The reciprocal space of the 2D square PC. Solid arrow $\mathbf{k}$ represents the wave vector of the initial wave. Dashed arrows $\mathbf{k}'$ represent the diffracted wave, which are scattered into other directions. Solid arrows $\mathbf{G}$ represent the reciprocal lattice vector [46]. (b) The graph of diffraction for each coupling constant. The green arrow represents the wave vector, the green circle represents the emission wave vector, the red vector represents the reciprocal lattice vector. [47].

In real situations, periodic perturbation generates an infinite set of diffraction orders as shown on Fig. 2.19. The coupling between the fundamental and high-order wave vectors can be achieved through a variety of reciprocal lattice vectors $\mathbf{G}_{m,n} = (\pm 2m\pi/a, \pm 2n\pi/a)$, where m and n are integers that are generated by the periodicity of the PC [18].

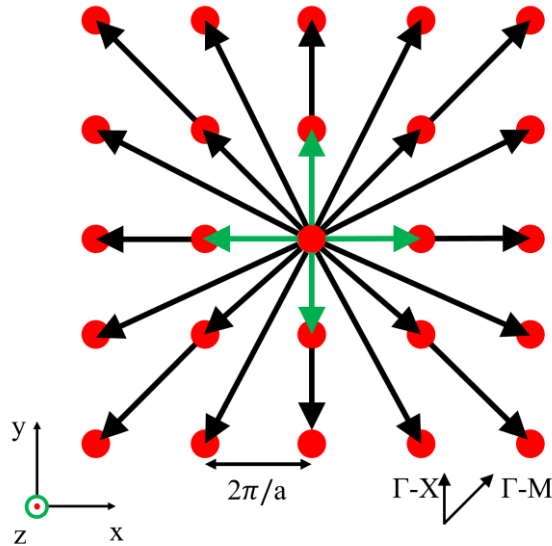


Fig. 2.19: The black arrow represents the basic wave vector, and the green arrow represents a higher-order wave vector in a reciprocal lattice space of a square lattice PC [18].

However, only the second diffraction order and below will have a dominant influence in the vicinity of the Bragg frequency [47] [48]. As mentioned above, the value of κ_2 will equal zero for a square lattice with TE mode, which means the direct coupling between orthogonal directions is impossible. However, the indirect coupling between orthogonal directions can happen through higher-order mode interaction. As shown in Fig. 2.20, the intermediate coupling between the basic waves (R_x, S_x, R_y, S_y) can happen through higher-order wave vectors (F_1, F_2, F_3, F_4), which can be obtained from κ_1 . Those basic light waves propagating in four different directions are intermediately coupled with each other and will finally form a 2D steady wave state in the PC plane [51]. This 2D coupling behaviour is unique to PCs and can help form multidirectional distributed feedback behaviour.

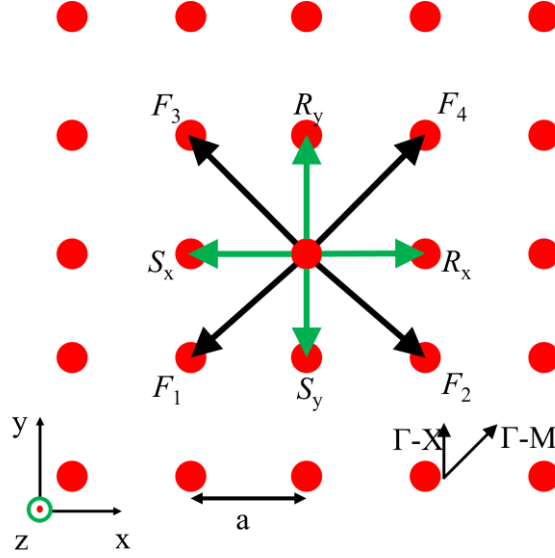


Fig. 2.20: R_x, S_x, R_y, S_y , represent four basic wave vectors, and F_1, F_2, F_3, F_4 , represent four higher order waves in a square lattice PC with circular holes [47].

In recent years, κ_{1d} and κ_{2d} are proposed to describe the above situation [52]. Fig. 2.21 presents a PC structure with a square lattice and circular atoms, where the lattice constant (the distance between adjacent circular atoms) is designed to match the wavelength of light propagating within the PC layer. The orange arrows represent the propagation of the fundamental light in four directions within the crystal. The purple arrows, κ_{1d} , represent the conventional 1D counter propagating light coupling, while the pink arrows, κ_{2d} , represent the unique 2D indirect coupling of fundamental light propagating in orthogonal directions. The in-plane coupled light can also be coupled and diffracted vertically through first-order Bragg diffraction, which is represented by the green arrow.

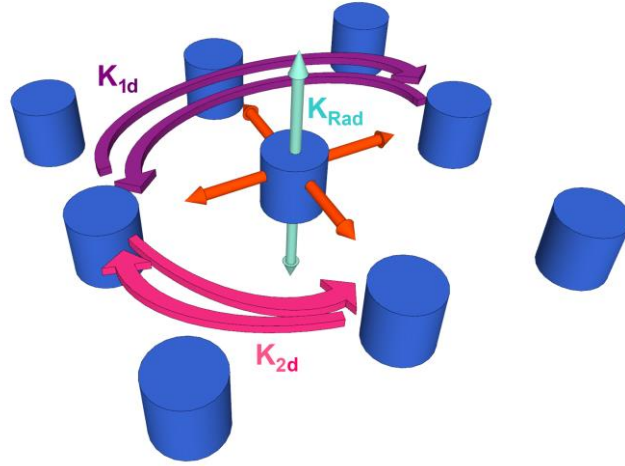


Fig. 2.21: Schematic illustration of the light coupling mechanism within the PC. The blue cylinder represents a lattice site in the PC, the orange arrow denotes the incident light, the green arrow indicates the surface emitted light.

2.8 The Details of Band Structure

For a PC, the photonic band structure is an important characteristic. When considering the structure of the PC, the material has a two-dimensional periodic arrangement. The characteristics of photons are influenced by this periodic modulation of the dielectric constant, which is similar to how the semiconductor crystal lattice potential acts on the propagation of electrons, and forms corresponding energy bands. Taking the formation of energy bands in the semiconductor crystal lattice as an analogy to help explain the formation of band structure in the PC, it can be partially explained by the Bragg reflection effect as shown in Fig. 2.22.

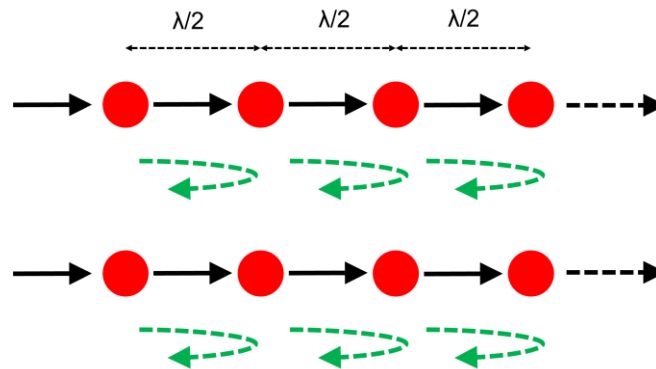


Fig. 2.22: The propagation of electrons in the semiconductor crystal lattice causes the reflected electrons to be all in phase [53].

The reflected electrons have a wavelength such that an integral number of half wavelengths fits the lattice spacing. The electron waves reflected from the atoms that satisfy the Bragg reflection condition will be in phase and reinforce each other. This means that those electrons cannot propagate easily due to reflection, which leads to the formation of forbidden bands in the energy band structure. Other forward propagating

electron waves that do not satisfy the Bragg reflection condition will destructively interfere and propagate freely.

The interaction of the electrons with the periodic potential of the crystal therefore gives rise to an electronic band structure [53]. In a related way, if an artificial periodic change of the refractive index of the material at lattice points, or changes in the geometry of lattice points, or the refractive index of the material between lattice points occur, a PC band structure can be formed. Fig. 2.23 presents the band structure of a PCSEL with hexagonal lattice, square lattice, honeycomb lattice structures [54], which shows the influence of PC structural on the band structure.

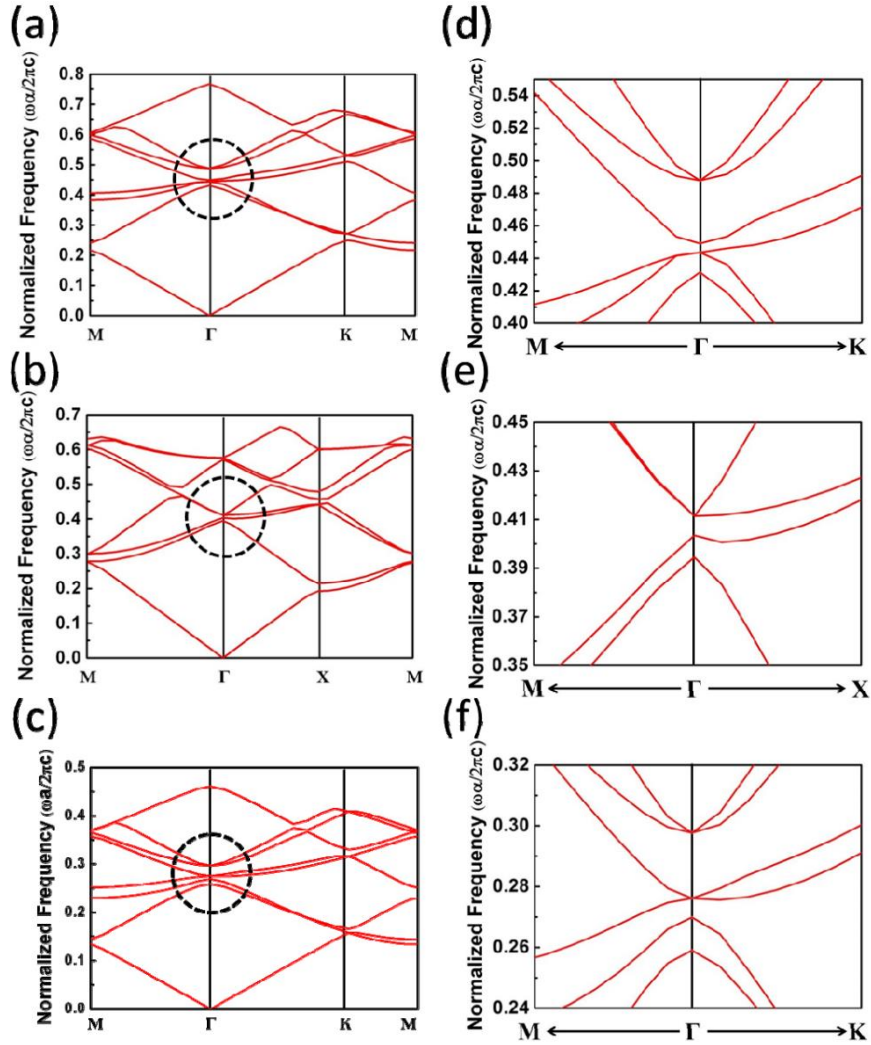


Fig. 2.23: The calculated band diagram of PCSEL with different lattice structures is shown, and the right part shows the details of the Γ band edge position marked by the dashed black circle. (a) hexagonal lattice (b) square lattice (c) honeycomb lattice [54].

There are many ways to calculate the band structure of a PCSEL. Three main methods are most extensively used: the finite difference time domain (FDTD), plane wave expansion (PWE) and coupled mode theory (CMT) [55]. The choice of one method

over the other depends on the details of the requirements and their capabilities. For example, the FDTD can maintain accurate results in very complicated geometries,[56] but the cost is that it can only treat small devices such as nano-cavity lasers because modelling large areas needs substantial computational resources [57]. PWE is only valid for infinite structures, which will lead to a certain deviation in practice [48]. CMT cannot explain what the eigenfunction and eigenmode of the PC with finite extent are [55].

Figure 2.24. Presents an example of PC band structure and lasing points of interest [58]. This band diagram is simulated using a 2D PWE method.

The peak wavelength (gain and spontaneous emission are considered to have the same peak) of the active layer is designed to match the 1st order Bragg condition coupling in plane light to the normal to the plane [25]. The coupling in multiple directions increases the interaction between light and the PC and results in zero group velocity of light in a large region of wavevector space. It results in a high density of states at the edge of the flat band, which is responsible for laser action and diffracts light vertically from the PC surface [51] [59]. The flat edge comes from the coupling of wave vectors at high-symmetry points of the PC reciprocal lattice [60].

Because the PC causes multidirectional wavevector coupling, laser behaviour may occur at many points on the Brillouin zone boundary, corresponding to different Bragg conditions. As shown in Fig. 2.24 (b), for point I in the Γ -X direction, this point corresponds to coupling only forward and backward wave vectors, similar to a conventional DFB laser. Six equivalent Γ -X directions can form three independent lasers and cavities in each direction, because three independent resonant state can be formed and the coupling between those directions are forbidden. However, the wavenumber at the point I is greater than that in air, so surface emission is not expected due to total internal reflection [33] [58]. For point II in the Γ -M direction, light coupling of three wave vectors differing by 120° forms two independent lasers and two cavities, but surface emission is still not expected because this band edge is non-radiative [33] [58]. For point III in the Γ - Γ direction, the light coupling of all six wave vectors differing by 60° from each other forms only one independent laser and one cavity mode. The group velocity of light is zero at this point, which enhances the feedback effect, surface normal emission can form at this band edge because it satisfies the first-order Bragg diffraction [33] [58]. Band edge lasing behaviour from points (A, B, C, D) depends on the PC structure [33] [44] [45] [58], increasing the threshold gain interval with each resonance mode benefits single mode lasing [61]. The coupling in multiple directions will produce other out-couplings at different frequencies at different points, but the angle of out-coupling will change from the vertical direction, which is not good for achieving a low divergence angle, as shown at point IV [33] [58]. The band structure can be measured experimentally by injecting current below the lasing threshold current and measuring the spontaneous emission spectra as a function of the angle relative to the PC plane. [62] [63].

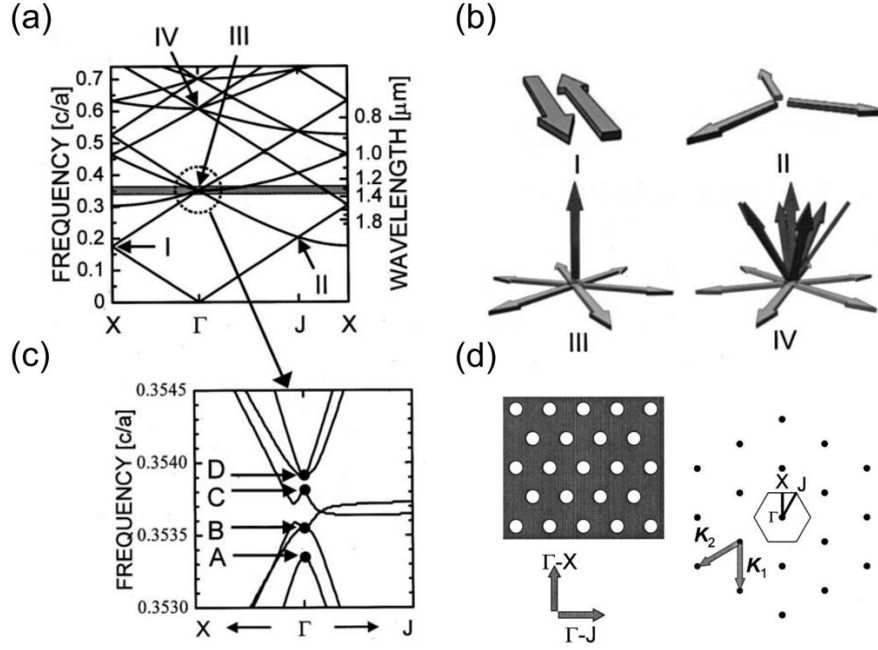


Fig. 2.24: (a) Band diagram of 2D PC for TE mode. (b) Propagating directions of coupled waves at points I-IV. (c) Enlarged band diagram of black circle point at point III. (d) The reciprocal lattice of PC [33][58].

2.9 Electromagnetic (EM) field Distribute and Definition of Leaky and Non-Leaky Modes

Figure 2.25 presents the electromagnetic field distribution at the Γ point in the band structure, which helps to indicate which modes are leaky and non-leaky [64]. The simulation is based on PWE method which assumes the size of PC is infinite. The arrow represents the direction of the electric field, and the black circle represents the air hole. It is expected that lasing will happen at one of the band edges of the Gamma point. When the electric field distribution is anti-symmetric with respect to the air hole, destructive interference will happen, and no vertical emission lasing occurs. Therefore, modes A and B are non-leaky modes because of strong vertical confinement, and modes C and D are leaky modes whose electric field distribution is symmetric with respect to the air hole. High emission power can be obtained due to reduced destructive interference [64] [65] [66]. However, it also means the threshold gain is higher compared with non-leaky modes. Non-leaky modes like A and B with higher Q factors will lase first due to their lower threshold current [47] [62] [67]. This means one of the main issues for PCSEL design is that the lowest efficiency mode will have the lowest threshold gain [65] [68]. The main reason for the square lattice circle pattern PCSEL to lase from a non-leaky mode is due to two reasons. First, during the fabrication process, it is hard to make a perfectly circular shape, which breaks the perfect destructive interference and increases the vertical emission power. The cost is that it reduces the quality of the beam shape and increases the divergence angle in the far field [50]. The second reason is the device's finite size effect. The finite device size will shift the

electromagnetic field distribution around the circle. This slight shift with respect to the circle is more obvious at the edge of the device because this perfect destructive interference shown in Fig. 2.25 only happens when the size of the device is infinite. This slight shift of electromagnetic field distribution will increase the vertical emission from the edge of the device [69]. So, one important way to improve efficiency is to make the electromagnetic field distribution have partial destructive interference around the atom shape [23].

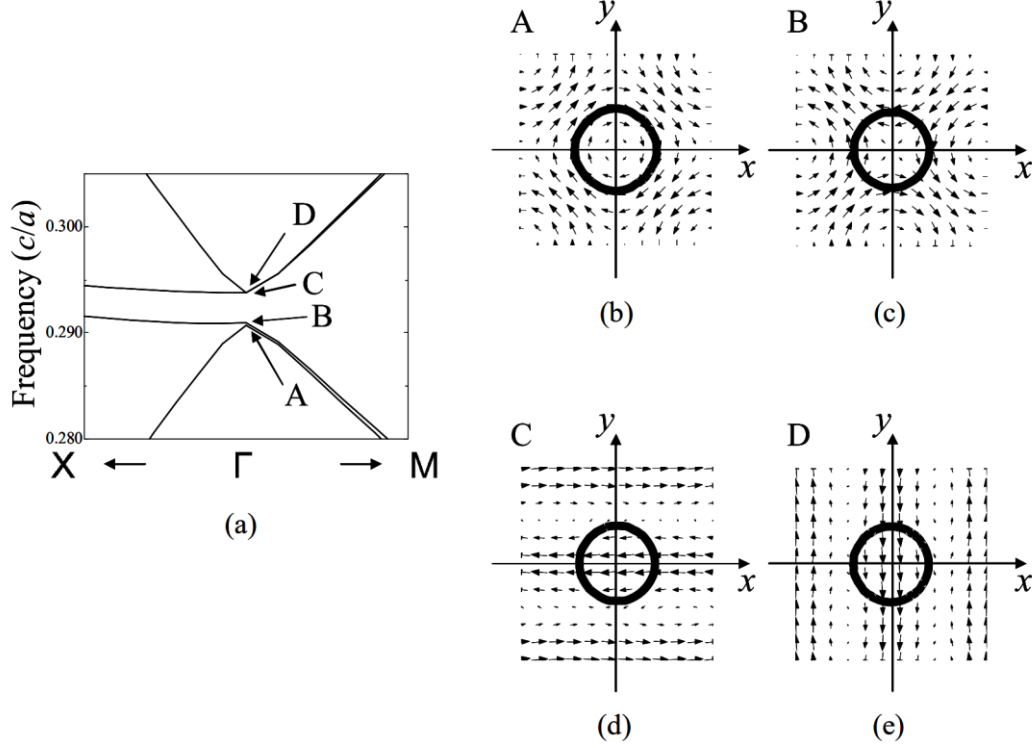


Fig. 2.25: Detailed view of the band structure around the Gamma point. (b)-(e) show the in-plane electric field distributions for band edges A, B, C, and D [64].

2.10 Loss Mechanisms in PC

Traditionally, the loss of an edge emitting laser comes from two parts, mirror loss (α_m) and internal loss (α_i). The former represents the loss from the cavity facets. The latter represents the loss from material absorption or scattering within the cavity. For PCSELs, mirror loss (α_m) is defined as external vertical loss ($\alpha_{\perp}$) that enables surface emission, combined with additional in-plane optical loss ($\alpha_{\parallel}$) from the device edge. As shown in Fig. 2.26, it presents the loss mechanism in a finite size PCSEL. Green arrows represent the vertical loss, brown arrows represent the in-plane optical loss from the device edge. The threshold gain is determined by the balance between gain and total optical loss in the cavity, the slope efficiency is further determined by the ratio of the incremental vertical emission power to the injected current above the threshold, these parameters are important for designing the PC layer within the device.

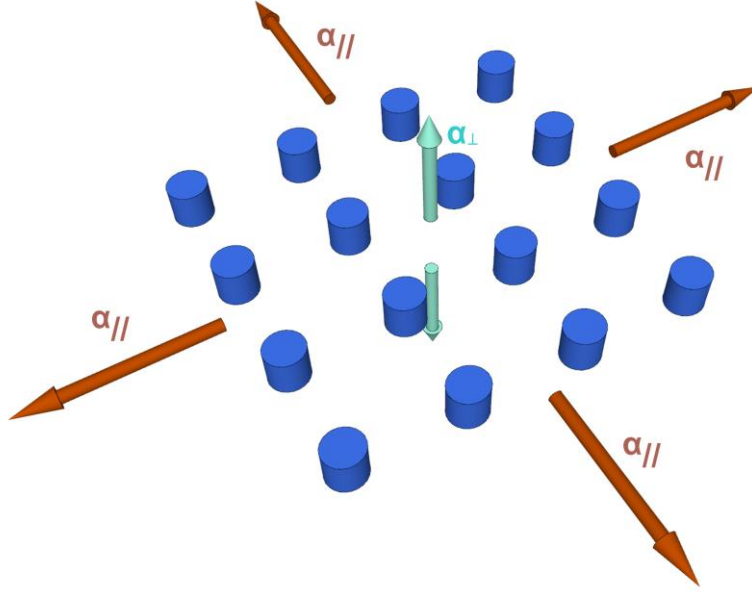


Fig. 2.26: Schematic illustration of the loss mechanism within a finite sized PC layer.

The relationships between threshold gain (g_{th}) and slope efficiency are quantified by the following equations [23]:

$$g_{th} = \alpha_{\perp} + \alpha_{//} + \alpha_i \quad (2.5)$$

$$\frac{d_P}{d_I} = \frac{h\nu}{e} \eta_i \frac{\alpha_{\perp}}{\alpha_{\perp} + \alpha_{//} + \alpha_i} \eta_{up} \quad (2.6)$$

h represents Planck's constant, ν represents the mode frequency, and e represents the unit charge. Internal efficiency (η_i) and upward radiation efficiency (η_{up}) are key parameters influencing the performance of PCSELS. The values of in-plane optical loss ($\alpha_{//}$) and out of plane radiation loss ($\alpha_{\perp}$) are mainly influenced by the refractive index contrast, the geometry of PC atoms and the overall device dimensions [23] [49] [50] [52] [67]. Meanwhile, the internal optical loss (α_i) is mainly influenced by the waveguide structure of the device and the free carrier loss characteristics of the constituent materials. The formula shows that higher in-plane optical loss ($\alpha_{//}$) will result in higher threshold current and lower slope efficiency, which is one of the main challenges for enhancing power conversion efficiency, and in miniaturizing PCSEL devices [24] [67] [70] [71], higher vertical radiation loss ($\alpha_{\perp}$) can lead to higher threshold current and higher slope efficiency.

Figure 2.27 presents an example of the simulated photonic band structure around the Gamma point of a square lattice PC with circular holes of radius $0.4a$, using the 2D PWE method for TE modes [72]. As mentioned in the Eq. (2.5), the differences in radiation loss for each mode will lead to different threshold currents, higher vertical radiation loss ($\alpha_{\perp}$) results in higher threshold currents. At the Gamma point, leaky

modes exhibit greater light loss (or leakage) in the vertical direction and thus tend to have higher threshold current compared to non-leaky modes. The gain spectrum of the laser diode active element is much broader compared to the separation between modes, the mode with the lowest threshold gain will lase first. For the non-leaky modes, the primary lasing mode will depend on the property of in-plane confinement [73]. If all lasing modes at the mode centre have equal in-plane optical loss and internal loss, lasing oscillation always happens at the resonant mode with the lowest vertical loss [29], then the primary lasing mode will be the mode with the lowest slope efficiency.

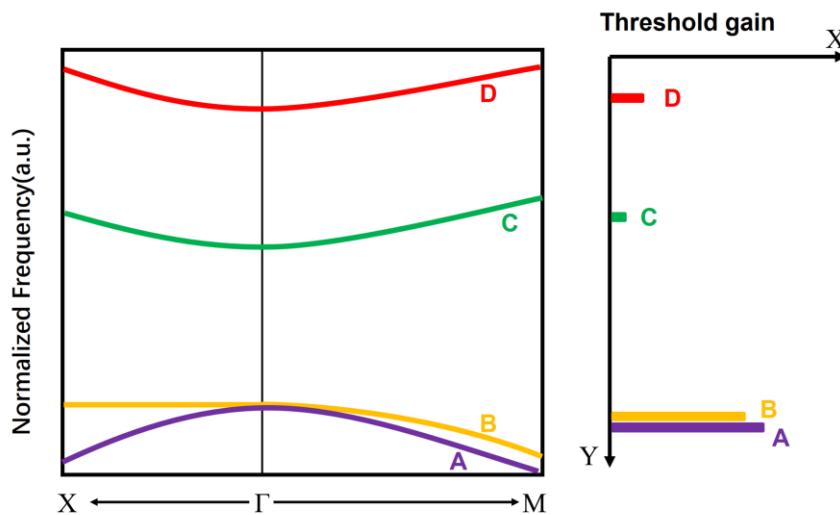


Fig. 2.27: Schematic illustration of the simulated band structure for a square lattice composed of circular atoms, along with its corresponding threshold gain.

Due to the structure of PCs that will influence band structure, the bandgap may disappear at the Gamma point. For example, Fig. 2.28 and Fig. 2.29 presents the band-structure and coupling coefficients of type II GaAs/InGaP square lattice and circular atoms PC, when the atomic radius is increased to $\sim 0.3a$, the bands at higher frequency will be degenerate at lower frequencies causing the band gaps to disappear. The band structure is simulated by using MIT photonic bands (MPB) [74], which is a free Linux based software by using a fully vectorial PWE [65]. This band edge overlap will lead to the coupling coefficient κ_3 being equal to zero and the disappearance of second order diffraction, which will increase the threshold current value. This is because once backward diffraction and coupling disappear, the lower one-dimensional resonance behaviour causes light to no longer be effectively confined within the PC region, large in-plane loss from the device edge will increase the threshold current [45] [47] [65].

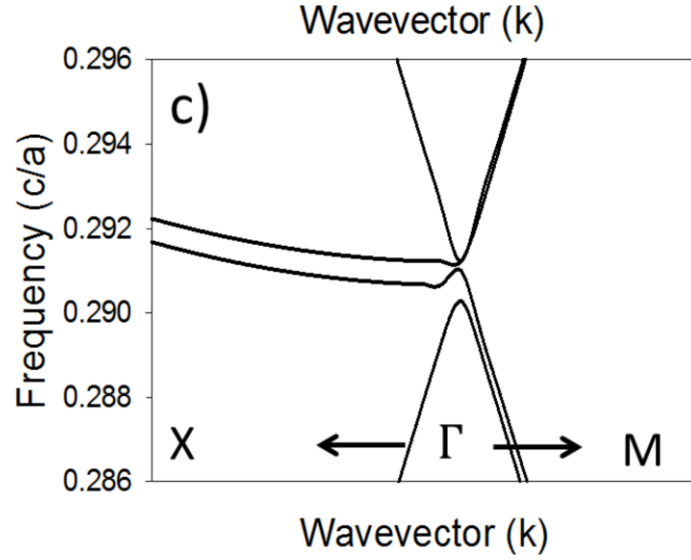


Fig. 2.28: A type-II GaAs/InGaP PC with circular atoms on a square lattice having a radius of $0.3a$ [65].

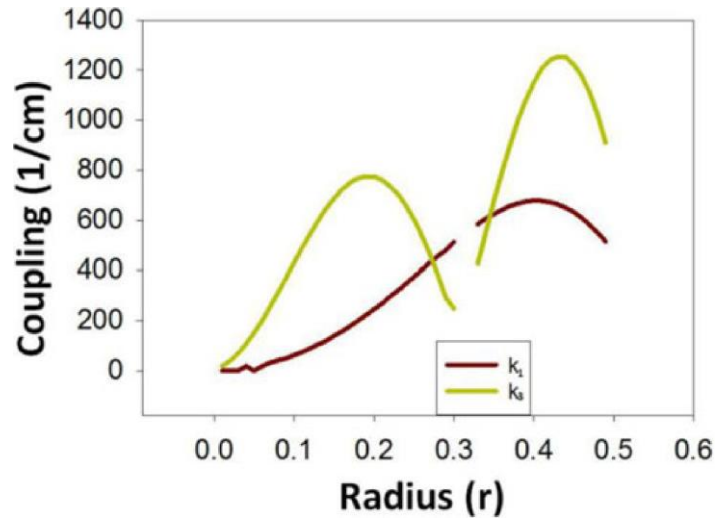


Fig. 2.29: The modelled coupling coefficients κ_1 (brown) and κ_3 (green) are for a type-II GaAs/InGaP PC [45].

2.11 Mode Profile Distribution in PCSELs

Figure 2.30 presents the mode profile distribution within the PCSEL [39]. To increase the mode interaction between the active layer and the mode profile, the average refractive index of the upper and lower layers is smaller than that of the active layer. Most of the mode profile will be confined between the PC layer and the active layer.

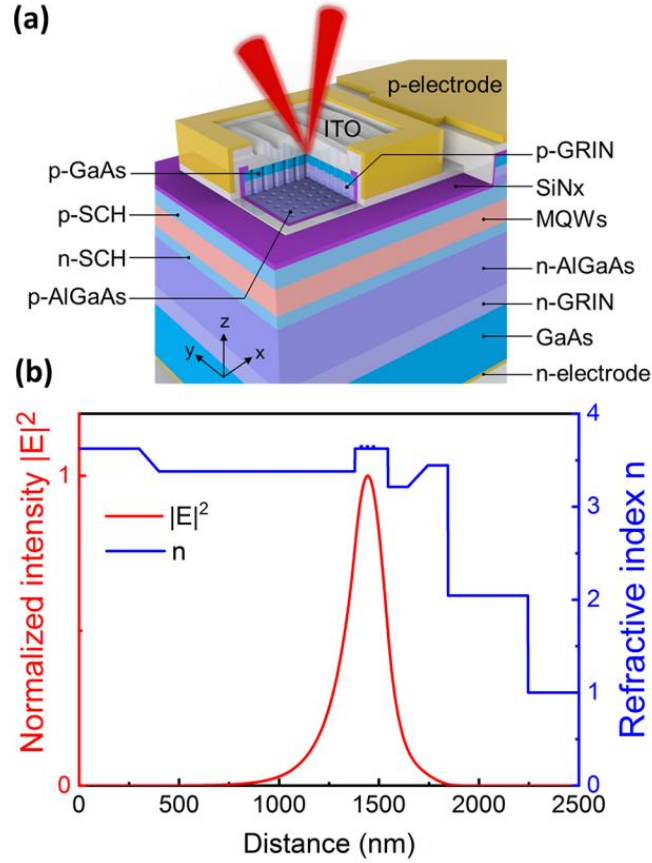


Fig. 2.30: Schematic illustration of (a) The PCSEL device structure. (b) The optical field distribution at the vertical direction [39].

2.12 Defect Cavity Laser

Another kind of PCSEL is called a defect cavity laser. It is formed by introducing a defect into the PC and forming an optical mode localised to this defect region [75]. When considering the energy band structure of electrons in the material, no energy state will exist between the conduction band and the valence band. However, if there is some impurity existing in the material or some defect due to lattice deformation, it is possible to form a unique energy state existing between the conduction and valence band, which allows electrons to stay at this state. Similarly, by artificially manufacturing a defect in the PC and forming a state in the bandgap of the photonic band structure, it allows photons to exist at this state and to localised within this defect.

Figure 2.31 presents an example defect optical cavity made by removing or enlarging a single atom in the PC, creating a defect that can support highly localised resonator modes [65] [76]. This is because this defect has the proper size to support one mode to propagate at this state, which can behave like a microcavity. The light mode cannot propagate out of this microcavity in-plane due to total internal reflection (or cannot propagate between this defect state and higher (or lower) states) [77]. So, this defect can be used to trap light and control light propagation within the structure. The quality factor Q represents the losses in the cavity. For in-plane direction, the Q -factor is

dominated by the distance between the defect and the waveguide, and for vertical direction, the Q-factor is dominated by the effective refractive index contrast between the defect and the cladding air [77].

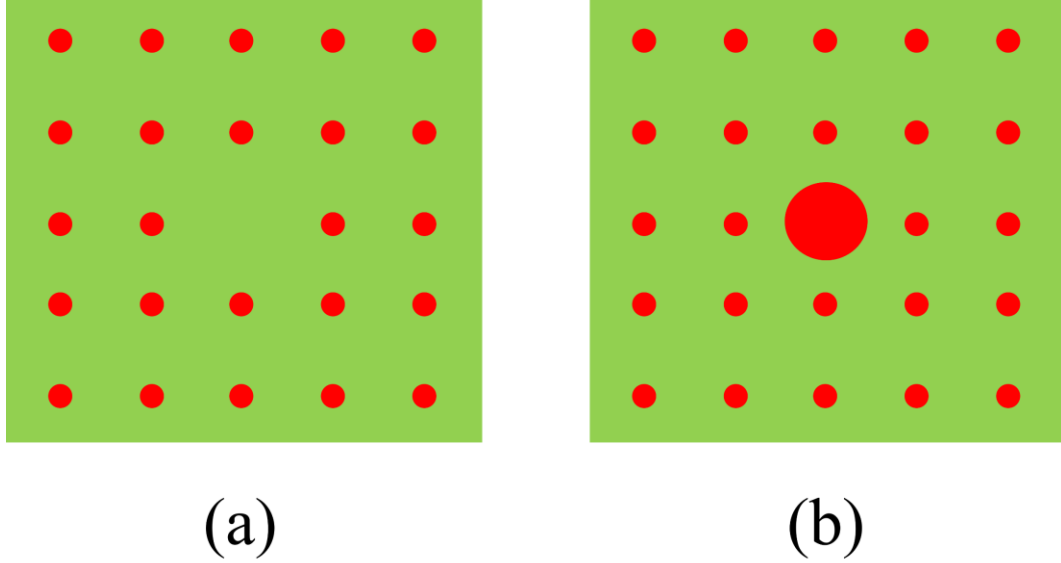


Fig. 2.31: (a) One atom is removed from the center of the square lattice PC (b) one atom is magnified at the center of the square lattice PC [65].

2.13 PCSEL Engineering

Due to the complexity of the structure and manufacturing process, many factors affect PCSEL performance. Initially, electrically pumped semiconductor PCSELs were achieved by using wafer fusion techniques, bonding two substrates (each side of the p-n junction) under high vacuum and high pressure, one of which contained the PC layer [25]. However, this method had drawbacks, such as the formation of undesirable electronic defect states at the fusion interface, leading to increased power consumption and excessive heating [33][37]. Nowadays, epitaxial regrowth technology is widely adopted in the fabrication process to avoid those problems and to enable PCSEL to achieve high power operation [23]. Based on regrowth conditions, both void and all semiconductor PCSELs have been developed [39] [78]. A high emission power PCSEL is achieved by using a void-containing PC structure with metalorganic vapour phase epitaxy (MOVPE) [23].

2.13.1 PC engineering

The shape of lattice atoms can influence the device's performance. For square lattice PC, one common way to increase the output power is to use an asymmetric unit cell to reduce electromagnetic field destructive interference to increase the light extraction in the surface normal direction. Fig. 2.32 presents SEM image of plan and cross section views of the triangular air hole with square lattice PC structure [79]. The detailed principle is explained in Fig. 2.33.

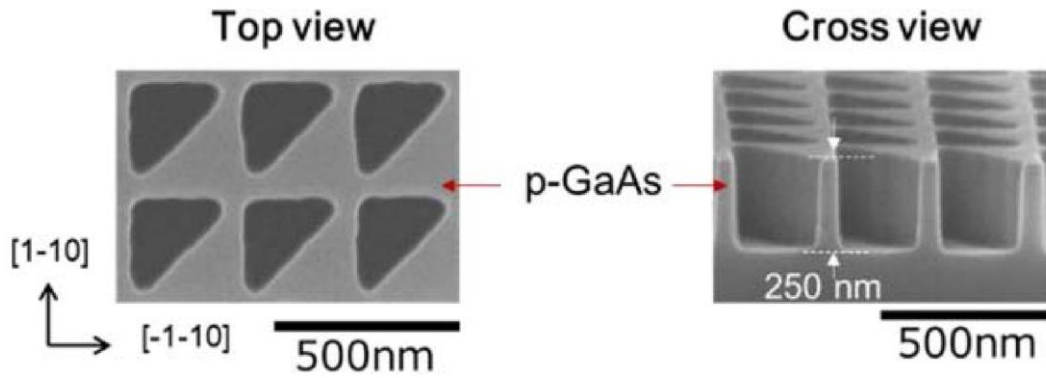


Fig. 2.32: Top and cross sectional views of the PC with triangular air holes arranged in a square lattice [79].

When considering the electromagnetic field interference occurring in the vertical direction of a photonic crystal (PC), the symmetry of the air hole geometry plays an important role in determining the vertical radiation efficiency. As shown in Fig. 2.33, the radiation field in a PC strongly depends on the phase relationship between the vertically diffracted waves generated by the counterpropagating basic waves inside the PC plane. For the symmetric circular air hole shape, the interaction of the basic wave at the circular hole is intrinsically out of phase. The phase difference between the diffracted waves in the vertical direction is π , which results in the two diffracted waves destructively interfering with each other and cancelling in the vertical direction, therefore reducing the output. If the symmetric circular air hole shape is broken into an asymmetric shape like a triangular hole, the phase difference between the interaction of the basic wave at the triangular hole moves away from π , reducing destructive interference and increasing constructive interference in the vertical direction, so a higher output power can be achieved [57].

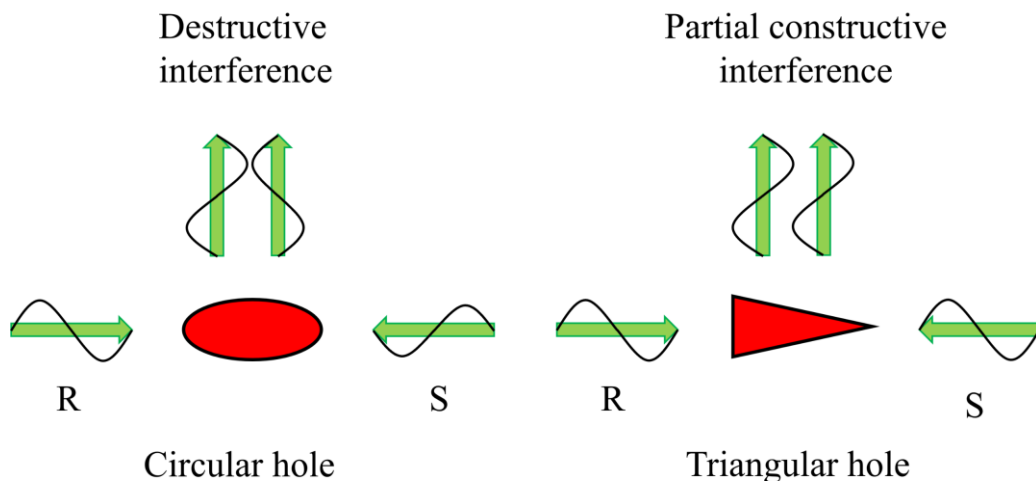


Fig. 2.33: The diagram shows the interference for the circular hole and triangular hole. The arrows represent the propagation direction, and the curves represent the phases of the fields for basic and radiative waves [57].

Another similar design is that the depth of the unit cell also needs to be considered carefully, as shown in Fig. 2.34. When the depth of the air hole is equal to $\lambda/2$, the phase difference of the radiation waves diffracted at the top and bottom boundaries will be equal to $\pi/2$, which can reduce destructive interference and increase vertical emission. When the depth of the air hole is equal to λ , the phase difference of the radiation waves diffracted from the upper half and lower half will be equal to π , which causes destructive interference and reduces the output power [80].

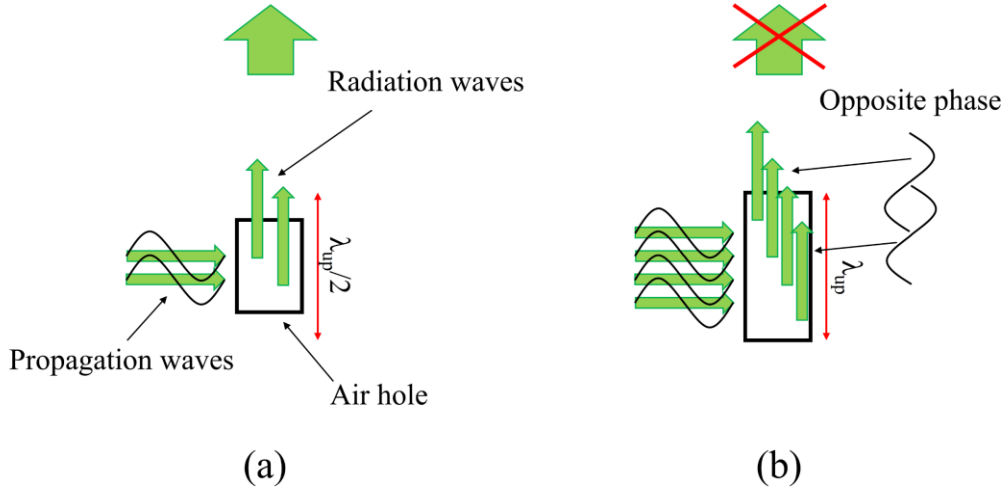


Fig. 2.34: The diagram of interference for different air hole depth (a) $\lambda/2$ (b) λ [80].

As mentioned in Fig. 2.28 and Fig. 2.29, maintaining a suitable κ_3 value to reduce the in-plane loss is beneficial for reducing the threshold. However, as device size increases, higher-order modes also tend to be confined within the PC area, multimode emission may happen as injected current increases. In this situation, reducing the value of κ_3 and making sure only the fundamental mode is confined within the PC is critical for increase the threshold gain margin and radiation constant difference between different modes and maintain high power single mode operation. In recent years, a double lattice structure [52] [81] has been proposed to achieve this goal, as shown in Fig. 2.35. The lattice constant is equal to the wavelength in the PC layer to satisfy the Bragg diffraction. The green atom lattice is located $0.25a$ away from the red atom lattice in the X and Y directions. By carefully designing the position of two different lattice points to achieve a light path difference equal to $\lambda/2$, the red light diffracted by the red atom will destructively interfere with the green light which is diffracted by the green atom [52]. It can reduce the confinement of fundamental and higher-order modes, and the mode will tend to propagate over the entire PC. The higher-order modes tend to distribute closer to the edge of the device compared with the fundamental mode, and fundamental mode tends to be located at the centre of the PC region. It will result in higher-order modes having higher in-plane loss, which increases the margin between the in-plane losses of the higher-order modes and the fundamental mode, increases the threshold current margin between higher-order modes and fundamental modes [52].

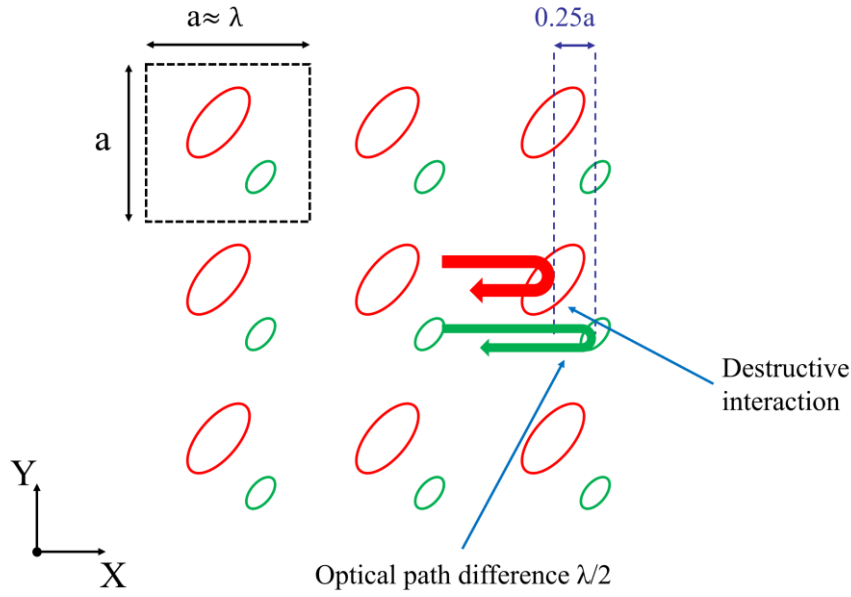


Fig. 2.35: The diagram shows the 3x3 PC double lattice photonic crystal resonator [52].

The variation of electromagnetic field distribution can influence the beam shape and far field polarisation. The far field beam profile is the Fourier transform of the near-field electromagnetic field distribution, this causes a different beam shape, the detailed explanation can be found in [82]. Different PC structures shown in Fig. 2.36. are proposed to control the electromagnetic field distribution. Because different fundamental waves for those patterns have different symmetries, which means the optical characteristics such as beam polarisation are symmetry dependent. By changing the lattice structure from square lattice to triangular lattice and measuring the polariser related far field pattern, it can partially reflect the cavity symmetry of PC layer. Even higher order vector beam can be produced at high order Γ point in band-structure as shown in Fig. 2.37 [82].

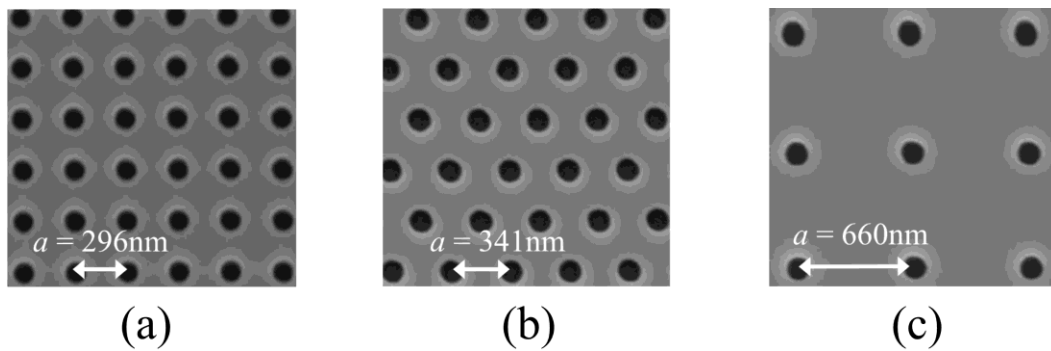


Fig. 2.36: The scanning electron microscope images of the PC layer with different lattice shapes and periods. (a) Square lattice, (b) triangular lattice, (c) square lattice [82].

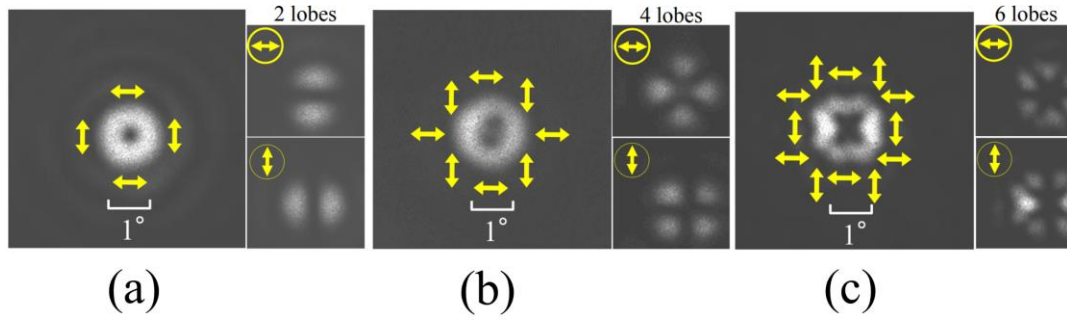


Fig. 2.37: The corresponding far field pattern for Fig. 2.36. Yellow arrows represent the electric field directions. The pattern shown on the right side of each pattern is the far field after the polariser [82].

2.14 Contribution to Knowledge in The PCSEL Field

Existing multi-wavelength PCSEL arrays [83] [84] share a common active element in which the range of accessible emission wavelengths is limited. In chapter 3, the use of large area 2D SAG (selective area regrowth) for PCSELs is described. The study of SAG for multi-wavelength laser sources has usually concentrated on 1D and small size optical components, with the exposed area typically requiring only a width of around 10-20 μm . The results indicate that a uniform growth area of over 100 μm x 100 μm can be achieved, with the peak emission from the MQW regions spanning 86 nm.

Recently, a PCSEL encapsulated by DBRs so as to act as a resonator structure was reported. The concept and detail of this resonator embedded PCSEL (REPCSEL) fabrication and simulation process was presented in [68]. The detailed spectroscopic study of the operating parameters of REPCSELs (and their associated PCSELs) is reported in chapter 4. This includes an L-I-V and spectral analysis of a range of devices, and describes detailed band-structure analysis of these new device structures.

Band-structure measurements are often used to study the properties of PCSELs, but limited information about e.g. the estimation of the Q-factor or threshold gain from this measurement process has been provided. A detailed study of band-structure measurement apparatus and procedures for quantitative analysis are presented in this work. Spatially resolved band-structure measurements are presented for the first time, and the effects of the variation of the collected wavevector Δk , current dependence, and effects of inhomogeneity on the measurement are critically discussed. Polarisation resolved band-structure measurements are also presented.

2.15 Summary

In this chapter, initially, the basic theory of light and the interaction between light and matter, and the formation of the electronic energy band in the material were presented. The basic theory behind interband transitions and intersubband transitions in a QW was then explained. FP resonant cavity and DBR structures were then presented, and the basic resonant behaviour in lasers was introduced. Next, the drawbacks of conventional semiconductor lasers were presented, followed by a brief introduction of the advantages of PCSELS.

The key definitions in PCs and basic coupling theory and the definition of coupling coefficient were then introduced. After that, the formation of PC band structure was introduced by analogy to electronic band structure. This was followed by an explanation of the high symmetry lasing points of interest and how the photonic band structure can be measured experimentally.

The electromagnetic field distribution in the PC and the details of the leaky mode and the non-leaky mode was discussed. The loss mechanisms in the PC were presented. The mode profile distribution in PCSEL was introduced. A brief introduction to defect cavity lasers followed. Then, a discussion of possible ways to engineer PCSEL was presented. Finally, the contribution of this work to the PCSEL field was outlined.

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Chapter 3. Large area 2D selective area growth for photonic crystal surface emitting lasers

3.1 Introduction:

Semiconductor lasers have a wide range of applications in the modern world [1][2][3][4]. However, some applications may require a multi-wavelength source. One common technology used in optical communication is wavelength division multiplexing (WDM), as shown in Fig. 3.1, which needs laser arrays to provide multiple wavelengths.

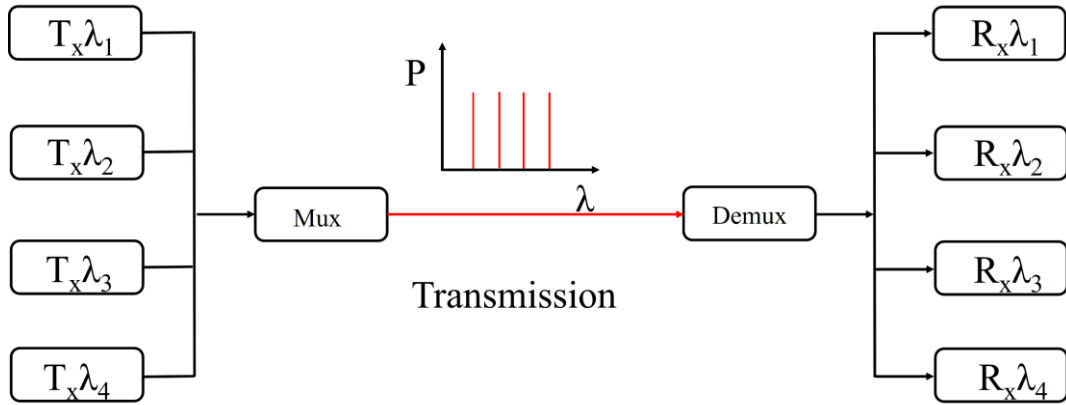


Fig.3.1: Schematic of the WDM technology in an optical communication system. To fully utilize of the optical fibre, two or more optical wavelength signals can transmit information through different wavelength channels at the same time in the same optical fibre, increasing bandwidth.

The application of monolithically integrated electro-absorption modulated laser (EML) in WDM system [5][6][7] for communication system was demonstrated. Selective area growth (SAG) is a solution for InP photonic integrated circuits allowing the realisation of EMLs [8][9][10]. As illustrated in Fig. 3.2, the blue region represents the masked area used to define the width (Λ) of the unmasked part of the wafer surface which is typically determined by a pair of oxide stripes serving as the mask. The yellow region corresponds to the active area, while the red region denotes the electro absorption modulator. By adjusting the width of the window opening, the thickness of the active region and the material composition can be altered due to SAG effect, enabling the tuning of the emission wavelength [8][9][10]. In this case, it allows the gain peak and wavelength of the DFB to be aligned to maximise operating characteristics of the device and creates a QW structure that can be used as electro-absorption modulator (EAM).

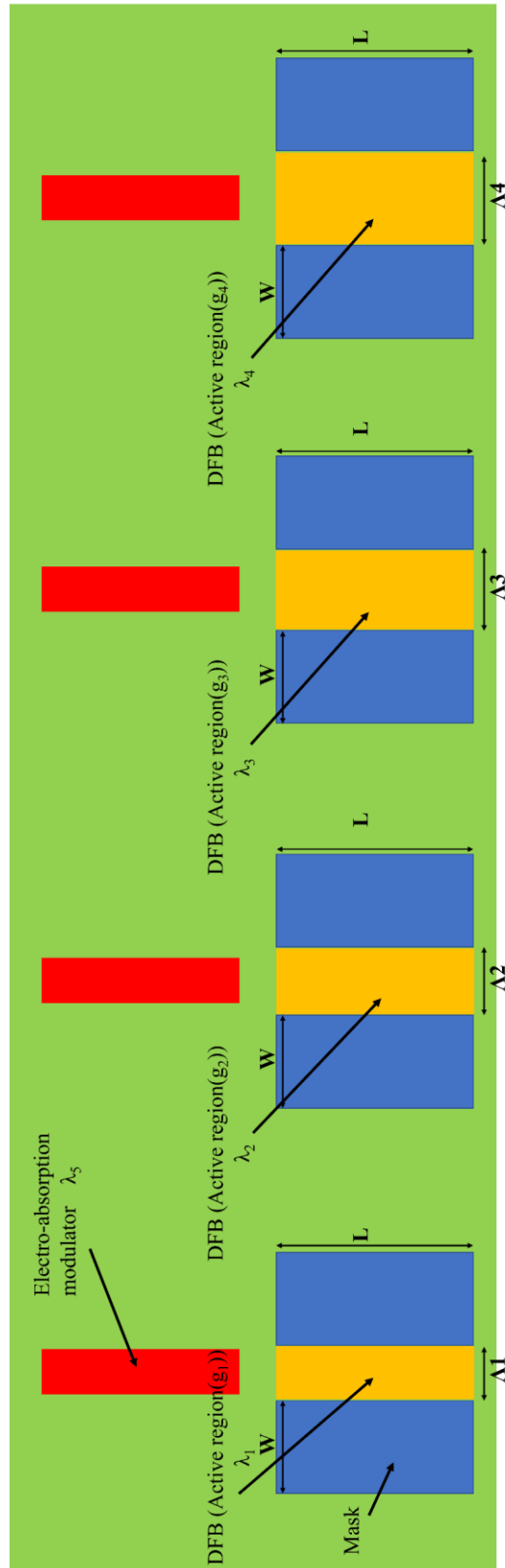


Fig. 3.2: Schematic representation of application of SAG to fabricate the EML [10].

Some sensor applications also need multiple wavelengths for detection. In Fig.3.3. Different gas species exhibit unique resonance absorption intensities at specific wavelengths. By analysing the intensity of the backscattered wavelengths, the concentration profile of the gas can be accurately estimated. This is typically satisfied by multiple wavelength devices.

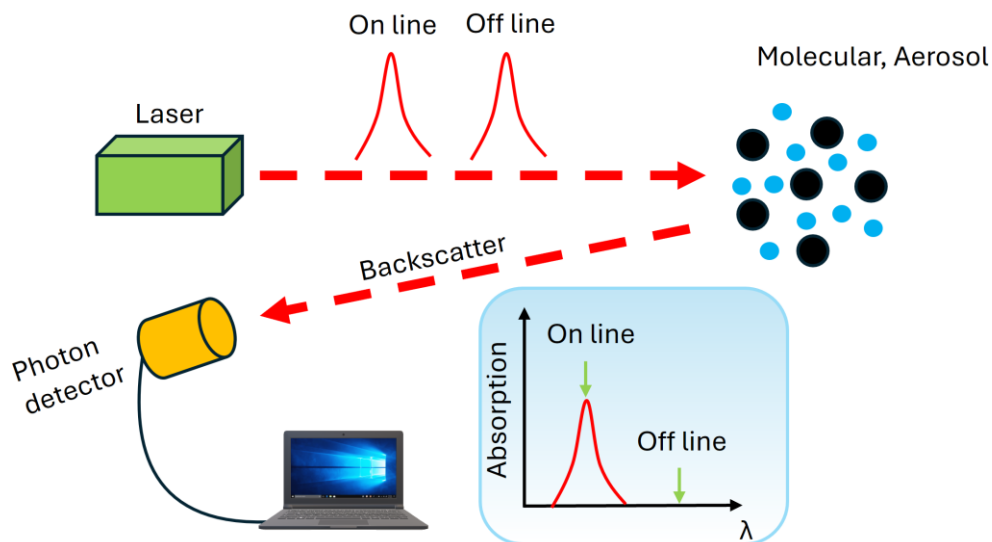


Fig. 3.3: Schematic illustration of the lidar sensor system [11].

Currently, most studies have concentrated on PCSEL devices with single emission wavelengths. There are a few research reports on multiwavelength PCSEL arrays. Existing approaches often concentrate on high brightness, using large area PCSELs with a common active element [12] or large area PCSELs arrays to achieve power scaling with a single mode coherent emission wavelength [13][14].

Multi-wavelength operation has been obtained by using a common active element and tuning the PC period to enable devices with neighbouring emitters with 4 channels in ~ 40 nm at 1300 nm [15]. Whilst not disclosed, it can be expected that the operating characteristics vary over this range as the different PCSELs access different parts of the same gain spectrum. Furthermore, the range of emission wavelengths that can be accessed in this approach is limited by the use of a single active element.

In other reports, multi-wavelength PCSEL operation was achieved by utilising novel properties of QD gain material as the active layer [16]. The strategy is changing the PC period to match the emission peak of ground state (GS) and excited state (ES) of QDs, which allows multi-wavelength operation from one heterostructure with 2 wavelength channels at ~ 1230 nm and ~ 1141 nm. However, the emission wavelengths that can be achieved in this approach are still limited by the use of a single active element.

To date, there has been no consideration of the spatial variation of gain of the active element for multiwavelength PCSEL arrays. A technology that allows several PCSELs with very different wavelengths (different gain peak) to be realised on one wafer (or

more precisely, on the same chip) is therefore of significant interest for a range of technology applications. This chapter explores 2D SAG for the first time to assess the efficacy of the technology in fine scale tuning of the gain peak, and in the maximum tuning that can be achieved on one wafer. Fig. 3.4 shows a schematic of a PCSEL array device with 4 wavelength channels.

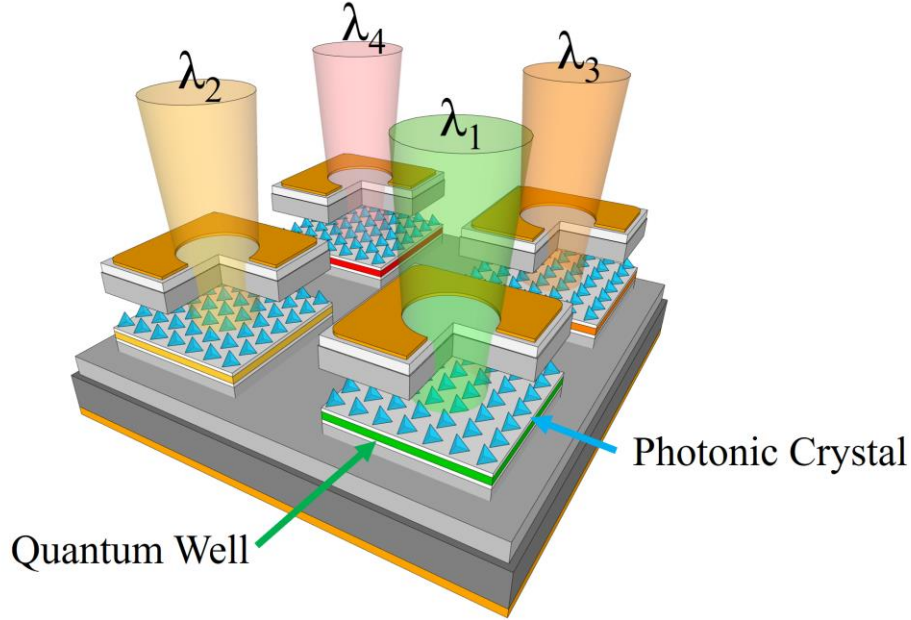


Fig. 3.4: Schematic illustration of the PCSEL laser array, each PCSEL with different emission wavelength. The colour layer represents dissimilar quantum well.

For SAG, the substrate will have predefined patterns or regions designated before growth. These patterns are created using a dielectric mask material such as silicon dioxide (SiO_2) or silicon nitride (SiN_x). The mask will block precursor material deposition and growth in masked regions, altering the flux of precursor materials to the exposed area, and selective growth will be restricted in the exposed areas of the substrate. During the growth process, extra material diffusion from the masked area will bring additional features such as composition and thickness variation within the exposed area. This variation will change the bandgap energy of gain material. The details of this principle will be explained later at section 3.4. Since the mask geometry, such as the shape, size, and spacing of the open area in the mask, can directly affect the growth dynamics. Based on those strategies, wide wavelength tuning range laser arrays with a 150 nm range were successfully achieved [17][18], which presents the potential to develop PCSEL arrays with wavelength tunability.

However, to apply SAG in making a PCSEL array, there are still some challenges. The photonic crystal is distributed in the 2D plane, and an efficient operating range requires at least $100 \times 100 \mu\text{m}^2$ to maintain a decent coupling strength κL (κ is the coupling coefficient and L is lateral device size) and to reduce the in-plane optical loss from the edges of a finite size photonic crystal region [19][20][21]. An even larger emission area is required to achieve an even higher single lasing mode output in recent novel designs

[12] [22]. SAG for such a huge area still needs to be investigated. In many previous reports, most of the studies concentrated on 1D and small size optical components, such as buried heterostructure (BH) quantum well (QW) lasers [17][18] [23] or photonic integrated circuits [24]. The exposed area typically only requires a width of around 10-20 μm for that kind of device, which is also the width magnitude required for the masked area. Although a few studies have reported exposed area widths exceeding 100 μm [25][26][27], there has yet to be a systematic investigation of the InGaAs/GaAs multi-quantum well (MQW) system. The application of 2D SAG is primarily concentrated in fabricating small area devices, such as micro-pyramids [28][29], nanopillar lasers [30], and nanowires [31]. However, the size of these devices remains constrained to the scale of approximately 10 μm .

In this chapter, the use of large area 2D SAG (using metal organic vapor phase epitaxy (MOVPE)) to grow large area InGaAs/GaAs MQW structures is reported. Results indicate that a uniform growth area of over 100 x 100 μm^2 was achieved, with wavelength variations within ± 2 nm from the centre point. Peak emission from the MQW regions spanned 86 nm, indicating that PCSELS operating at an optimal gain PC wavelength detuning could be realised in the future. This highlights the potential of 2D SAG for fabricating PCSEL multi-wavelength arrays.

3.2 Contents of This Chapter:

This chapter begins with an introduction to the metal organic chemical vapour deposition (MOCVD) process. Then, it moves to an introduction to the principle of normal growth and 1D SAG in MOCVD. Then, it extends to an explanation of the principle of 2D SAG in MOCVD.

The details of sample preparation are then introduced. A 5 x 5 array SAG pattern with different mask widths and window open areas were grown on the same substrate with an InGaAs/GaAs MQW structure. Then, an introduction to the principle of photoluminescence (PL), the PL apparatus, and the operating principle of the monochromator. The measurement system is carefully optimised before sample characterization.

Then, the PL spectrum of three samples was analysed, and the results indicate that high-quality MQWs have been achieved. Then, the peak PL wavelength at the centre of the mask shows that a wavelength shift of 86 nm is achieved across the sample. Optical profilometer 3D mapping measurements also indicate that no significant roughness was found on the surface. The growth rate enhancement (GRE) is defined as the ratio of the thickness of material growth under the influence of the SAG effect to the nominal thickness of the unmasked area, without the influences of the SAG effect (2 mm is adopted in this work). The X and Y direction from the optical profilometer measurement results reveals that a symmetric growth shape was achieved and material distribution tends to be a concave profile. The GRE is more pronounced at the edge of the window, and a GRE factor of 1.19 to 2.23 at the centre of the open window were achieved for

all the patterns.

Then, the principle of the energy transition process for the simplified InGaAs/GaAs QW structure is explained. The simulation was based on changing the QW width and the indium percentage in the InGaAs/GaAs QW structure. Then, the wavelength, only considering the influence of the GRE effect, was simulated. The simulation result shows that the peak wavelength was shorter than the measured result, which indicates that only considering the influence of GRE and not considering the influence of indium composition variation cannot match the measured result. Then, the influence of indium was accounted for by correlating the observed QW emission wavelengths with the measured enhanced QW thicknesses for simulation, and the highest indium percentage (~17%) was achieved at the centre position.

Then, 2D μ -PL map for the SAG sample indicates that a uniform emission wavelength region (± 2 nm) of ~ 110 μm was achieved. The X and Y direction measurements of three representative SAG features show that uniform wavelength emission areas of ~ 80 μm , ~ 100 μm , and ~ 110 μm are achieved. Similar measurement processes for other features are presented at the end.

3.3 Metal-Organic Chemical Vapour Deposition (MOCVD):

Fig. 3.5 shows the main components of an MOCVD system. As can be seen from Fig. 3.5, the main part of the system is composed of a gas handling system, a reactor chamber, and the exhaust and safety apparatus [32]. The gas handling system is responsible for injecting and controlling the different gaseous compound flows. Usually, for III-V materials, alkyl radicals attached, like methyl, ethyl, and hydride sources, will be used as carrier gases, such as TMAI, TMGa, AsH₃, PH₃, and III-V gases will be spatially separated and injected into the reactor chamber until mixed over the heated wafer [33]. An example of such MOCVD reaction is GaAs growth [34]:

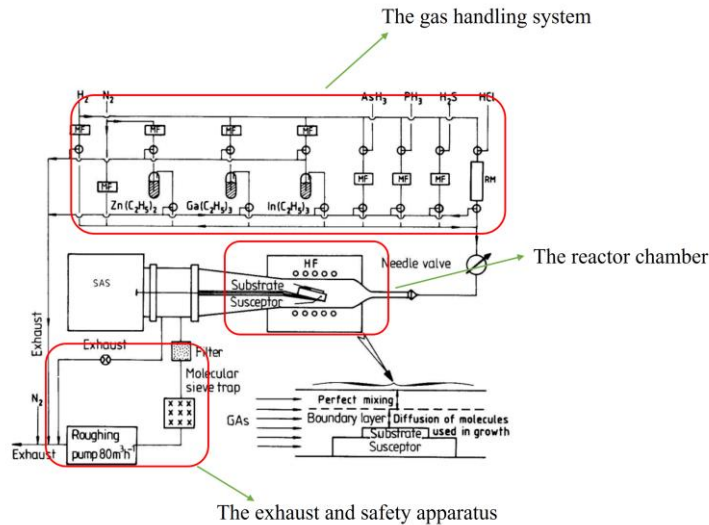


Fig. 3.5: Schematic illustration of the main structure of MOCVD system [32].

By precise control of the sequence, flow rate, and composition of gases flowing into the reactor chamber, the percentage of compounds in each semiconductor layer and layered structures can be deposited. Since the purity of the sources is a very important part that can affect the properties of semiconductor devices, any kind of contamination should be avoided within the entire MOCVD system. One type of reactor chamber is shown in the Fig. 3.6.

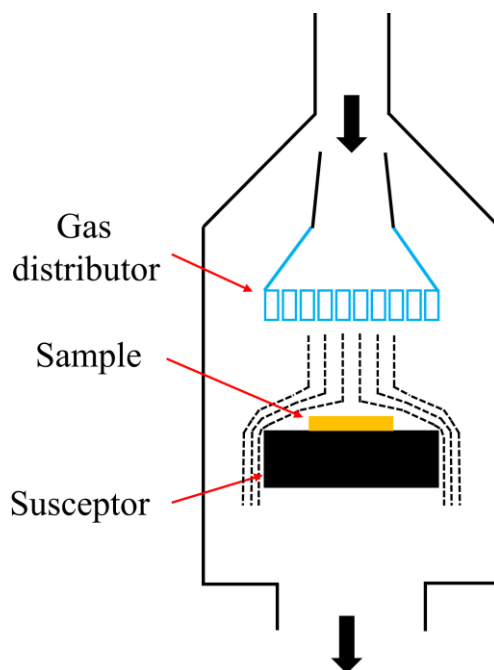


Fig. 3.6: Schematic illustration of a vertical MOCVD reactor geometries [32].

As illustrated in Fig. 3.6, because the growth rate is directly related to the gas flow rate [32], by mixing and uniform diffusion of gas into the reactor chamber, for a vertical MOCVD reactor chamber, the main carrier gas will keep flowing parallel near the heated substrate surface where deposition happens. Since the reactant depletion effect results in non-uniform reactant concentration when laminar flow occurs over the entire wafer, usually the susceptor keeps rotating to improve the quality of uniform growth of materials. Since the growth rate is also affected by the temperature of the substrate, inhomogeneous deposition may occur due to local heating of the substrate. Then, after finishing the reaction and deposition on the substrate, the by-products of the growth reaction will be processed by the exhaust and safety apparatus.

3.4 Selective Area Growth in MOCVD:

For normal semiconductor growth situations in MOCVD, by carefully controlling growth variables like growth temperature, flow rate, and pressure, the material tends to be deposited uniformly over the substrate. Take the growth of the GaAs layer on the GaAs substrate as an example in Fig. 3.7. As can be seen from Fig. 3.7, without the influence of external factors, substrate strain, crystallinity, or orientation, the atoms tend to deposit homogeneously over the substrate during the growth process. However, the situation changes when selective area growth is introduced into MOCVD.

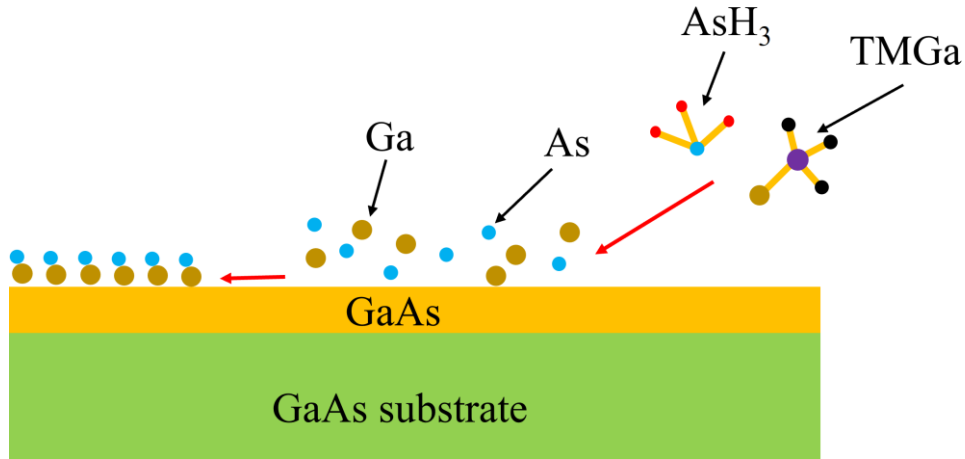


Fig. 3.7: The schematic diagram illustrates the molecular distribution on the surface of the GaAs substrate.

Usually, SAG is implemented by patterning two parallel stripe regions on the substrate to change the local reaction rate as in Fig. 3.8 (a) [24]. The stripe geometry mask usually uses amorphous material like SiO_2 or SiN_x to reduce or prevent the precursors from being adsorbed and reacting on the mask. Since the growth process involves gas phase diffusion and surface diffusion from the mask region, the growth rate will depend on the relative width of the masked region (W), the widths of the stripe between two masked regions (Λ) which define the SAG region, and the length of the masked region (L). This is why SAG is widely used in making laser arrays, utilising QW actives, since the photon energy from electronic transitions between the conduction band and the valence band (or sub-band transition) is mainly decided by the well thickness and composition percentage. By changing the width of the mask and the stripe open region, different lasing wavelength devices, or active and EAM (passive when no bias is applied), can be fabricated on the same wafer through one single MOCVD growth process.

Fig. 3.8 (b) shows one common fabrication method for SAG. Taking a GaAs substrate as an example of growth GaAs, first, two parallel stripes of the dielectric mask (SiO_2) were patterned on the substrate through standard photolithography and etching process, then the sample is placed in an MOCVD reactor chamber for the SAG process. Since the SAG is strongly dependent on the growth condition parameters like different III-V species, growth pressure, and growth temperature, usually, a combination of low pressure and high temperature is commonly used to improve the quality of growth [29][35]. Fig. 3.8 (c) shows a very idealized and simplified growth situation in an MOCVD reactor chamber. A more accurate vapor phase diffusion model to predict the growth profiles for complicated growth over the entire SAG area has been widely studied in other work [24] [36] [37][38], which is not the main purpose of this work. Then after SAG in the reactor chamber, the oxide can be removed to test the growth thickness profile as shown in Fig. 3.8 (d).

The theory behind SAG can be simply explained in Fig. 3.8 (c). When the mixed gas arrives above the SAG area, the deposition situation above the dielectric mask and the window open area will be different.

First, for atoms on the surface of a dielectric mask, ideally, no deposition should happen on the mask area, because the products of active precursors cannot adsorb onto the amorphous material in theory [24]. However, in a real MOCVD reactor chamber, there still exists a very low probability that atoms stick to the dielectric mask surface, depending on the specific properties of the mask material. Most atoms tend to desorb from the dielectric mask surface and return to the gas phase, as illustrated in Fig. 3.8 (c). Even if a small fraction of atoms is adsorbed onto the mask, due to the high mobility of adsorbed atoms on the surface of the mask, the atoms tend to diffuse to the edge of the mask. Because different species exhibit distinct surface diffusion characteristics during this migration process on the surface of the mask, which is one of the reasons that result in deposition composition percentage varying across the window open area [39][40]. Studies have shown that increasing the substrate temperature can suppress deposition on the mask and enhance surface adsorbate diffusion within the open window area, since this is an activated process [24]. It is one of the reasons selective area growths depends on the extent of decomposition of the reactant above the mask and decomposition temperature [41]. As a result, SAG typically employs high temperatures to improve growth quality.

Second, for open window areas, the source of atoms comes from two sources. First, the growth rate of III-V compounds comes from gas phase diffusion. As precursors are consumed above the open window area, a vertical concentration gradient will be formed until it reaches a boundary layer where the concentration of reactants will remain constant beyond this layer. This concentration gradient will drive the atoms closer and deposit them onto the unmasked area. Second, due to the minimal reactivity on the dielectric mask, a lateral concentration gradient can also form. This nonuniform concentration is a reservoir to supply extra atoms from the space above the masked region. The growth rate will depend on the relative stripe and mask width. Consequently, the growth rate is affected by the relative widths of the stripes and the mask, which is the main reason for additional inhomogeneous reactant GRE over the open window area in the lateral direction [40][42].

Additional deposition due to this lateral supply of atoms includes two different sources. First, the atoms come from the surface of the mask when the atoms on the mask migrate towards the edge of the mask. Second, the atoms come from the space above the mask area through vapor phase diffusion process. Because the surface effective diffusion of the dielectric mask is different for different species, which process will become the dominant process is dependent on the relative mask surface diffusion length of reactants and the size of the mask. Some studies [39] have shown that when the mask size is much larger than the diffusion length of atoms on the mask (especially around 10 μm), the vapor phase diffusion process is the dominant process for a larger growth rate in the

window open area. If the surface diffusion length is large and mask size is small, the surface diffusion process will dominate the GRE at the edge of the mask. So, the balance of vapor phase and surface diffusion will relate to diffusion length on the mask, diffusion lifetime ratio of atoms on the mask (the time before an atom desorbs from the mask during diffusion), the length of the mask, and diffusion length on the window open growth area.

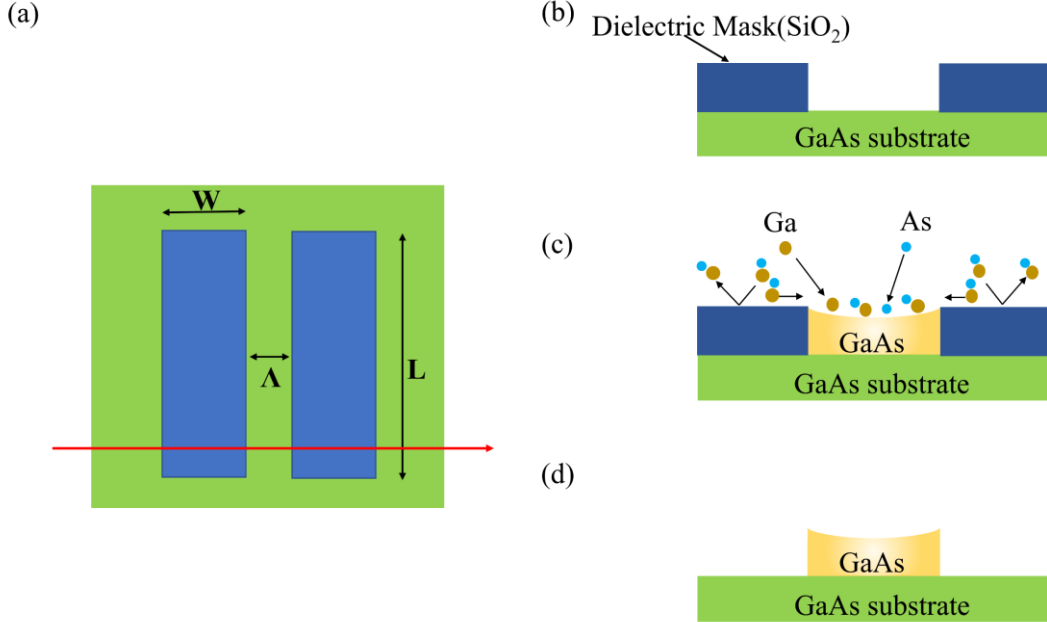


Fig. 3.8: Schematic of the top view of the traditional SAG pattern and fabrication steps for the SAG process, the blue region represents the dielectric mask region. (a) Top view of the SAG pattern with the dimensions W , L , Λ . (b) The window open growth region is defined within two parallel stripes. (c) The simplified model of GaAs selective growth within the window open region on the GaAs substrate. (d) The growth thickness profile after removing the dielectric mask [36][37].

Consequently, employing the MOCVD technique to achieve SAG enables a degree of design flexibility for fabricating various QW epitaxial structures across an entire wafer in a single growth step. The in-plane bandgap of the QW can be controlled by adjusting the layer thickness and composition through a carefully designed mask, which is the key element for SAG-based devices. Typically, if we do not consider the influence of uneven temperature distribution within the SAG region, surface crystallinity, crystal orientation, and surface stress, the material deposition tends to exhibit the highest GRE near the mask edges, while maintaining a relatively flat profile in the central regions. This behaviour arises due to the limited diffusion length of reactants and the tendency of the growth layer to maintain lattice constant matching with the substrate during deposition. As a result, the grown layer often adopts a concave profile, as illustrated in Fig. 3.8 (d). Moreover, a higher ratio of dielectric masked substrate to open area tends to exacerbate this nonlinear GRE due to a very large lateral gradient in reactant concentration [38][43][44]. As the thickness of the QW becomes thicker than the standard growth area, the emission wavelength will tend to red shift as the ground state

transition energy reduces. At the same time, the different decomposition and diffusion properties of different III-V reactants will lead to spatial composition variation and contribute to localised changes in the effective energy bandgap within the window open area.

In this study, the growth process is extended to two dimensions, with mask and window opening sizes differing from conventional configurations. A brief explanation of these modifications is provided in Fig.3.9. Compared with traditional one-dimension SAG, this extra dimension can provide an extra effect on material growth within the window. First, like the one-dimensional SAG mentioned above, for the vertical direction gas phase diffusion process above the window area, the vertical concentration gradient below the boundary layer will drive reactants diffusion and deposit into the window area. At the same time, lateral concentration gradient above the 2D SiO₂ mask area also provides extra reactants for window area growth, which is the dominant process for additional inhomogeneous reactant GRE over the open window area when the width of SiO₂ mask is over 10 μm in this paper (the minimum size is 100 μm). During epitaxy the two (110) direction are not equivalent, and preferential diffusion is unexplored. Especially at the corners of window, the reactants diffusion is not only driven by lateral concentration gradient along the X direction but also by the Y direction and the 45-degree direction between the X and Y axes, which may result in extra GRE at corner positions, and is discussed later.

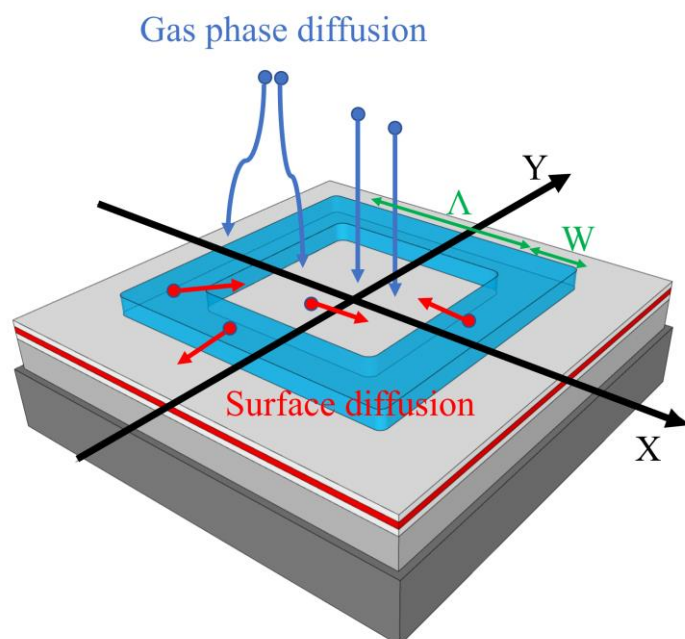


Fig. 3.9: Schematic representation of the SAG process in two dimensions. The blue dot represents a reactant molecule in the gas phase, while the transparent blue area represents the SiO₂ mask. The red dot indicates a reactant molecule on the surface of the mask. The blue and red arrows illustrate the directions of movement of the gas phase and surface bound molecules, respectively.

Even though SiO_2 will ideally prevent reactants from reacting and depositing directly on the mask surface, there is still a possibility for some molecules to be captured and adsorbed on the surface of SiO_2 . But the high mobility of molecules on the SiO_2 mask surface will quickly lead to their diffusion towards the mask edge. And 2D dimension design will further enhance the influence of the diffusion property of different species on the mask surface, which can make the inhomogeneous material component distribution within the window area more complicated than that observed with one-dimensional SAG.

3.5 Sample Preparation:

Fig. 3.10 (a) shows the 5x5 array SAG pattern used in this study. The features on the substrate were at distances from each other (2 mm centre to centre) to avoid any interference effect between neighbouring patterns during the growth process.[44] W represents the width of the SiO_2 mask and Λ represents the width of the window open area; both of these had minimum values of 100 μm and varied in increments of 50 to 300 μm . A 200 nm thick SiO_2 layer was used as the masking material for this study. The main reason is that SiO_2 has better physical and chemical stability than dielectrics such as silicon nitride (SiN) or amorphous silicon (a-Si), which can give better growth selectivity [45]. The SAG region was patterned using standard photolithography combined with a reactive ion etch (RIE) process. The final mask was aligned along the $\{110\}$ crystal plane directions.

Fig. 3.10 (b) shows the cross-sectional epitaxial structure. A 50 nm GaAs buffer layer is deposited first, then a 50 nm thick $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ layer is deposited to improve carrier confinement and room temperature PL intensity due to its larger conduction band gap offset. Then, three nominally 6 nm thick $\text{In}_{0.12}\text{Ga}_{0.88}\text{As}$ QWs are sandwiched inside four 30 nm thick GaAs quantum barrier layers and are deposited. The QW emission wavelength is designed at 945 nm. Then, 50 nm $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ layers are deposited again, with a 20 nm GaAs cladding layer above the stack. All structures were grown on a wafer oriented with a 2° offcut from the (100) plane towards $(1\bar{1}0)$ n-GaAs wafer, at a temperature of 650 $^\circ\text{C}$ and pressure of 100 mbar in a Thomas Swan closed coupled showerhead reactor through MOVPE. Trimethyl gallium (TMGa), trimethyl aluminium (TMAI), and trimethyl indium (TMIn) were used as the Group III precursors, whilst the Group V source used was arsine (AsH_3). To avoid any possible polycrystalline growth on the large masked areas and improve the quality of material deposition over the substrate far away from the oxide masks [26], a V/III ratio of 300 was used for the deposition of InGaAs and a growth rate of 23 nm/min.

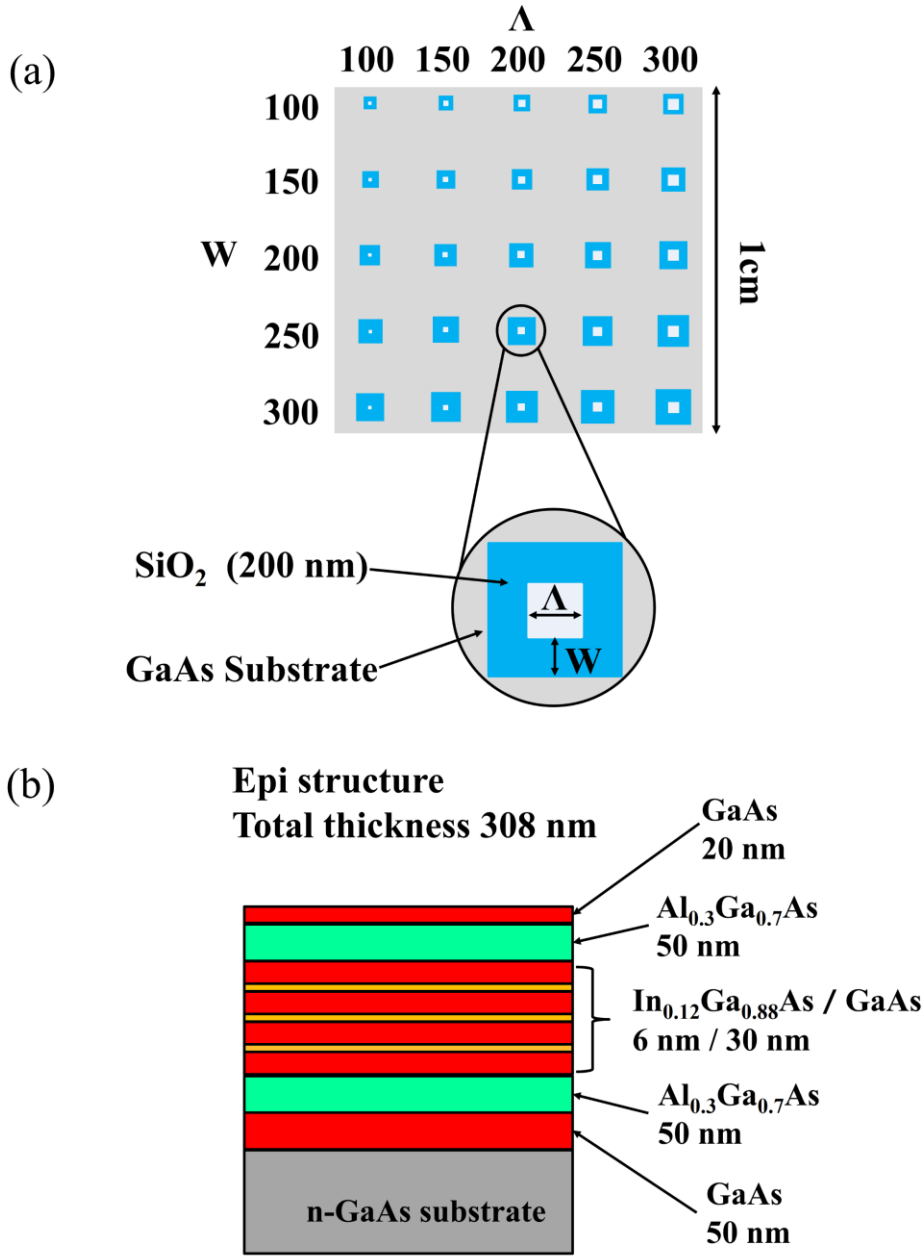


Fig. 3.10: (a) Schematic representation of the masked 5x5 array SAG area (b) Cross-sectional schematic structure of the epitaxial with three 6 nm thick $\text{In}_{0.12}\text{Ga}_{0.88}\text{As}$ QWs sandwiched inside four 30 nm thick GaAs quantum barrier layers formed above an n-GaAs substrate.

3.6 Measurement Apparatus and Sample Characterization:

3.6.1 Photoluminescence (PL)

In order to characterize sample properties, PL is used for this study as a contactless and non-destructive optical technique to analyse the optoelectronic properties [47]. The technique involves irradiating the material with photons of higher energy than its bandgap. After the photon excitation process, which involves the material absorbing

photons with sufficient energy to excite electrons from their ground state to a higher energy level, then after a brief period, these electrons will drop to a lower energy state, releasing the excess energy in the form of emitted photons through the spontaneous emission process. Then that PL information can be used to characterize the material's electronic structure, providing valuable insights into the electronic structure and properties of the material [48].

A schematic representation of the PL process is shown in Fig. 3.11. Due to many body effects in semiconductor material, which help form the conduction band and valence band as explained above in the second chapter of background introduction, and the quantized energy levels in QWs due to quantum effects [33], spontaneous emission will arise from the transition process between the conduction band and the valence band. When a photon is annihilated, an electron may be excited to higher energy states. After this excitation process, the electron will relax to lower energy levels within the conduction band through a phonon emission process [49][50]. Subsequently, it recombines with a hole in the valence band, releasing the excess energy in the form of luminescence photons. The energy of the emitted photon corresponds to the bandgap energy.

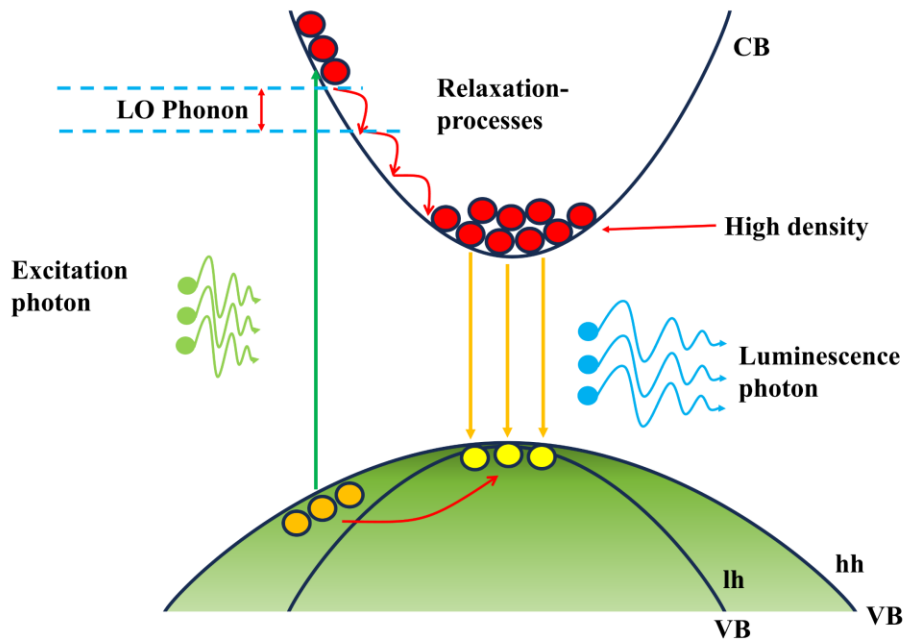


Fig. 3.11: Schematic representation of the principle of photoluminescence excitation [50] [51].

The impact of phonons is very important in the PL process, in QW structures, the confinement of electrons in one dimension creates discrete sub-bands within the conduction band, however, the band dispersion still exists in the other two dimensions. As temperature increases, the thermal population of phonons increases, which enhances the probability of electron-phonon interactions. After absorbing the energy of thermal phonons, the electrons are thermally excited to higher energy states within these sub-bands, which can increase the range of energy states involved in the emission process and broaden the PL spectrum. Additionally, since electrons can emit or absorb multiple phonons as they transition between those sub-band energy states, this can introduce further energy states that contribute to the broadening of the PL spectrum [33][52][53].

Another important influence during the PL measurement process mainly comes from localised defects and impurities within the material, since these imperfections often lead to nonradiative recombination, which can influence the transition process and reduce PL efficiency. At the same time, localised defects also can provide localised energy states. Phonons can help the transition between those states, which will broaden the PL spectrum. [48][54][55]

3.6.2 PL apparatus:

Fig. 3.12 illustrates the key components of the PL setup used for the characterization of SAG features. The excitation light comes from a 532 nm diode pumped solid state laser. After the laser beam is reflected by two mirrors, the laser beam is directed through a pair of beam expanders, since the curved wavefront may result in power loss at the end of the optical path. Those two beam expanders are used to collimate laser beams and maintain a constant planar wavefront. Subsequently, two neutral density filters are employed to partially absorb the laser energy and change the output power according to the real measurement requirements. A dichroic mirror (DM1) is placed to prevent potential laser back reflection into the source, which may bring noise and instability. A second dichroic mirror (DM2) is used to combine the laser beam with blue light from an LED source. After the laser beam is reflected from dichroic mirror 3 into a collimator, the laser beam will be focused on the sample surface.

Then the PL signal is collected by a collimator and passed through the first mirror, which is used to reflect LED light to the camera to give a view of the sample. Then, two parallel dichroic mirrors are used to filter out shorter wavelength pump laser light while allowing the longer wavelength PL signal to pass. Since the first dichroic mirror will shift the PL signal propagation path, the second parallel placed dichroic mirror also has the function of shifting the path back into the centre. Finally, the PL signal is directed to a top mounted parabolic mirror, which focuses it into the entrance slit of the monochromator. The slit is used to control the entrance size and propagation direction of the PL signal that enters the monochromator.

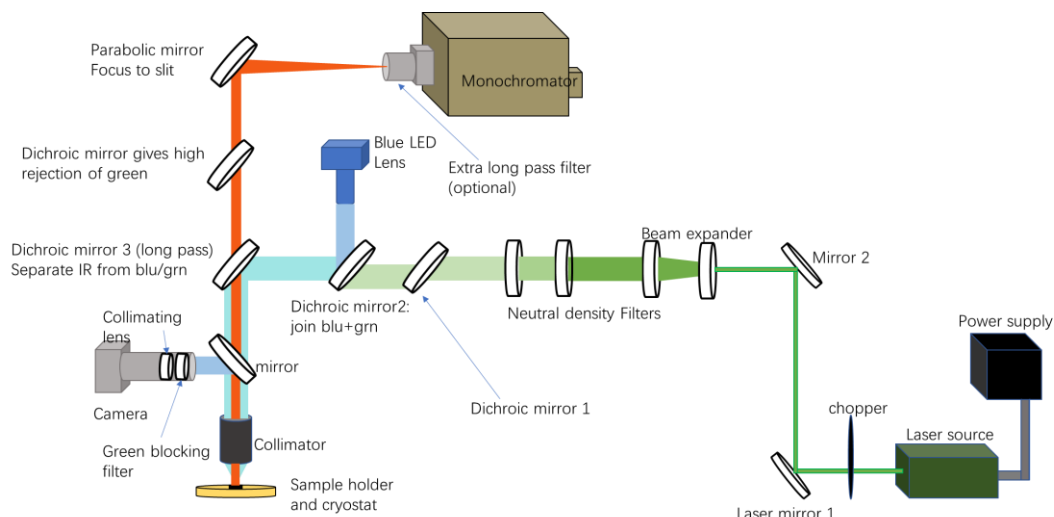


Fig. 3.12: Schematic representation of the PL apparatus.

Figure 3.13 depicts the working principle of the monochromator. The principle behind the grating monochromator can be described as a wavelength filtering process. First, the incoming signal is focused by additional optical lenses at the entrance after the light enters the monochromator. The focused light beam is transformed into collimated light after striking the diffraction grating. This transformation is achieved by adjusting the width of the entrance slit, as well as the position of mirror 1, as illustrated in Fig. 3.13. The diffraction grating consists of equally spaced grooves or parallel lines. The collimated light will be diffracted when it reaches the grating, with each wavelength being reflected at a specific angle. This diffraction angle varies according to the wavelength of the light and the spacing of the grating's lines. After the beam is dispersed by the grating, the wavelength selection can be achieved by physically adjusting the grating angle, combined with controlling the position and width of the exit slit. The exit slit will allow only the desired wavelength range to pass through while blocking the rest. For example, as shown in Fig. 3.13, red, orange, and green light rays are diffracted at slightly different angles and reflected by mirror 2 toward the exit slit. By precisely controlling the exit slit, the red light and green light will hit the wall and only the orange light will be transmitted. By rotating the grating and adjusting the exit slit, the monochromator can scan across the spectrum and isolate different wavelengths sequentially.

For the measurements reported in this thesis, the monochromator is a double grating Bentham DMc150, and Si detectors can be used for the range 300-1100 nm.

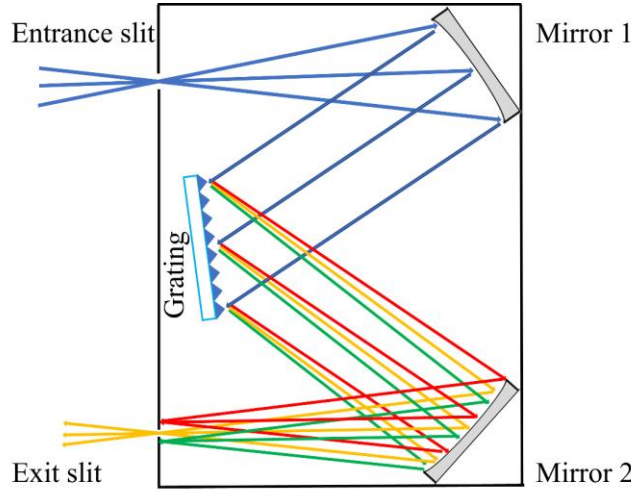


Fig. 3.13: Schematic representation of the principle of the grating monochromator [56].

Since the slit width influences the spectral resolution of the PL measurement, precise alignment of the slit width is essential prior to characterizing the SAG features.

As illustrated in Fig. 3.14, the resolution can be improved as the slit width is reduced. However, a narrower slit width reduces the throughput and reduces the signal to noise ratio. To keep a balance between resolution and a clear signal, a suitable slit width should be determined before measurement.

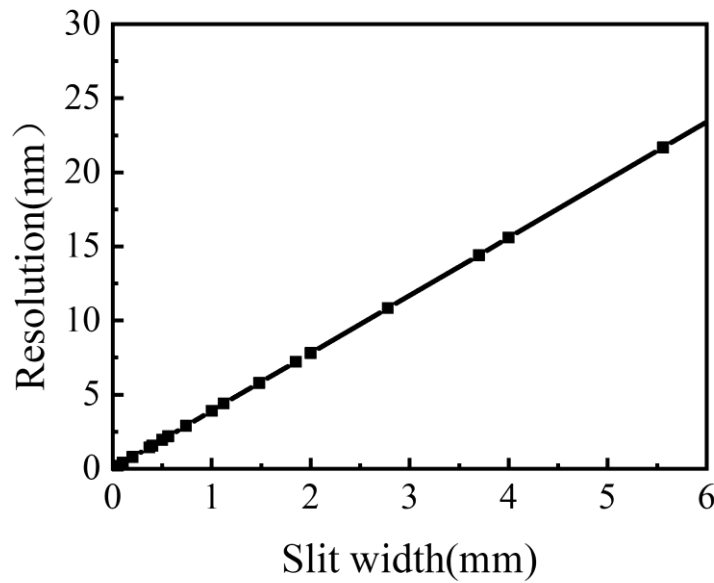


Fig. 3.14: Graph of the wavelength resolution of the Bentham DMc150 Spectrometer.

Figure 3.15 plots the measured spectral linewidth of PL emission of a QW structure as a function of the spectrometer slit width. The red curve represents the predicted FWHM (full width at half maximum), using the following formula [57]:

$$\left(\frac{\Delta\lambda_R}{\lambda_R}\right)^2 + \left(\frac{\Delta\lambda_F}{\lambda_F}\right)^2 = \left(\frac{\Delta\lambda_m}{\lambda_m}\right)^2 \quad (3.2)$$

$\Delta\lambda_R$ represent the FWHM of the "real" spectrum, which means the actual linewidth of the spectral feature had been measured without the influence of any filter function. $\Delta\lambda_F$ is the broadening introduced by the filter, and $\Delta\lambda_m$ is the experimentally measured (or predicted if $\Delta\lambda_R$ is known). $\lambda_R = \lambda_F = \lambda_m = 980$ nm. At small slit widths the measured linewidth can be expected to be close to the true spectral linewidth as $\Delta\lambda_F/\lambda_F$ is negligible (tends towards zero) and $\Delta\lambda_R = \Delta\lambda_m$ and is ~ 14 nm. As the slit width is increased, there is a jump in spectral linewidth and it then remains essentially constant with increasing slit width. For this range of slit widths, the predicted increase in measured linewidth caused by the slit width increase is relatively small, increasing from 14 nm at 0.25 mm to 15.7 nm at 2 mm. However, the experimentally measured linewidth shows a much larger increase, from 14 nm at 0.25 mm to 21.6 nm at 2 mm. This deviation from the predicted trend is worthy of discussion.

When the input signal is focused into a circular shape, the behaviour of the FWHM can be explained as follows. Initially, when the slit width is very narrow, the resolution is significantly higher than the FWHM of the PL signal. As the slit width keeps increasing, the resolution decreases, leading to a gradual increase in the FWHM of the PL signal. However, once the slit width exceeds the diameter of the focused spot, no extra PL signal is injected into the grating monochromator, and the resolution is determined by the spot size, not the slit width. Beyond this point, the FWHM of the signal tends to remain constant, and the wider slit width introduces more environmental noise to influences the PL signal.

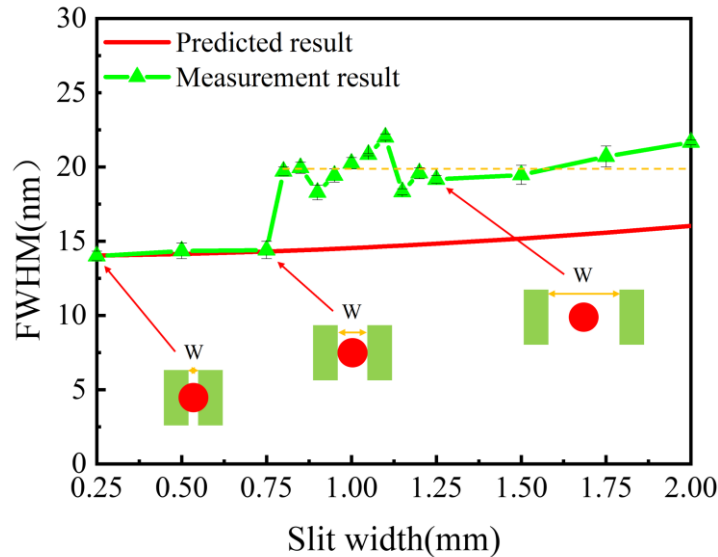


Fig. 3.15: Schematic representation of FWHM of PL signal in theory and measurement result.

A slit width of 0.5 mm was chosen as a trade off between resolution and signal intensity, to balance precision and practical considerations for weak signal analysis. This slit width provides approximately 1 nm broadening of the PL spectrum. This is used as the uncertainty in determining the peak PL wavelength, and in choosing the wavelength steps at which data was acquired.

The next important step in PL system alignment is optimising the incident laser power. Higher incident power can enhance the signal to noise ratio of the PL signal and make it easier to analyse. However, increasing the intensity of the incident laser beyond a certain threshold will introduce additional problems. For example, excessive laser power may cause the temperature of the sample to increase, which may result in sample degradation or at lower powers, distort the PL spectrum and compromise the accuracy of the measurement if the centre of the excitation spot is at a higher temperature than the rest of the spot and wafer.

Fig. 3.16 presents normalized PL spectra under different injected laser power at the same position of the sample. The spectrum is observed to broaden asymmetrically to longer wavelengths as the excitation power is increased. At high excitation powers a clear, longer wavelength peak emerges. There are two possible reasons that may cause the FWHM of the PL spectrum to increase. First, as the incident laser power increases, the temperature of the sample may rise. Increased temperature leads to band gap reduction and broadening of the Fermi-Dirac distribution of carriers which can lead to a red shift of the emission peak and homogeneous broadening of the emission spectrum [32]. Since the pumped laser wavelength is 532 nm, the peak at 1064 nm is due to second-harmonics generation effect from pumped diode laser [59][60]. The side peak next to main peak may be due to the spectral leakage of the lasing line in monochromator.

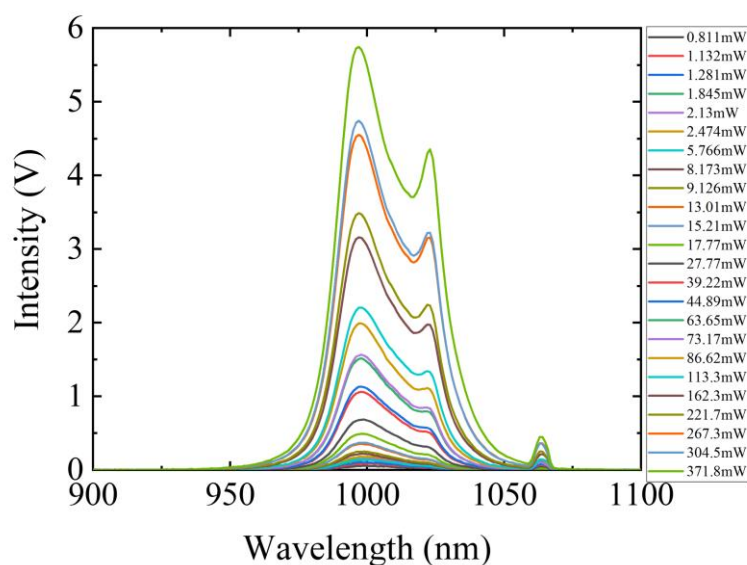


Fig. 3.16: Schematic representation of normalized PL spectra under different injected laser energies.

Fig. 3.17(a) shows how the peak wavelength of the PL shifts with varying incident laser power. Fig. 3.17(b) plots the variation of the FWHM of the PL spectrum at the same sample position under different incident laser powers. Both plots are derived from data in Fig 3.16. As shown, there is a very gradual increase in peak position with increasing power, close to my assumed resolution limit of ± 1 nm. When the incident laser power exceeds 18 mW, the FWHM begins to increase. This indicates that the optimal laser power for measurement is below 18 mW to avoid distortion of the PL spectrum. Considering the trade-off between the FWHM of the PL spectrum and enhance signal to noise ratio of the PL spectrum for analysis, the choice of 18 mW was chosen as the maximum incident laser power for measurements.

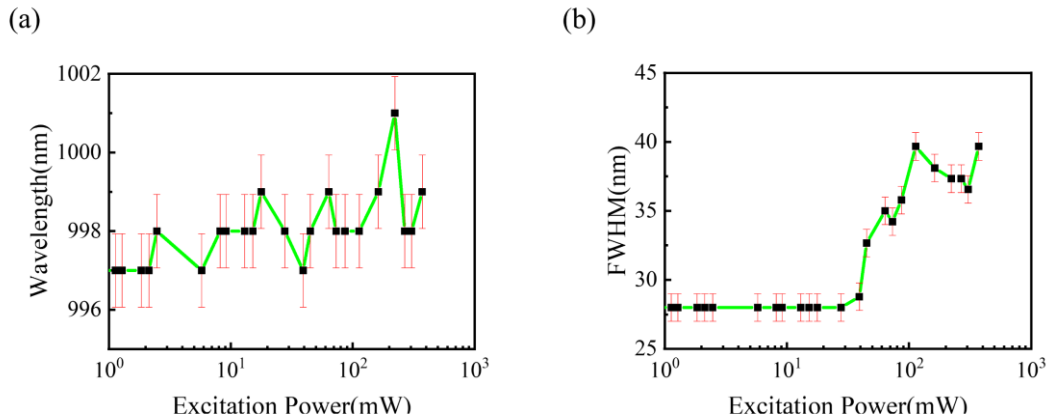


Fig. 3.17: Graph of (a) peak wavelength of PL spectrum under different injected laser energy; (b) FWHM of PL spectrum under different injected laser energy derived from Fig 3.16.

The measured linewidth may be influenced by the size of the laser spot, particularly when characterizing the inhomogeneous properties of materials. A smaller laser spot size reduces any inhomogeneous broadening of λ_R . In this study, the laser spot was focused to a diameter of approximately 10 μm on the sample surface, which represents the smallest spot size that the current system can reach.

3.6.3 Sample characterisation:

Fig. 3.18 presents PL spectra on three different samples at the centre of the SAG open area window under room temperature conditions. As can be seen from Fig. 3.18, the result exhibits noticeable differences in peak emission wavelengths. The peak wavelength for each sample tends to red shift as mask size increases, from 985 nm (red curve) to 991 nm (blue curve), and 994 nm (green curve).

This redshift can primarily be attributed to two factors. First, for the same window size, the GRE will be influenced by the reactant concentration that is above the mask. Larger mask size will bring larger reactant concentration gradient differences, which can enhance the QW GRE effect at the centre of the window [61] where a wider QW thickness will cause a redshift off the emission wavelength. At the same time, the greater enhancement for indium compounds in the QW due to the enhanced GRE will

also contribute to redshift as the mask size increases. The underlying mechanisms responsible for these shifts will be further discussed in subsequent sections.

The FWHM of the emission spectra for the three samples is 19 nm (red curve), 15 nm (blue curve), and 14 nm (green curve). The largest recorded FWHM, observed at the centre of all samples, is 26 nm. This broadening may be attributed to the effect of interface roughness introduced during the growth process of the MQW structure. As the quantum well width (L) is increased, the mono-layer fluctuations (ΔL) of the barrier/well and well/barrier interface have a lower impact on the FWHM as $\Delta L/L$ reduces [58][62]. Overall, those comparatively narrow FWHM [63][64][65] and sharper peaks observed in the PL spectra in this work indicate that high-quality MQW growth with uniformity and smooth interfaces at the centres of the samples have been achieved.

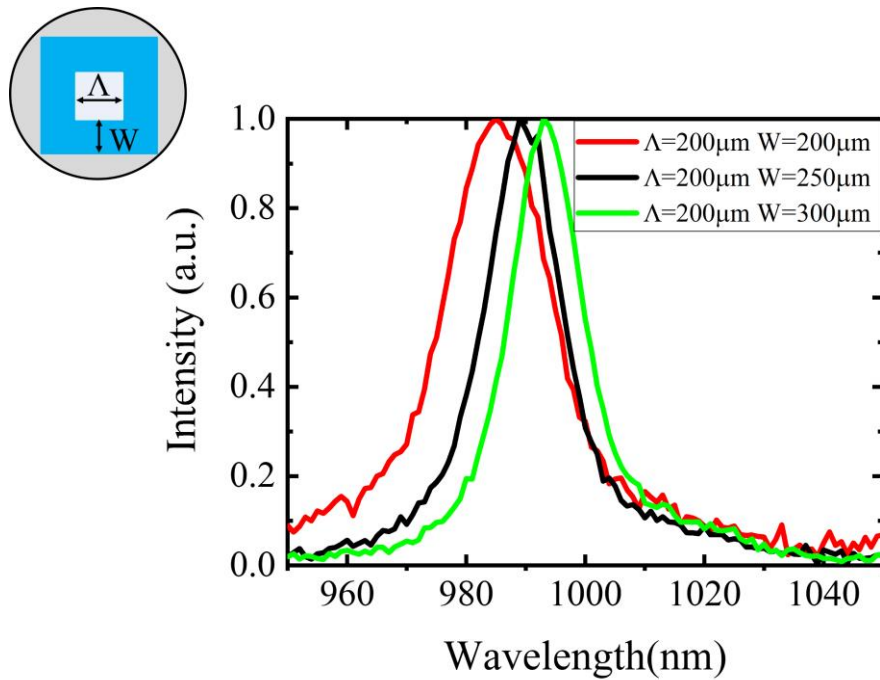


Fig. 3.18: Graph of the room temperature PL spectrum at the centre of three SAG samples with the same window width $\Lambda = 200 \mu\text{m}$ and different mask widths $W = 200 \mu\text{m}$, $250 \mu\text{m}$, and $300 \mu\text{m}$.

In Fig. 3.19, the peak emission wavelength is plotted as a function of mask width (W) and window size (Λ). A total wavelength shift of 77 nm was achieved for all SAG samples at the centre position under room temperature conditions. The smallest redshift occurred at $\Lambda = 300 \mu\text{m}$ and $W = 100 \mu\text{m}$, with an emission wavelength of 954 nm, and the largest redshift was observed at $\Lambda = 100 \mu\text{m}$ and $W = 300 \mu\text{m}$, with an emission wavelength of 1031 nm. These results indicate that even in areas with the weakest SAG effect (with the largest open window size and smallest mask width), a GRE still occurs. The agreement with simulation (Fig 3.24) indicate that a difference of 86 nm is achieved for the centre of a SAG mask to the emission from the unmasked MQW area (945 nm).

Overall, the wavelength tends to red shift as the width of mask W increases when the

size of the windows Λ is kept constant. At the same time, the red shift tends to be more obvious for smaller window size as W increases (or larger mask to window width ratio (W/Λ)). From a total 28 nm red shift range for $\Lambda = 300 \mu\text{m}$ to a total 46 nm red shift range for $\Lambda = 100 \mu\text{m}$. This behaviour is primarily attributed to the higher mask to window width ratio, which enhances the influence of the reactant concentration gradient at the centre of the open window area and amplifies the GRE effect [66].

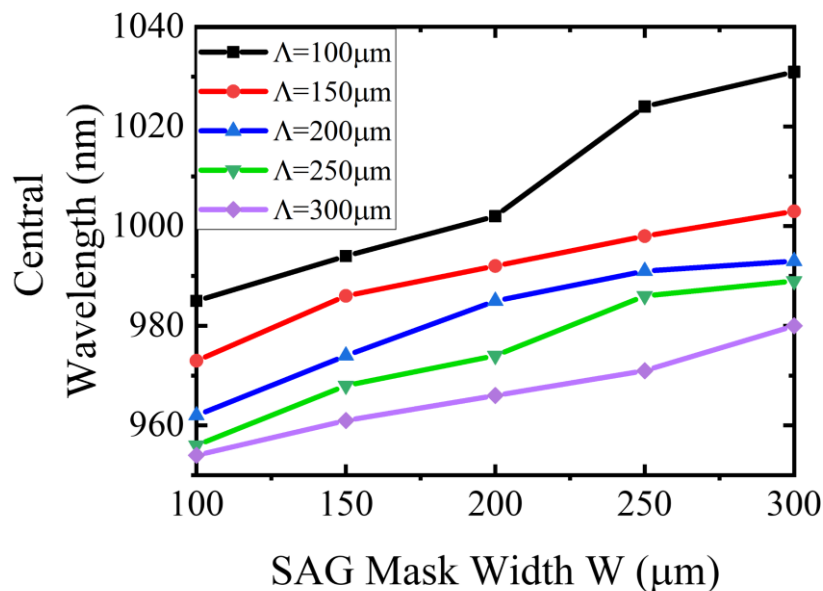


Fig. 3.19: Graph of the PL peak wavelength measured at the centre of each SAG sample at room temperature.

The variation in the GRE with SAG feature dimensions was characterized by using white light interferometry (WLI) measurements, performed with a Bruker Contour Optical Profilometer. The vertical resolution of the measurements was ~ 5 nm. The entire sample was treated with a 10:1 buffered HF wet etch solution to remove the SiO_2 mask before mapping the feature profiles. This process was performed to ensure that the reference measurement level corresponded to the wafer substrate. An example of a WLI thickness profile map is presented in Fig. 3.20, illustrating the feature shape across the sample.

As shown in Fig. 3.20, in the unmasked regions that are far away from the mask edge, the surface remains relatively flat with no significant roughness. However, on approaching the mask edge, the GRE effect starts to appear. Within the window area, the overall thickness profile looks like a paraboloid and is relatively symmetrical along both the X and Y directions. The corners of the window exhibit the highest GRE, with material growth forming a concave shape along the mask edge. This behaviour can be attributed to the effect of the 2D nature of this study, where the corner regions of the mask opening experience an effective increase of reagent supply akin to having a larger W/Λ as compared to points at the midpoint between two corners. Similarly, the outside corners of the SAG mask experience a lower reagent supply, akin to a lowering of W/Λ . This increased reagent supply results in a steeper concentration gradient of reactants,

leading to an even higher GRE in the corner areas, as explained above in Fig. 3.9.

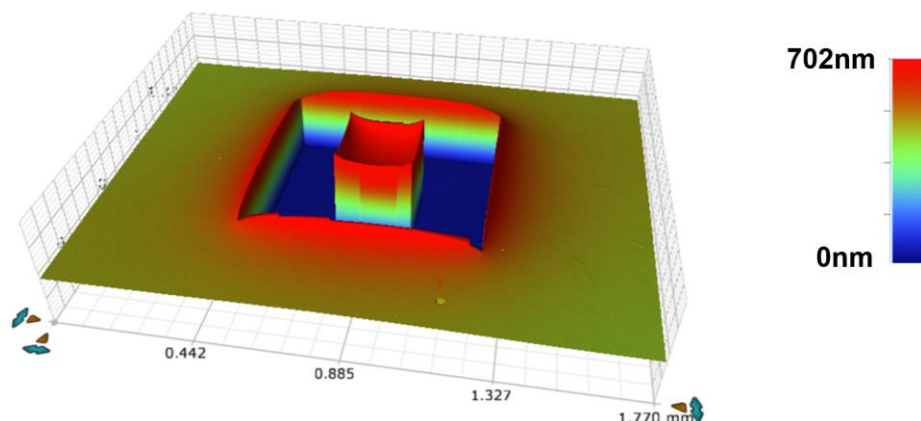


Fig. 3.20: Schematic representation of the optical profilometer for 3D mapping of the thickness profile with $\Lambda = 250 \mu\text{m}$, $W = 250 \mu\text{m}$.

The Fig. 3.21 presents the thickness enhancement factor as a function of the sample centre position along the Y and X directions. The red line and dark line represent the measured thickness enhancement factor.

By using the 308 nm thickness (without the influence of SAG) as a reference level, the thickness enhancement factor is defined. The first feature is that the thickness profiles along the Y and X directions are almost identical, which indicates that the influence of anisotropy in the growth kinetics of the material along the orthogonal crystal planes of the SAG mask is very small, even in large growth areas. The second feature is that the material distribution tends to have a concave profile, with the higher GRE factor occurring at the mask edge, and the material growth tends to become relatively flat toward the centre of the sample. This behaviour is mainly due to the weakening influence of the reactant concentration gradient between the mask and the window, which becomes more obvious as the distance from the mask edge increases [37]. The third feature is that the GRE tends to increase as the ratio of the mask to the window area increases, as seen in Fig. 3.21(a) to Fig. 3.21(c). This increase is mainly due to larger lateral reactant concentration gradients created by a higher ratio of W/Λ , which further amplifies the GRE effect on the open window area.

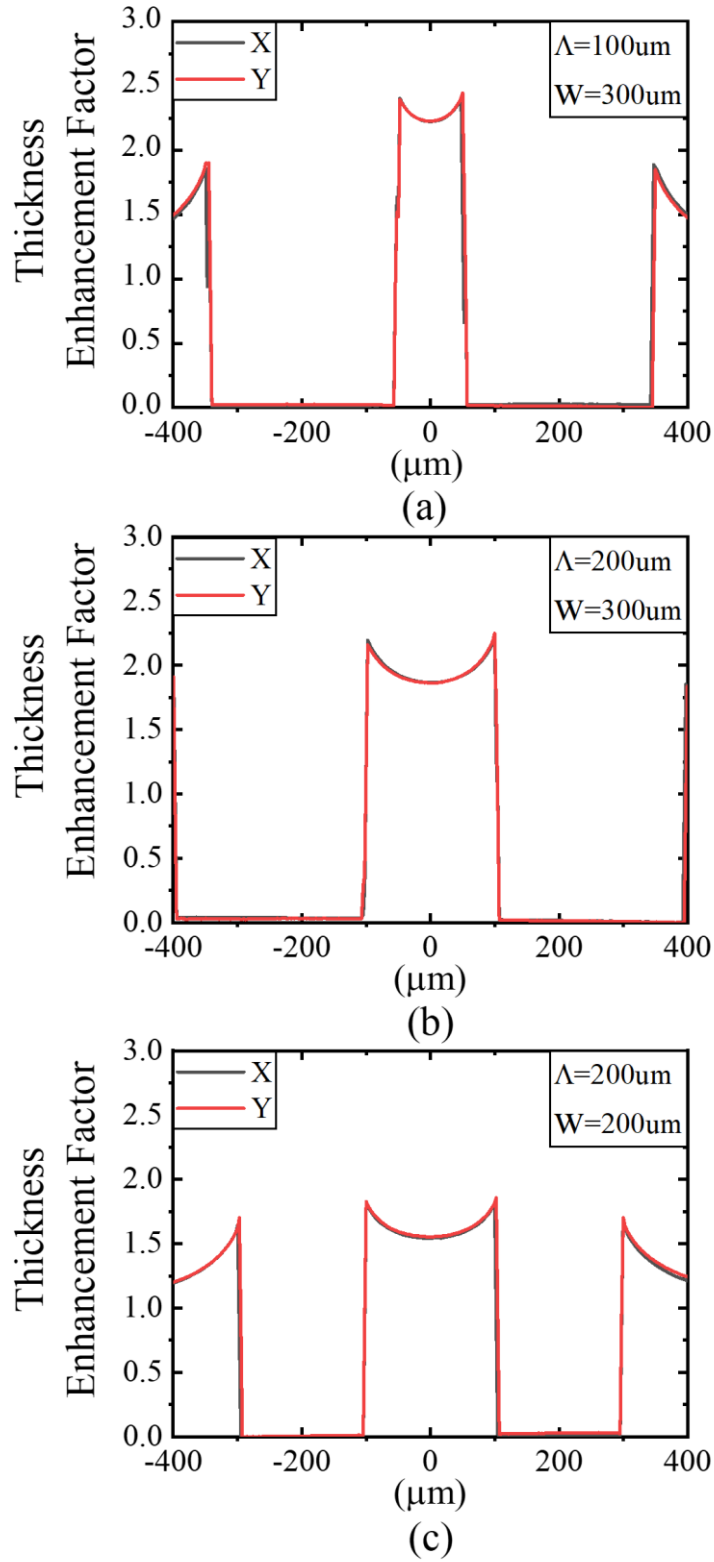


Fig. 3.21: Graphs of the measured growth thickness profiles of three SAG samples with (a) $\Lambda=100\ \mu\text{m}$, $W=300\ \mu\text{m}$, (b) $\Lambda=200\ \mu\text{m}$, $W=300\ \mu\text{m}$, (c) $\Lambda=200\ \mu\text{m}$, $W=200\ \mu\text{m}$.

As shown in Fig. 3.22, the central thickness enhancement is plotted as a function of mask width and window size. Overall, the GRE factor at the centre increases as the ratio of the mask area to the window area increases. The minimum GRE factor of 1.19 occurred at $\Lambda = 300 \mu\text{m}$ and $W = 100 \mu\text{m}$ and the maximum GRE factor of 2.23 occurred at $\Lambda = 100 \mu\text{m}$ and $W = 300 \mu\text{m}$, which is the same tendency as the wavelength shift in Fig. 3.19, with values typical of those seen in the SAG of InGaAs/GaAs structures [46].

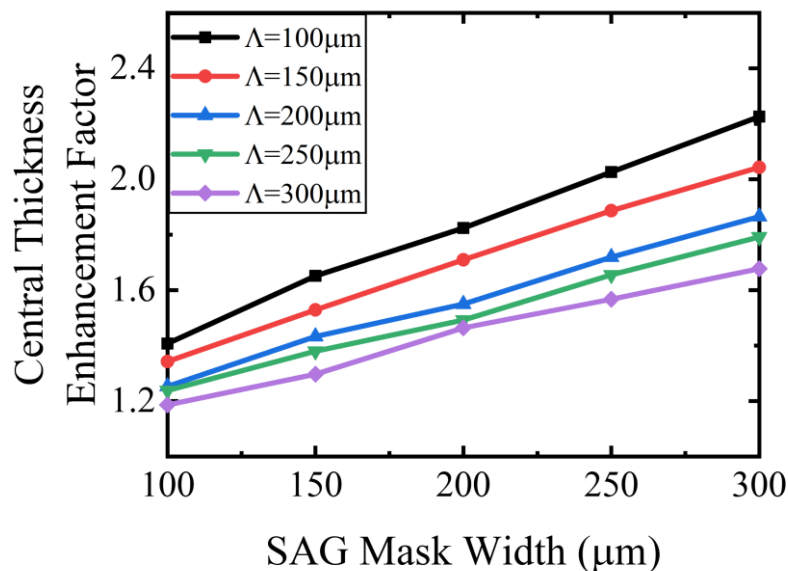


Fig. 3.22: Plot of GRE factor as a function of mask width for different window sizes at the centre of each SAG sample.

To get a deeper understanding of the composition of the MQWs, X-ray diffraction (XRD) is often used in combination with PL. The fitting of XRD data gives structure information and this must be consistent with the electronic-state information of PL. This allows the determination of the thickness and composition of the epitaxially grown material. However, due to the large (~several mm) spot size and spatial resolution limitations of laboratory-based diffractometers they do not meet the requirement of SAG sample measurement [67]. Therefore, the indium composition of the QW was simulated, based on the wavelength that was observed in the μ -PL measurement and the information of QW thickness (GRE) obtained from optical profilometer measurements. The simulation mode is based on a simplified InGaAs/GaAs QW structure model as shown below Fig. 3. 23.

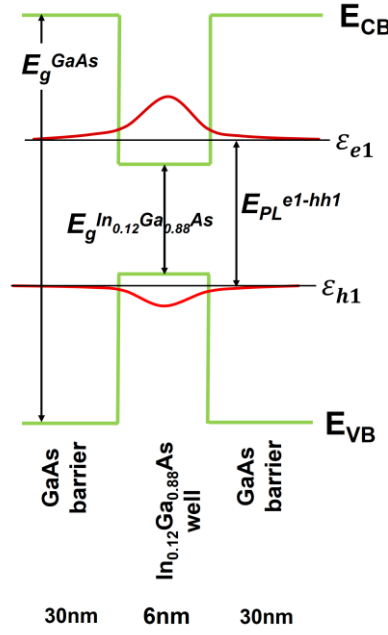


Fig. 3.23: A schematic representation of the simplified band structure within the MQW structure. ϵ_{e1} is the conduction energy level of the QW, and ϵ_{h1} is the valence energy level of the QW. The red line represents the wavefunction of the electrons and the heavy holes [36].

As shown in Fig. 3.23, the observed PL transition occurs between the lowest energy optical states in the conduction and valence bands. For the MQW region of the SAG sample, two main factors influence the PL wavelength. First, increasing the thickness of the InGaAs QW can reduce the transition energy due to the reduced quantum effect in the QW. Second, an increase in the indium content of InGaAs also results in a redshift of the PL spectrum. The relationship between the wavelength and QW width for different indium compositions in InGaAs is simulated and shown in Fig. 3.24. The commercialized software EPITAXYproject was used for simulation. By changing the MQW width and indium percentage of InGaAs, the emission wavelength can be adjusted within a wide range. Since GaAs is the dominant component during the MQW epitaxial growth process (high gallium concentration alloys In_{0.12}Ga_{0.88}As and Al_{0.30}Ga_{0.70}As were used), and gallium has the longest vapour phase diffusion length of the group III species, this longer diffusion length benefits the material homogenized distribution over a larger window area. So it is assumed that the thickness of each layer is uniformly enhanced during the MOCVD epitaxial growth process [24][44], which means the GRE factor is assumed to be the same for each layer of the entire epitaxial structure at a given position. However, assuming that the GRE is the same for all the epitaxial layers may not be correct, which will be explained later.

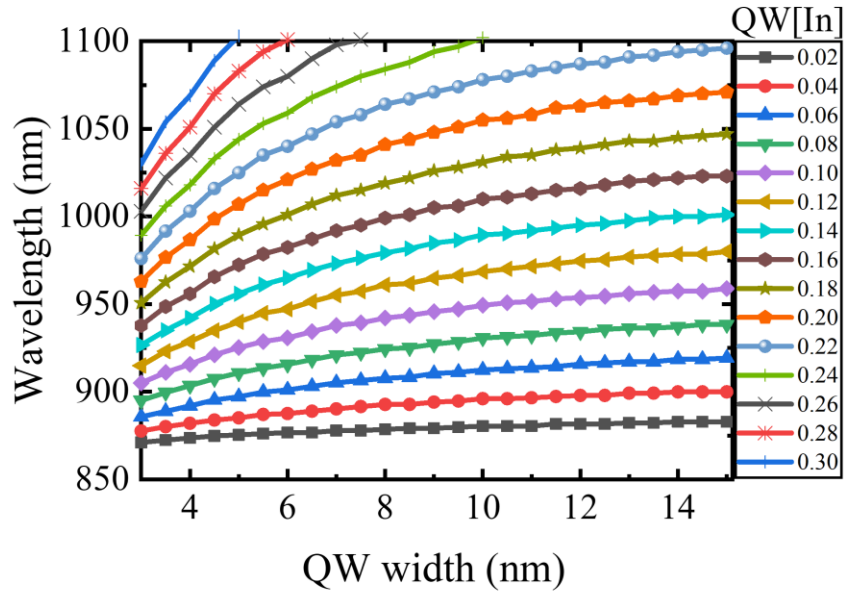


Fig. 3.24: Simulation of e_1-h_1 emission wavelength under different QW widths and indium percentages.

Fig. 3.25 plots the predicted emission wavelength by only considering the influence of the variation of MQW thicknesses due to GRE. Overall, the wavelength will tend to redshift as the thickness of the QW increases. The total redshift is only 32 nm when using the nominal MQW structure as a reference, which is significantly smaller than the measured shift of 77 nm. For $\Lambda = 300 \mu\text{m}$ and width $W = 100 \mu\text{m}$, where the GRE factor is at its lowest (1.19), the difference between the simulation and measurement results is less than 1 nm. However, for $\Lambda = 100 \mu\text{m}$ and $W = 300 \mu\text{m}$, where the GRE factor is the largest (2.23), the difference between the simulation and measurement results is 54 nm. This indicates that considering only the effect of thickness variation on the wavelength shift is insufficient to explain the results from the $\mu\text{-PL}$ measurements. Therefore, additional indium must be incorporated into the QW to account for the discrepancy between the simulation results and the $\mu\text{-PL}$ measurement data.

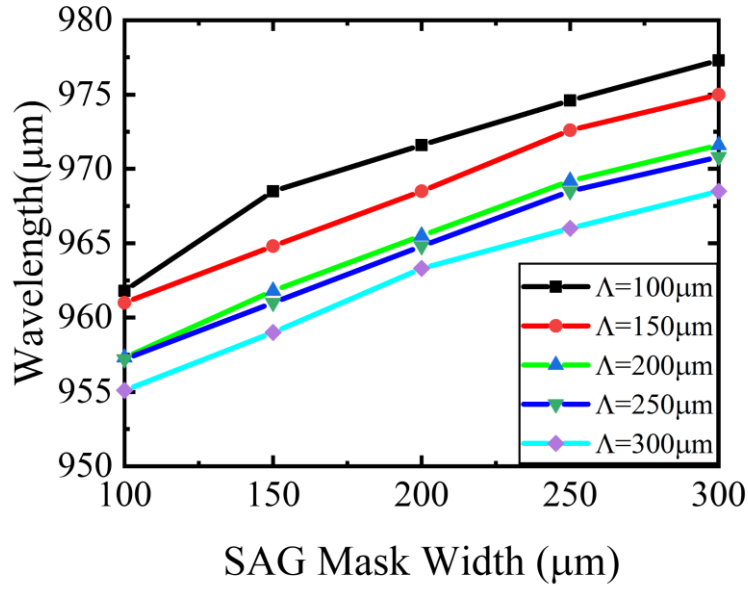


Fig. 3.25: Simulation of e_1 - h_1 emission wavelength under different mask widths for different window sizes at the center point of the sample.

The indium composition required to match the experimentally observed emission is shown in Fig. 3.26. A higher ratio of W/Λ results in an increased indium percentage. The smallest change occurs at $\Lambda = 300 \mu\text{m}$ and $W = 100 \mu\text{m}$, where the indium percentage almost does not change compared to the nominal epitaxial MQW structure, which means the main reason for the red shift comes from the thickness of QW increasing due to the GRE effect in this case. The largest change occurs at $\Lambda = 100 \mu\text{m}$ and $W = 300 \mu\text{m}$, where the indium percentage increases to $\sim 17\%$, which also corresponds to the highest observed wavelength red shift. As explained in the earlier figures Fig. 3.8 and Fig. 3.9, since molecules cannot deposit on the mask, a higher ratio of W/Λ will tend to result in a stronger lateral concentration gradient above the 2D SiO_2 mask area. This lateral concentration gradient provides additional indium for material growth in the window area, resulting in a higher indium mole fraction at the centre of the window [24][61][66].

It is important to note that this result is based upon the assumption that the GRE is the same for GaAs and InGaAs. This assumption ignores the influence of strain change, the composition will influence the strain of each layer, and strain will drive material redistribution [68][69]. This assumption (same GRE for each layer) may be over simplified, and in future work, a TEM cross section image of the entire epitaxial structure may need to be checked this in detail.

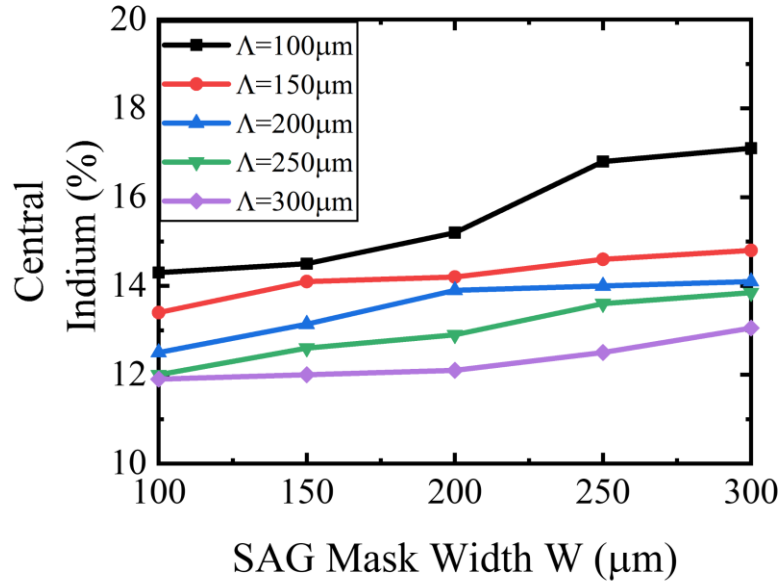


Fig. 3.26: Simulation of indium compositions required to fit experimental values using measured GRE.

Fig. 3.27 presents a 2D μ -PL map for the entire SAG window of $\Lambda = 250 \mu\text{m}$ and $W = 300 \mu\text{m}$, where the emission wavelength is plotted as a function of position. A similar paraboloid shape is observed in the 2D μ -PL map, as seen in the optical profilometer thickness measurement in Fig.3. 20. The uniform emission area, indicated by the purple region within the green circle, has a shape that appears circular. The diameter of the defined uniform emission wavelength region ($\pm 2 \text{ nm}$) is approximately $110 \mu\text{m}$, with a measurement resolution of $\pm 5 \mu\text{m}$.

At the four corners of the mask window, the wavelength can reach approximately 1040 nm , which corresponds to the regions with the highest GRE effect. As explained in detail in Fig. 3.9 and Fig. 3.20, where the highest thickness enhancement and local indium enrichment at the corners leads to the most pronounced redshift in the emission wavelength.

The second phenomenon observed is the rapid increase in emission wavelength as the mask edge is approached. It suggests that the indium concentration increases significantly in this area, as the thickness increment alone within this short distance is insufficient to account for the wavelength shift. This phenomenon can be attributed to the differences in the diffusion coefficients of gallium and indium species, and the difference in migration lengths of gallium and indium on the open window area surface during the MOCVD process. As explained in Fig. 3.8 section, since the existence of a large size mask will tend to result in gas phase diffusion becoming the dominant process for GRE effects within the SAG window. The high concentration gradient of the reactants above the boundary layer drives the reactants into the window area, and additional indium from the vapor phase is available for deposition in the window. However, since the diffusion coefficient of indium species is much smaller than that of

gallium species in the vapor phase, and the migration length of indium on the open window area semiconductor surface is also shorter than that of gallium, indium becomes more concentrated at the edge of the mask, resulting in a greater redshift in the emission wavelength. [24][37][44][66].

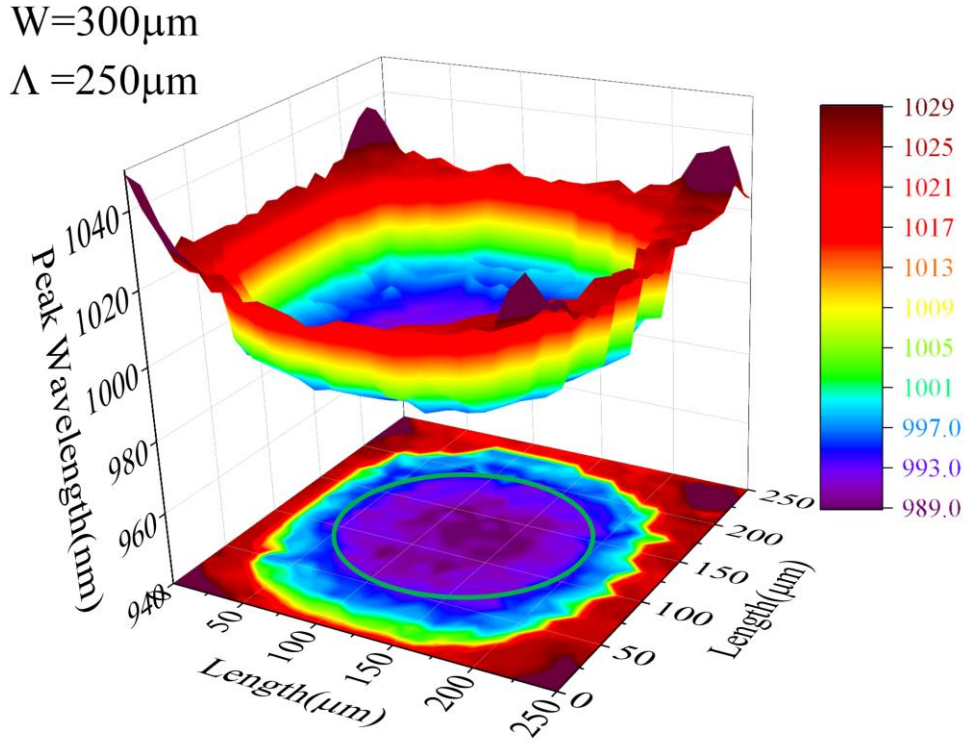


Fig. 3.27: A schematic representation of the 3D image of the 2D μ -PL map for the entire SAG sample with $\Lambda = 250 \mu\text{m}$ and $W = 300 \mu\text{m}$.

To further understand the relationship between the thickness enhancement factor, wavelength, and indium percentage, three representative SAG features are presented in Fig. 3.28: $\Lambda = 200 \mu\text{m}$, $W = 250 \mu\text{m}$; Fig. 3.29: $\Lambda = 200 \mu\text{m}$, $W = 300 \mu\text{m}$; and Fig. 3.30: $\Lambda = 250 \mu\text{m}$, $W = 300 \mu\text{m}$. Overall, for all three SAG features, the variations in the thickness enhancement factor, wavelength, and indium percentage along the X and Y directions exhibit a concave profile, with relatively constant values near the centre. The profiles also appear to almost overlap along both the X and Y directions. Combined with the 3D WLI measurement image in Fig. 3.20 and the 2D μ -PL peak wavelength map in Fig. 3.27. These results suggest that the influence of any natural anisotropies in growth kinetics is not significant, even within a large 2D window.

The green region in the figure represents the defined uniform wavelength emission area within a $\pm 2 \text{ nm}$ range, accounting for a $\pm 1 \text{ nm}$ variation due to the peak wavelength resolution of the PL measurement, plus an additional $\pm 1 \text{ nm}$ uncertainty. The width of the uniform wavelength emission area for these SAG features is approximately Fig. 3.28: $80 \mu\text{m}$, Fig. 3.29: $100 \mu\text{m}$, and Fig. 3.30: $110 \mu\text{m}$. Expanding the definition of the uniform area to $\pm 6 \text{ nm}$ results in an increased uniform area of Fig. 3.28: $160 \mu\text{m}$, Fig.

3.29: 120 μm , and Fig. 3.30: 140 μm . This suggests that the uniform area could be further enhanced if the MOCVD growth conditions are optimized to improve reactant diffusion within the window.

When compared with the variation in the thickness enhancement factor along the X and Y directions for each SAG feature, the changes in wavelength and indium percentage are more pronounced near the window edges over short distances. The observed peak wavelengths at the centre points are Fig. 3.28: 991 nm, Fig. 3.29: 993 nm, and Fig. 3.28: 989 nm, shifting to Fig. 3.28: 1024 nm, Fig. 3.29: 1025 nm, and Fig. 3.30: 1023 nm at the edges of the window. Similarly, the calculated indium percentages at the centre points are Fig. 3.28: 14.2%, Fig. 3.29: 14.2%, and Fig. 3.30: 13.6%, increasing to Fig. 3.28: 16.9%, Fig. 3.29: 16.5%, and Fig. 3.30: 16.3% at the edges, with a calculated error range of $\sim 0.2\%$. The main reason for the phenomenon is due to the increased concentration of indium at the window edges, as explained above in Fig. 3.27. Since the gas phase diffusion process is the primary mechanism responsible for indium diffusion across the window, combined with a shorter migration length, indium becomes concentrated within approximately 20 to 30 μm from the mask, which is the same order of gas phase diffusion length reported in other group's work [24] [44]. Since gallium has a longer gas phase diffusion distance and longer migration length compared with indium, as it gets close to the centre, the ternary composition will tend to meet lattice match growth condition with slightly gallium rich, which finally results in the material distribution becoming slightly flat and wavelength uniform at the centre of larger surface [44] [66] [70].

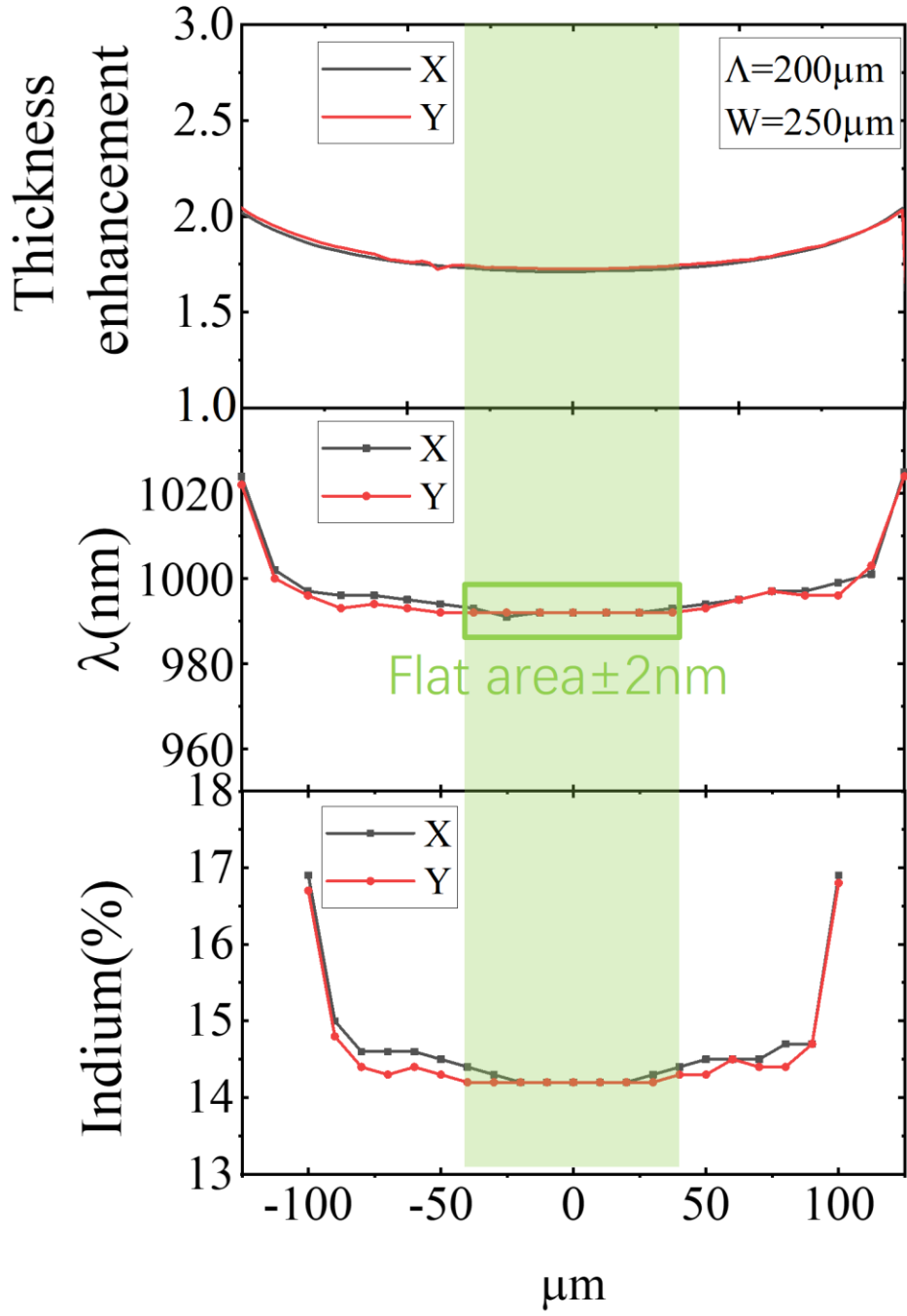


Fig. 3.28: Graphs of GRE factor, μ -PL wavelength, and indium percentage versus window position across the centre point of the window in X and Y directions with $\Lambda=200\text{ }\mu\text{m}$, $W=250\text{ }\mu\text{m}$.

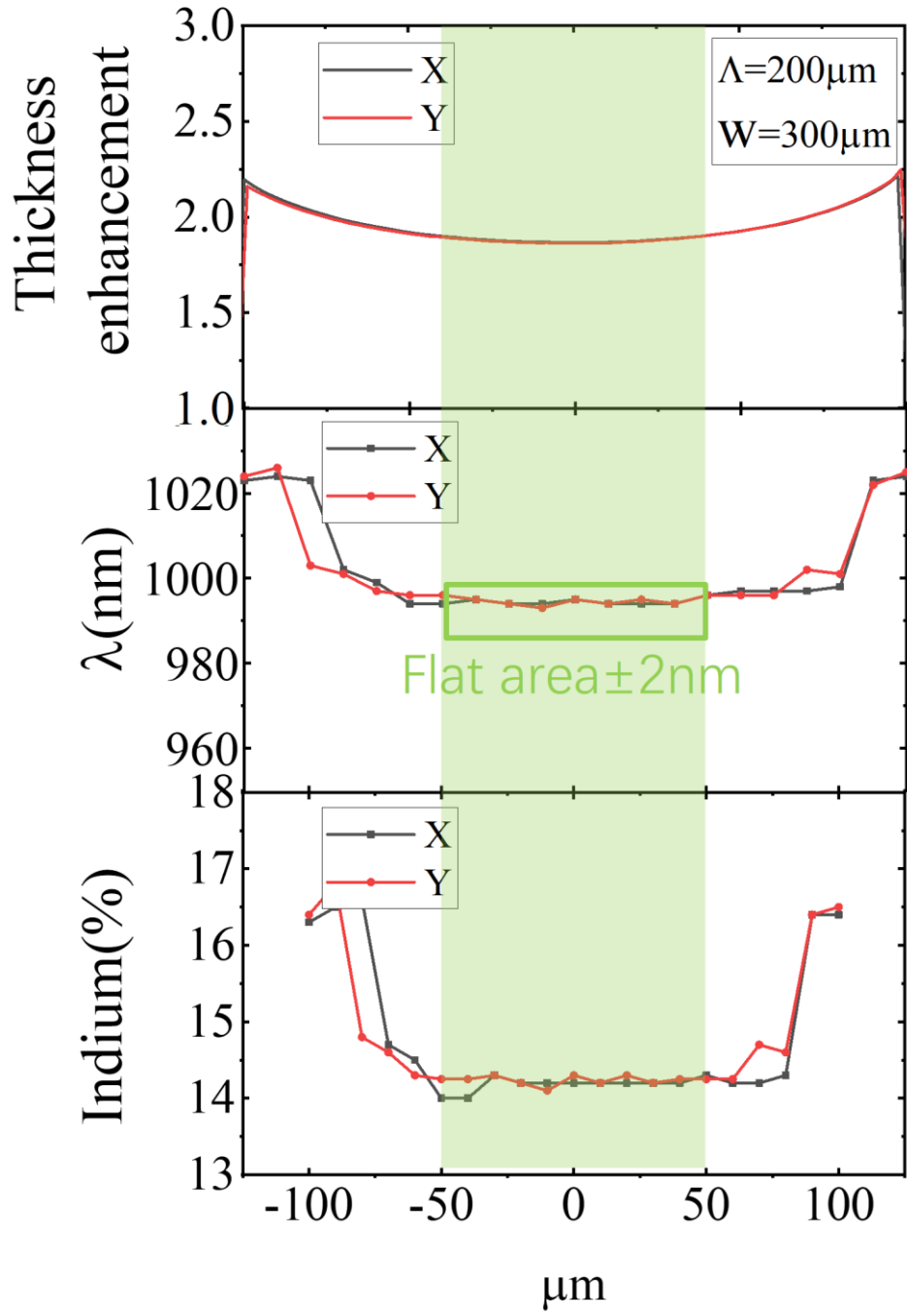


Fig. 3.29: Graphs of GRE factor, μ -PL wavelength, and indium percentage versus window position across the centre point of the window in X and Y directions with $\Lambda=200\mu\text{m}$, $W=300\mu\text{m}$.

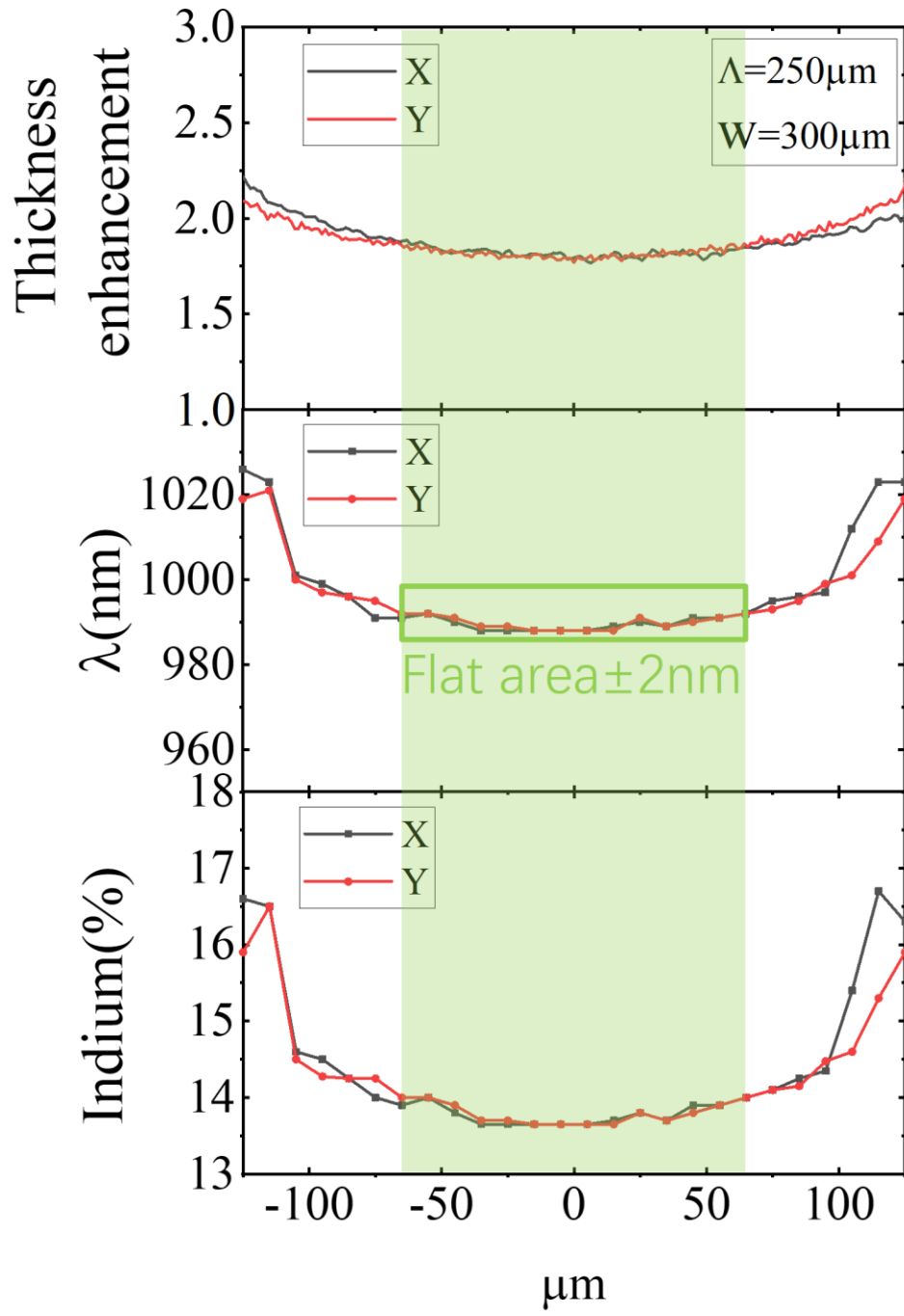


Fig. 3.30: Graphs of GRE factor, μ -PL wavelength, and indium percentage versus window position across the centre point of the window in X and Y directions with $\Lambda=250\text{ }\mu\text{m}$, $W=300\text{ }\mu\text{m}$.

Expanding the 2D analysis to the other SAG features, the summary of information is shown in Table 3.1. λ (nm) is the PL peak wavelength at the centre of the window and W_{uniform} represents the width of the uniform area with $\pm 5 \mu\text{m}$ PL spatial measurement resolution. The green area represents the uniform wavelength emission area $\pm 2 \text{ nm}$. Overall, as explained above, for the wavelength at the centre position, a higher ratio of mask size to window area will lead to a larger wavelength red shift. Second, when the mask width is fixed, the width of W_{uniform} uniform area will tend to increase as window area Λ increases. And when the window area Λ is fixed, the width of W_{uniform} uniform area also tends to increase as mask width increases. Especially for $\Lambda = 200 \mu\text{m}$, $W = 300 \mu\text{m}$ and $\Lambda = 250 \mu\text{m}$, $W = 300 \mu\text{m}$, the uniform wavelength emission area is around $100 \mu\text{m}$ and $110 \mu\text{m}$, which meet the request for fabrication of PCSEL, and this uniform area can increase further if the MOCVD growth process can be optimized.

Table. 3.1: The table shows the peak centre wavelength and uniform wavelength emission area for different SAG features.

$\Lambda(\mu\text{m})$	$W(\mu\text{m})$	$\lambda(\text{nm})[\pm 2\text{nm}]$	$W_{\text{uniform}}(\mu\text{m})[\pm 5\mu\text{m}]$
100	250	1024	40
150	250	998	60
200	200	985	60
200	250	991	80
200	300	994	100
250	300	989	110

3.7 Conclusion:

In this chapter, possible future need for multi-wavelength PCSELS was highlighted. A brief introduction to MOCVD was presented, and the details of 1D and 2D SAG processes were introduced. This highlights key questions that this chapter addressed. A 5×5 array SAG sample with different feature sizes was prepared. The principle of PL was introduced, and the PL apparatus was detailed, and procedures were optimised. Optical profilometry allowed the growth enhancement to be mapped and locally determined, and in combination with simulation, the indium composition enhancement was deduced.

The symmetric GRE, observed by profilometry, in the X and Y directions suggests that the influence of anisotropy in the growth kinetics of the material is very small during the growth process. The simulation result considering only the influence of GRE cannot

match the measurement result. When indium variation was accounted for to match the measurement result, the result shows that an indium percentage of ~17% was observed at the centre position. From the 2D μ -PL map process, the result shows that a uniform emission wavelength region of ~110 μm was achieved for these mask sizes. The symmetric PL wavelength confirms the small influence of growth anisotropy. A maximum SAG centre peak wavelength shift of 86nm, and uniform wavelength emission areas >100 μm was observed for these mask designs.

3.8 Discussion & Future Work:

Overall, in future work, developing 3D models to predict material growth profiles in larger 2D features presents a valuable direction for research to make multi-wavelength PCSELs arrays. Such efforts could improve our ability to predict wavelength shifts and material distribution behaviour. A deep understanding of the reactant chemical reaction behaviour and parameters within the MOCVD growth process is required.

From the μ -PL wavelength emission result, a higher ratio of mask size to window area can bring a larger wavelength red shift, which means it would be interesting to further investigate the properties of much larger window areas and wider mask size than 300 μm . This may increase the uniform emission area, but strain relaxation due to thick, high indium composition layers will be a limiting factor. In addition to scales of the mask and window, it would be interesting to investigate other mask shapes and symmetries, such as a circular window shape which may increase the possible uniform area in the future.

I note that the mask sizes used in this study were not so large that the SAG effect in the centre of the window began to be diminished as window size was increased. A constant, then reducing peak wavelength with increasing window size would indicate the limit to GRE that could be obtained, and limit to the wavelength tunability of the SAG process. This would need to be conducted with low indium composition QWs to minimise thickness strain product issues as mentioned above.

With regard to making a multi-wavelength PCSEL array in future, the position of the SAG of the active element in the process flow for the device manufacture is important. The SAG process realises a non-planar semiconductor surface that may impact PC grating definition. Ideally, the PC grating should already have been defined (like in n-side grating as used in InP PCSEL fabrication [71] [72]). If such a process does not exist, as is the case for GaAs PCSELs at the time of submission of this thesis, then more care needs to be paid to the effect of a non-planar semiconductor surface on the e-beam lithography process.

3.9 Reference:

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Chapter 4. Analysis of Resonator Embedded Photonic Crystal Surface Emitting Lasers (REPCSEL)

4.1 Introduction:

Recently, the REPCSEL has been proposed and demonstrated [1]. Photonic crystal structures were realized from low refractive index contrast material (all components are semiconductor materials). DBR regions were added, surrounding the photonic crystal. Fig.4.1 shows the schematic structure of the REPCSEL. The InGaAsP/AlGaInAs/InP system is discussed in this chapter. Adam F. McKenzie and Neil D. Gerrard developed epitaxial processes and structural characterisation of the epitaxial materials. Zijun Bian, Stephen Thoms, Paul Reynolds, Daehyun Kim, Katherine Rae. and Connor W. Munro. developed device fabrication process flow. The detail of fabrication process, epitaxial layer structure, device structure and SEM image can be found at Bian [1].

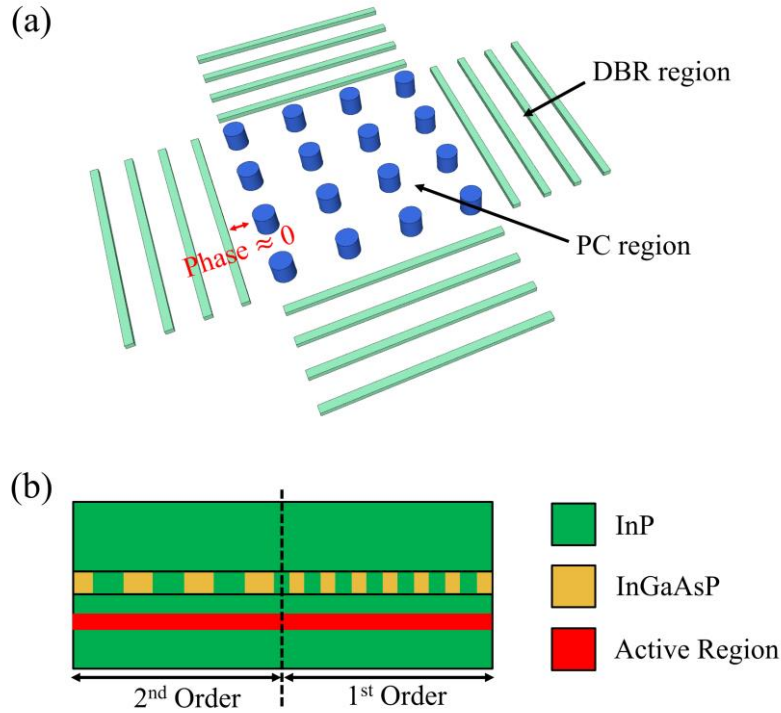


Fig. 4.1: (a) Schematic illustration of the REPCSEL structure, the blue cylinder represents a lattice site in the PC ($\sim 500 \times 500$ and $\sim 1000 \times 1000$ PC atoms), the light green strip represents the DBR region ($100 \times$ DBR pairs). (b) Schematic illustration of the device cross section [1].

The simulation result indicated that to achieve resonant behaviour, the strength of coupling κL should be less than ~ 10 and was chosen to be ~ 2 [2] (κ : the coupling strength in PC plane, L : the lateral size of device). The simulated reflectance showed that selective modification of the in-plane loss could be achieved at different wavelengths. Fig. 4.2 shows the LI response for PCSEL and REPCSEL with $200 \mu\text{m} \times 200 \mu\text{m}$ size, no PCSEL device showed lasing behaviour up to 1.1A, whilst the

REPCSEL demonstrated a threshold of 324 mA (860 A/cm^2). This result demonstrated the influence of DBR region, where the in-plane loss was reduced by the perimeter DBR.

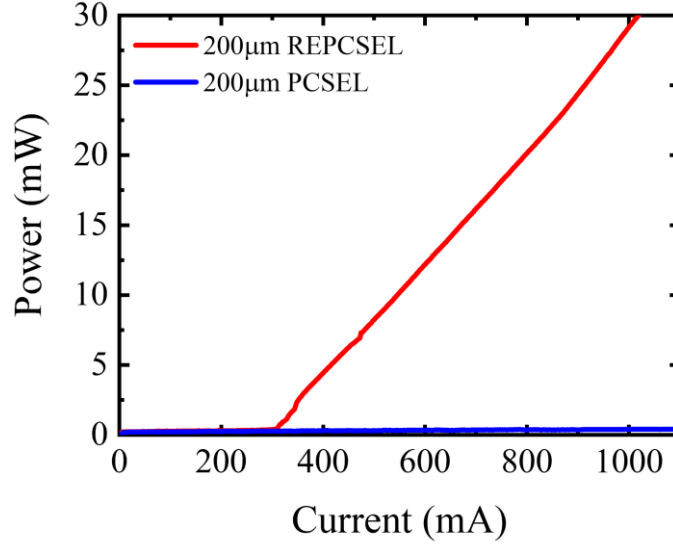


Fig. 4.2: Current-power characteristics of REPCSELs and PCSELs at same device sizes [1].

A systematic study of REPCSEL structure at 1550 nm with different DBR periods (and hence peak reflectivity wavelengths) suggested that the resonance effects could selectively modify the in-plane loss of different zone-center PC modes within the cavity [1].

4.2 Gaps in Knowledge:

For the REPCSEL, the concept and detail of the fabrication and simulation process was presented by Bian [1]. A detailed spectroscopic study of the operating parameters of REPCSELs (and their associated PCSELs) is therefore required.

4.3 Contents of This Chapter:

In this chapter, work is presented on detailed opto-electronic characterisation of a range of REPCSELs and their associated PCSEL equivalents (i.e. without DBRs). First, nominally identical PCSELs and REPCSELs of different size are analysed with the following characteristics:

200 μm x 200 μm no boundary	400 μm x 400 μm no boundary
200 μm x 200 μm with 100 periods DBR	400 μm x 400 μm with 100 periods DBR

All these devices have nominally identical values for all other parameters, like the period of the PC and the number of DBR pairs, and were fabricated in the same processing run. PC structures were designed with square lattice with circular atom shape, a $\sim 0.4\pi/a$ is defined for atom size. The mark/space ratio (MSR) of DBR region

is defined as $\sim 50\%$. From the characteristics result, the influence of DBR in reducing threshold current and increasing slope efficiency is demonstrated. This confirms the expected reduction in in-plane loss through the use of the perimeter DBR. Then, for $400\text{ }\mu\text{m} \times 400\text{ }\mu\text{m}$ REPCSELs, the variation of PC and DBR period is explored in detail, and the result shows the effect of detuning with respect to the gain spectrum on threshold and slope efficiency. Then, for a $200\text{ }\mu\text{m} \times 200\text{ }\mu\text{m}$ REPCSEL (PC period = 400 nm), single wavelength peak behaviour over current is presented, but peak broadening is noted. Near field images shows an almost flat-top profile, as expected for $\kappa L = 2$ (the strength of coupling) at high current injection. The temperature dependent current power characteristics and temperature dependent spectrum measurements are subsequently detailed. Band-structure analysis of the REPCSEL as a function of injected current is carried out. To the best of my knowledge, this is the first such study. The results show that at low currents, the leaky and non-leaky mode intensity is linear in current. At higher currents, whilst the linear relationship remains for the leaky modes, the surface emitted power for the non-leaky lasing mode becomes super-linear with injected current. Superluminescence of one set of modes and not for the other suggests in-plane loss is higher for leaky modes. The zone centre electroluminescence (EL) spectra at $\ll I_{th}$ (cold cavity) shows that the scattering intensity (normal emission) of the non-leaky and leaky modes is almost equal, which indicates a wavelength selective enhancement of the non-leaky mode through the resonator effect was achieved. The band-structure analysis is discussed in detail, with reference to a range of device simulations.

4.4 Sample characterization:

The measurement apparatus for characterizing current power and spectral properties of PCSELs and REPCSELs is depicted in Fig. 4.3. BS2 (Thorlabs CM1-BP145B3) is an AR-coated pellicle beam splitter which reflects $\sim 45\%$ of the collimated light in the perpendicular direction. BS1 (Thorlabs CM1-BP108) is a pellicle beam splitter which reflects $\sim 8\%$ of the collimated light in the perpendicular direction for imaging. Lens 1 (Thorlabs AL2520M-C) is an anti-reflection (AR) coated aspheric lens with a numerical aperture (NA) of 0.54.

The green line represents the LED illumination, and the yellow line represents the emission from the sample. Lens 2 is employed to focus the LED onto the sample surface. Lens 3 is employed to focus the image of the sample onto the camera, providing a visual view of the sample surface. The sample is placed on a Cu stage coated with Au, and is driven by either a continuous-wave (CW) or pulsed current source. A temperature controller is positioned beneath the stage to control the sample temperature.

For the characterisation of the current power properties of the PCSEL in Fig. 4.3 (a), the sample is located at the focal point of Lens 1, ensuring that the emitted signal is collected and collimated by Lens 1. $\sim 45\%$ of the emitted signal is directed to a calibrated power meter (Thorlabs S122C) for measurement. The apparatus utilises a pin-probe for current injection.

The measurement apparatus for spectral analysis uses the same concepts as the apparatus for characterising the current power property of REPCSELs in Fig. 4.3 (b). The key difference is that the power meter is replaced by Lens 4 (Thorlabs AL2520M-C). In this configuration, the collimated emission signal is focused by Lens 4, and an optical fibre (AR-coated multimode with a core diameter of $62.5\ \mu\text{m}$) is placed at the focal point to maximize the collection of optical power. The collected signal is subsequently sent to an optical spectrum analyser (OSA) (HP 70004A) to record the spectrum. An Infrared camera (Hamamatsu C2741) was used for nearfield measurements.

The power-current characteristics of all devices was measured under the same pulse condition to reduce self-heating issues with a pulse width of $5\ \mu\text{s}$ and a duty cycle of 2% at a temperature of $15\ ^\circ\text{C}$. I-V was conducted C-W in Fig. 4.12, as was the spontaneous emission measurement in Fig. 4.10.

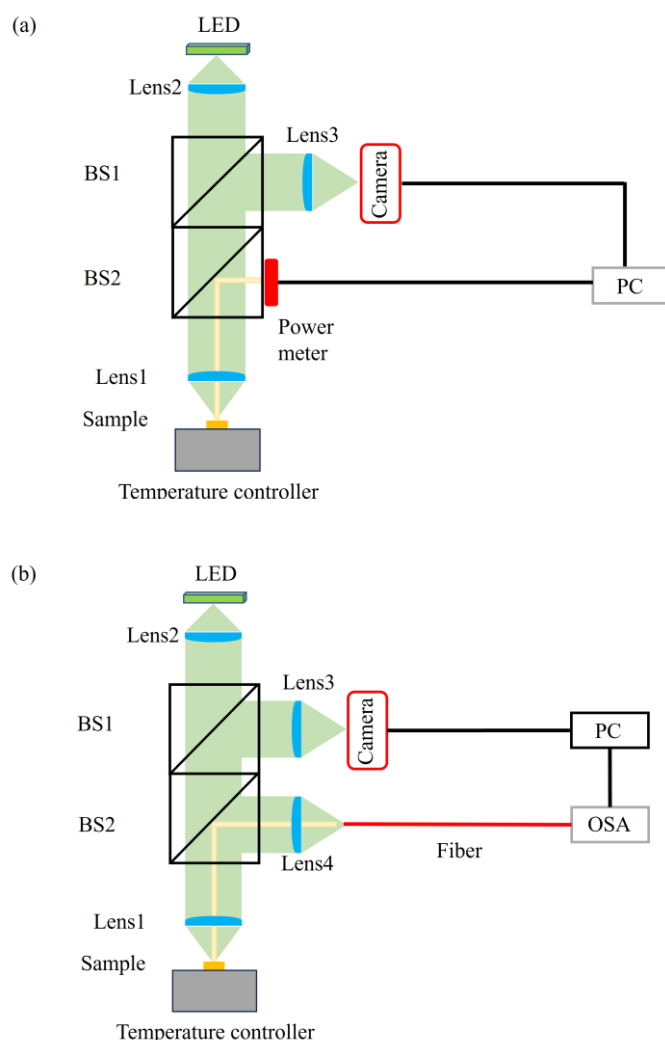


Fig. 4.3: Schematic illustration of the measurement apparatus for characterizing (a) the current-power(L-I) properties of REPCSELs, and (b) the spectral properties of REPCSELs.

4.5 400 μm PCSEL, REPCSEL:

The current power properties of PCSELS and REPCSEL are shown in Fig. 4.4. For two representative devices with an identical PC period of 400 nm. The threshold current is determined by two segment fit method, by using a straight line fit to the linear portion of the L/I curve. The threshold current value is taken as the intercept point where two fitted straight lines cross each other [3]. The threshold current density is calculated by dividing the threshold current by the contact area.

As can be seen from Fig. 4.4, for the 400 μm sized REPCSEL, the threshold current is 673 mA ($420/\text{cm}^2$) and a slope efficiency of ~ 0.014 W/A. The 400 μm sized PCSEL shows lasing behaviour at the threshold current of 910 mA ($568\text{A}/\text{cm}^2$), and a slope efficiency of ~ 0.003 W/A. The result demonstrates a reduction in threshold current and an increase in slope efficiency for the 400 μm sized REPCSEL and PCSEL. This is in line with a reduced in-plane loss for the REPCSEL.

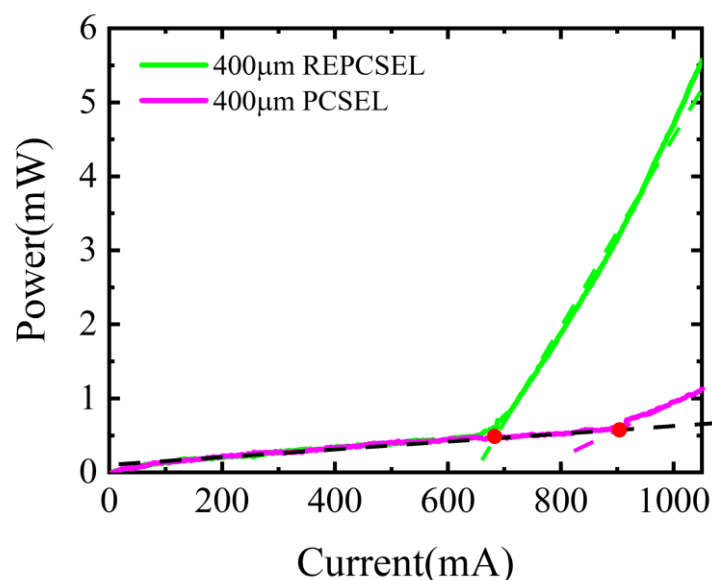


Fig. 4.4: Current-power characteristics of REPCSELs and PCSELs with 400 μm device sizes.

Figure. 4.4 provides threshold current densities and slope efficiencies that can be compared to experimental and theoretical data. Fig. 4.5 presents the experimentally determined threshold current density and threshold gain from broad area lasers using the same active region as that used in the PCSEL/REPCSEL [4]. Also plotted are the experimental data obtained from Fig. 4.4, with simulation to determine the threshold gain. The probabilistic Markov chain model (PMC) [5] simulated the in-plane loss, and Fig. 4.4 was fitted with a single out of plane loss to match the slope efficiency of the lasing, providing gain threshold of device in Fig. 4.4. PMC modelling was carried out by Jingzhao Liu. The result shows a good agreement between the simulation of our device and the experimental measurement results. For 200 μm sized REPCSEL and

PCSEL, the simulation results show that the in-plane loss $\alpha_{//}$ is $\sim 11 \text{ cm}^{-1}$ for REPCSEL and $\sim 104 \text{ cm}^{-1}$ for PCSEL. This higher in-plane loss of PCSEL results in an unachievably high threshold current as compared with the REPCSEL. In reality, fabrication errors limited the number of matching devices that could be identified, and ultimately only two matching devices were obtained.

This sample set were part of a wafer run made by collaborators Vector Photonics Ltd. There was only one PC wavelength, PCSEL size, and DBR number chip for each variant. The full details of wafer yields remain company confidential, but it has been indicated that the yields, and properties of the active these are “essentially the same as InP DFB’s” [6]. I note that the lasing wavelength vs period plot, and behaviour of the device with regard to detuning are all in line with the effect of DFB grating-gain detuning [7][8]. This is discussed in the following section.

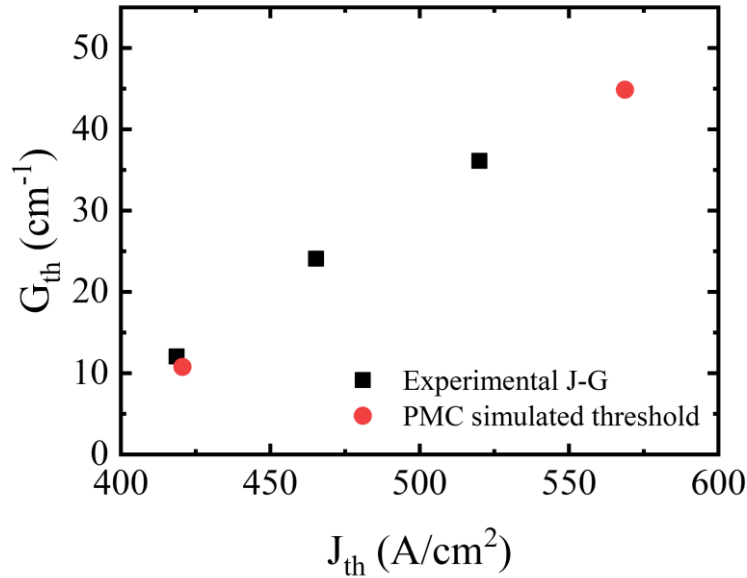


Fig. 4.5: Experimental current density modal gain characteristics (J-G) of the laser active element and deduced threshold gain of the PCSEL and REPCSEL devices in Fig. 4.4. The measurement data was provided by Dr J. Orchard, Vector Photonics Ltd.

Figure. 4.6 presents the peak wavelength of $400 \mu\text{m}$ REPCSELs with four different photonic crystal periods. The result shows that the lasing wavelength is linear dependence on the lattice constant. A linear fit to this data ($y=mx+c$) gives $m=2.92$ and $c=125.7 \text{ nm}$. This provides a small value of n_{eff} . Locally extracted values (dividing wavelength by PC period) provide much higher but varying values of n_{eff} (~ 3.235 at Period = 400 nm , 3.222 at Period = 414 nm). This empirical equation provides a more accurate route to choosing PC periods for a required emission wavelength. The deviation from $y=mx$ in this data is worthy of future study, as it has been observed in other reports [40].

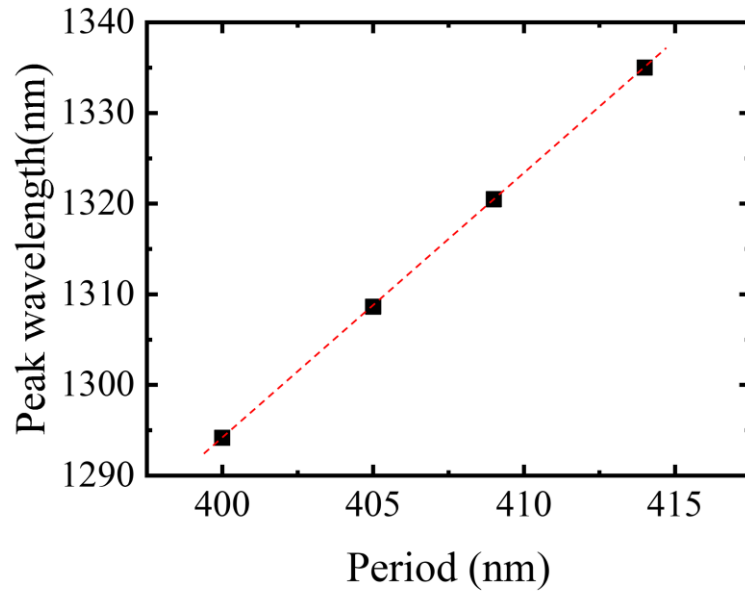


Fig. 4.6: The peak wavelength of 400 μm REPCSELs with four different periodicities.

Figure. 4.7 presents the threshold properties of 400 μm REPCSELs with four different photonic crystal periods. As can be seen, the threshold current is 696 mA at a period of 400 nm, reduces to 607 mA at a period of 405 nm, and continues to increase to 913 mA at a period of 414 nm.

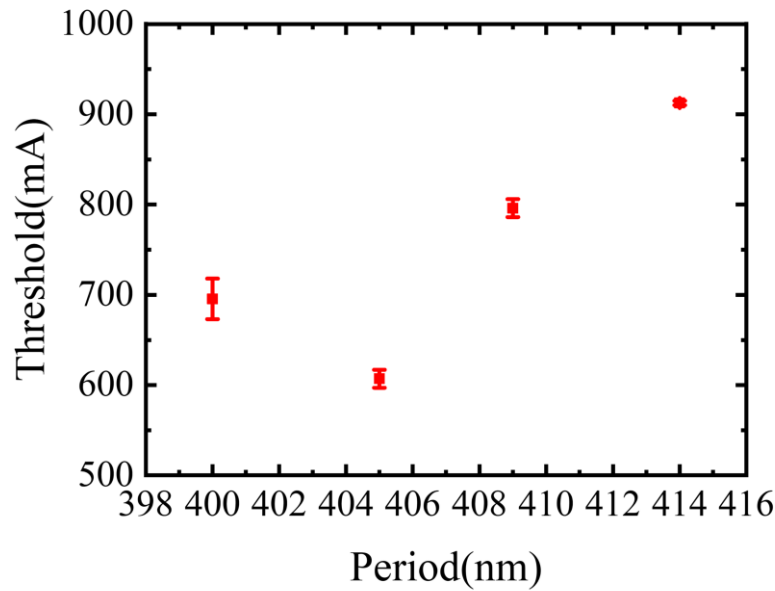


Fig. 4.7: Threshold characteristics of 400 μm REPCSELs with four different photonic crystal periods.

Figure. 4.8 presents the slope efficiency of the 400 μm REPCSELs with four different periods. As can be seen in Fig. 4.8, a slope efficiency of ~ 0.014 W/A at a period of 400 nm, increases to ~ 0.045 W/A at a period of 405 nm, and then decreases to

~ 0.014 W/A at a period of 414 nm. The result shows that the maximum slope efficiency also occurs at a period of 405 nm. This is discussed later with reference to Fig 4.9.

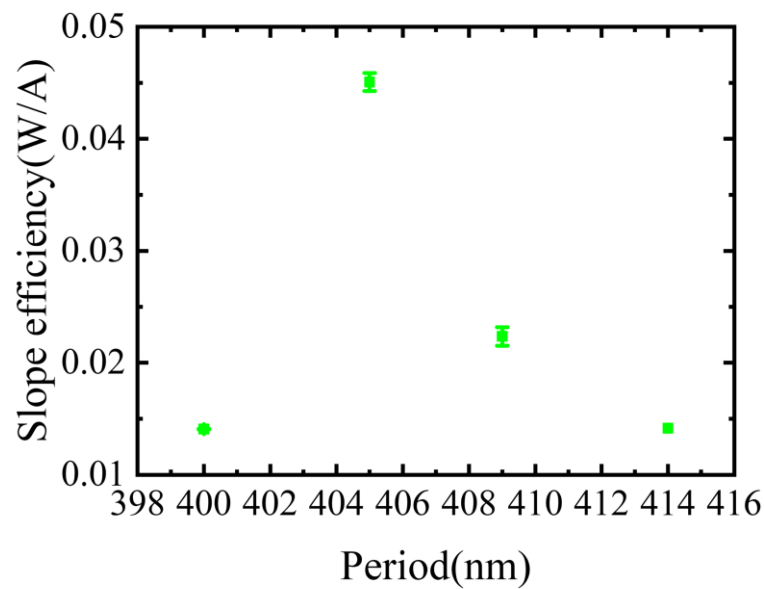


Fig. 4.8: Slope efficiency of a 400 μ m REPCSEL with four different periodicities.

Figure. 4.9 shows a schematic plot of the simulated material gain spectrum of the active element in the REPCSEL as a function of current density. Commercial software Lasermode was used for simulation. Also plotted are the possible predicted positions of the REPCSEL lasing peaks (four different PC grating periods) with respect to material gain. The light green straight line represents notional threshold gain.

As can be seen, the lowest threshold current density would be obtained where the PCSEL lasing wavelength coincides with the peak in material gain. Higher threshold current densities are required as detuning of the lasing peak and gain peak are increased. This predicted alignment also explains the change of slope efficiency as higher threshold currents bring higher intrinsic losses due to increased free carrier density and loss.

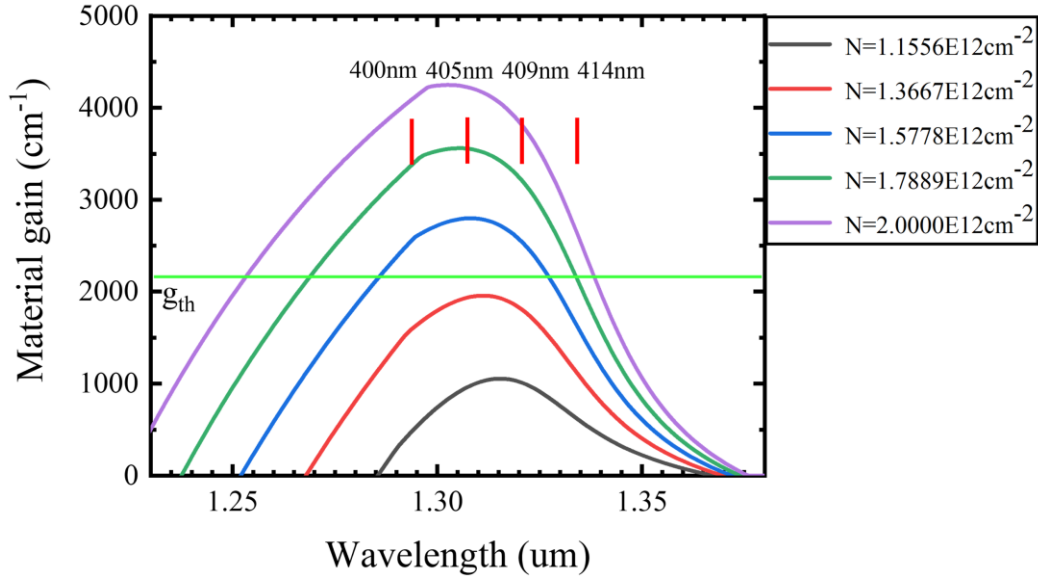


Fig. 4.9: The predicted variation of material gain as a function of wavelength under increasing inject current density.

In order to confirm this assignment, sub-threshold CW EL spectra are shown for the shortest wavelength 400 μm REPCSEL (PC period=400 nm) in Fig. 4.10. The spontaneous emission spectrum is often taken as a proxy for the gain spectrum position, and this spectrum is in good agreement with the qualitative prediction in Fig. 4.9.

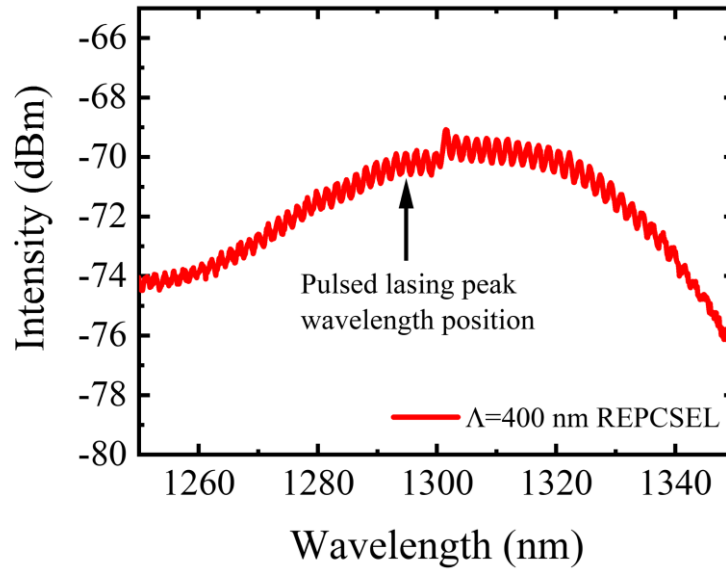


Fig. 4.10: Sub-threshold CW EL spectra of the 400 nm REPCSEL showing lasing peak-SE (stimulated emission) detuning.

4.6 200 μm REPCSEL:

The current power characteristic of the 200 μm REPCSEL and its corresponding spectra at different injection currents are shown in Fig. 4.11. The 200 μm PCSEL was chosen

for further study as it showed the biggest difference (lasing/non-lasing) between the PCSEL and REPCSEL. The threshold current is 324 mA (810 A/cm^2) and a slope efficiency of $\sim 0.041 \text{ W/A}$. The inset spectra are recorded at a temperature of 15°C , which demonstrates the emergence of a single resonant lasing peak with a lasing wavelength of 1294 nm.

Compared with the $200 \mu\text{m}$ sized REPCSEL, the $400 \mu\text{m}$ sized REPCSEL has a lower threshold current density of 420 A/cm^2 and a slope efficiency of $\sim 0.014 \text{ W/A}$. The reduced threshold current density demonstrates that a larger PC region can reduce the in-plane loss, as expected for a larger PC area [9] [10] [11] [12]. The perimeter DBR is expected to reduce the in-plane loss further. Further, more detailed quantitative comparison between the $200 \mu\text{m}$ and $400 \mu\text{m}$ devices is clouded by the very different electrical characteristics of the devices.

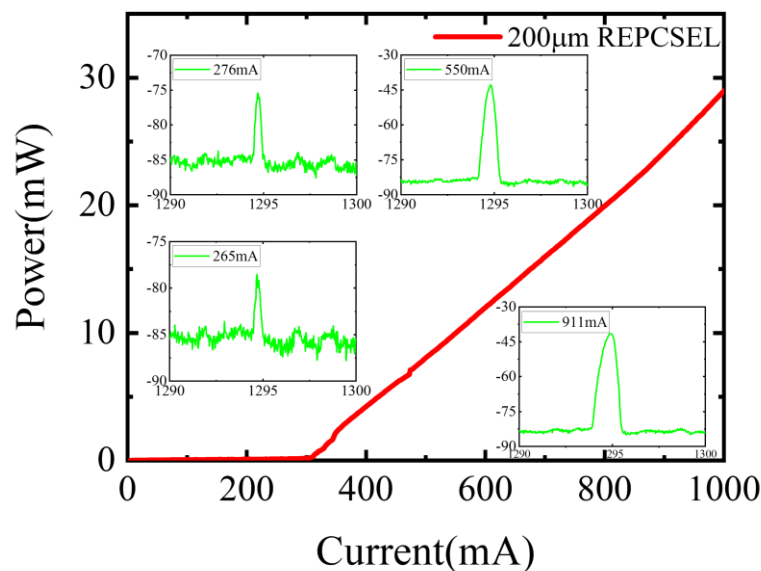


Fig. 4.11: Spectral characteristics of a $200 \mu\text{m}$ REPCSEL under various pulsed injection currents. The inset spectrum confirms the achievement of a single resonant peak.

Figure. 4.12 presents the V-I characteristics of the $200 \mu\text{m}$ REPCSEL, $400 \mu\text{m}$ PCSEL and $400 \mu\text{m}$ REPCSEL. It shows that the series resistance is $\sim 2.9 \Omega$ for the $200 \mu\text{m}$ REPCSEL and $\sim 0.5 \Omega$ for $400 \mu\text{m}$ PCSEL and $400 \mu\text{m}$ REPCSEL. This means that for the $200 \mu\text{m}$ REPCSEL, the five times higher series resistance will produce more heat during the measurement process compared with the $400 \mu\text{m}$ PCSEL and $400 \mu\text{m}$ REPCSEL. This internal difference is evidenced by a $\sim 0.8 \text{ nm}$ higher lasing wavelength for the $200 \mu\text{m}$ REPCSEL as compared to the $400 \mu\text{m}$ REPCSEL. This corresponds to $\sim 10^\circ\text{C}$ higher junction temperature for the $200 \mu\text{m}$ device (discussed with regard to Fig 4.15 later).

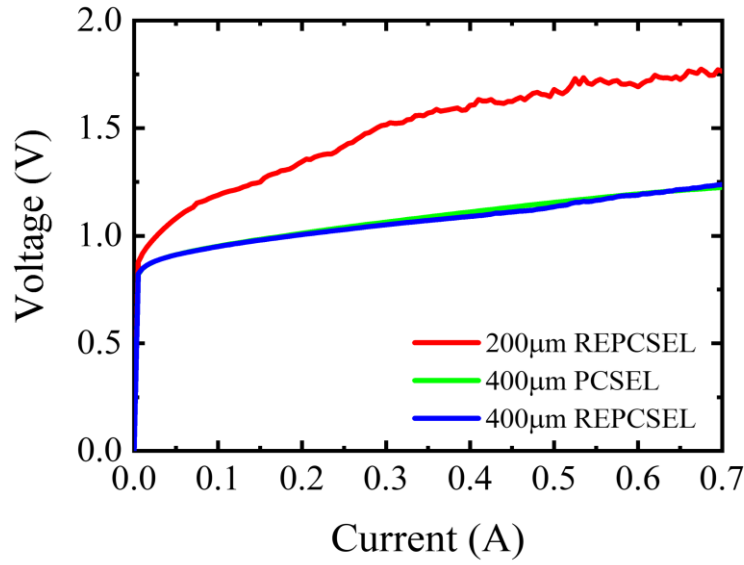


Fig. 4.12: Voltage-current(V-I) of 200 μm REPCSEL, 400 μm PCSEL, 400 μm REPCSEL with identical period at 400 nm.

Figure. 4.13 shows the lasing spectra measured at 911 mA, with a single mode lasing peak at 1294.9 nm. A side mode suppression ratio (SMSR) exceeding 43 dB and a spectral linewidth of 0.4 nm are observed. The inset shows the near field of the device at $1.6 \cdot I_{th}$, demonstrating uniform emission after the onset of lasing.

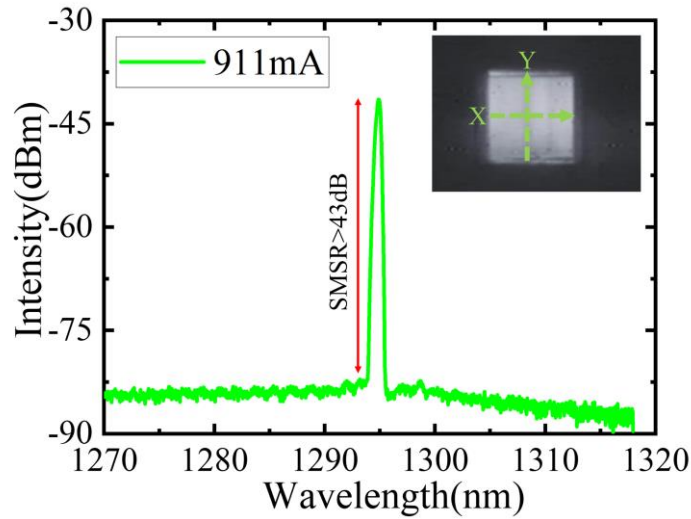


Fig. 4.13: Lasing spectrum at 911 mA. The inset displays the measured near-field emission profile at an injection current of 1 A [13]. X and Y indicate the direction.

The temperature dependent characteristics of the REPCSEL are shown in Fig. 4.14, with measurements conducted under temperatures ranging from 15°C to 50°C in 5°C increments. The laser maintains operation up to 50°C. The threshold current increases from 324 mA at 15°C to 632 mA at 50°C. The details of the analysis of the change of

threshold current with temperature is presented below in Fig. 4.15.

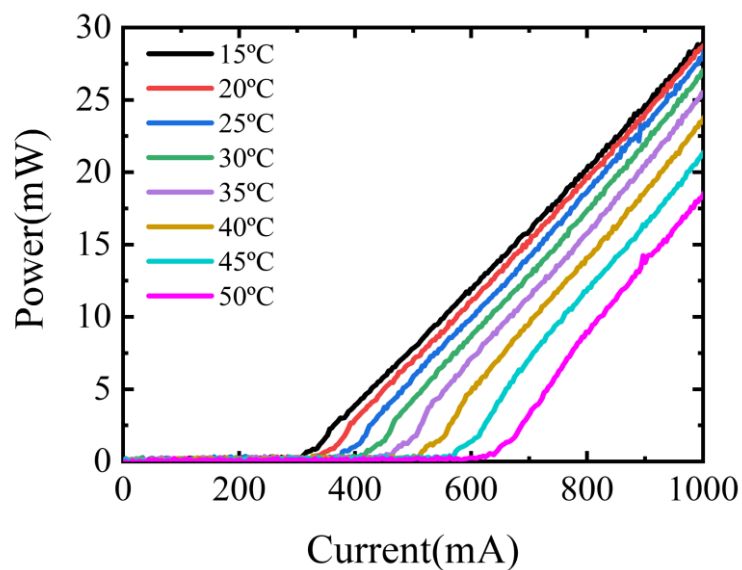


Fig. 4.14: Electrical properties of a 200 μm REPCSEL as a function of temperature, measured from 15°C to 50°C in 5°C increments.

Figure. 4.15 presents the variation in threshold current of the 200 μm REPCSEL with temperature, ranging from 15°C to 50°C in 5°C steps. The threshold current increases as the temperature rises. First, gain peak redshifts at $\sim 0.5 \text{ nm}/^\circ\text{C}$ as compared to $\sim 0.07 \text{ nm}/^\circ\text{C}$ for the lasing peak [14]. This results in a reduction in gain at the lasing wavelength as temperature increases. Furthermore, the peak gain at a given current reduces with temperature. [15] [16] [17] [18]

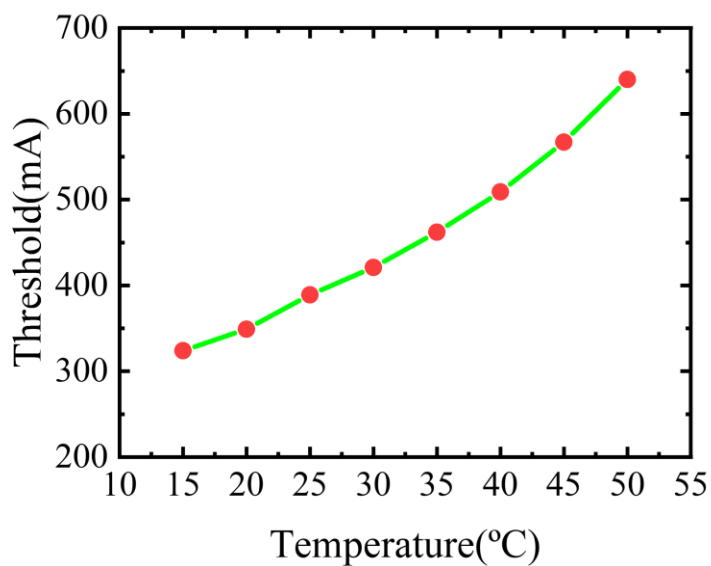


Fig. 4.15: Threshold of a 200 μm REPCSEL as a function of temperature, measured from 15°C to 50°C in 5°C increments.

The characteristic temperature T_0 is used to quantify how sensitive the threshold is to temperature variation. A higher T_0 means the device is less sensitive to temperature variation. Fig. 4.16 shows the log of the threshold current density $\ln(J_{th})$ of a 200 μm REPCSEL as a function of temperature. The formula for T_0 is obtained from [19].

$$T_0 = \frac{\Delta T}{\Delta \ln(J_{th})} \quad (4.1)$$

J_{th} represents the threshold current density. T_0 is the inverse of the slope of the line, which is in Kelvin ($K = ^\circ\text{C} + 273.15$). For this device, T_0 is ~ 120 K. This is very competitive with that reported for other InP PCSELS where T_0 of ~ 100 K [20] and T_0 of ~ 110 K [21] were reported. It should be noted that T_0 will be very sensitive to the gain peak detuning [22], suggesting room for improvement in future PCSEL device engineering in this regard.

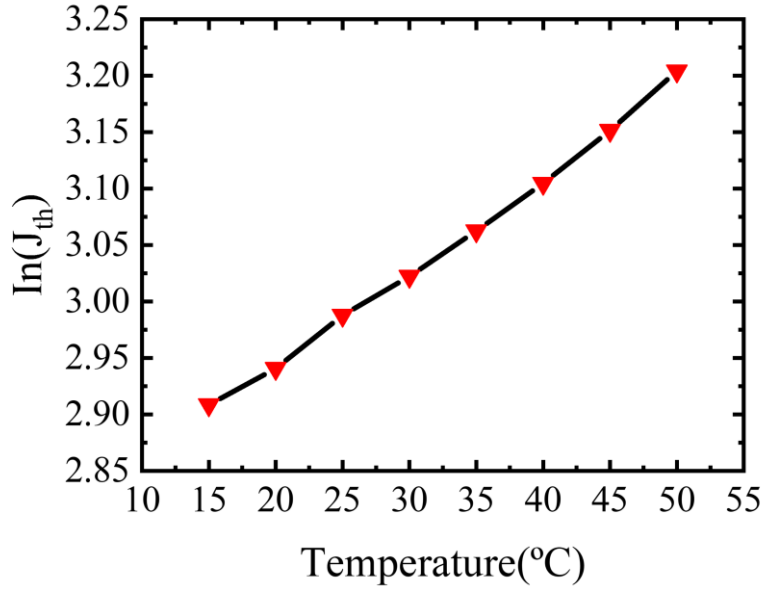


Fig. 4.16: $\ln(J_{th})$ of a 200 μm REPCSEL as a function of temperature, measured from 15°C to 50°C in 5°C increments.

Figure. 4.17 presents the slope efficiency of the 200 μm REPCSEL as a function of temperature. The results show that slope efficiency rises from ~ 0.041 W/A at 15°C to ~ 0.046 W/A at 50°C. This was not expected considering the increase in threshold current seen over this temperature range. One possible is that the laser is not 2D coherent, and lasing does not occur uniformly over the PCSEL. As temperature is increased, and more of the PCSEL area lases, an increase in slope efficiency may result.

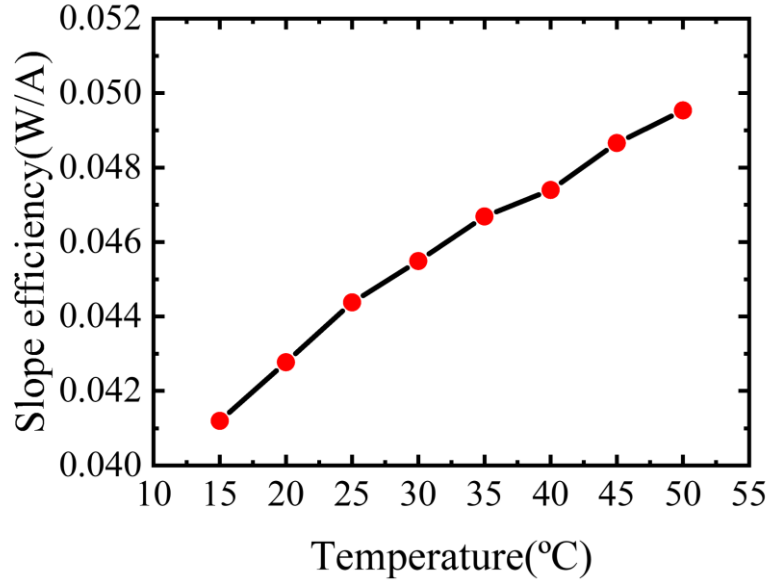
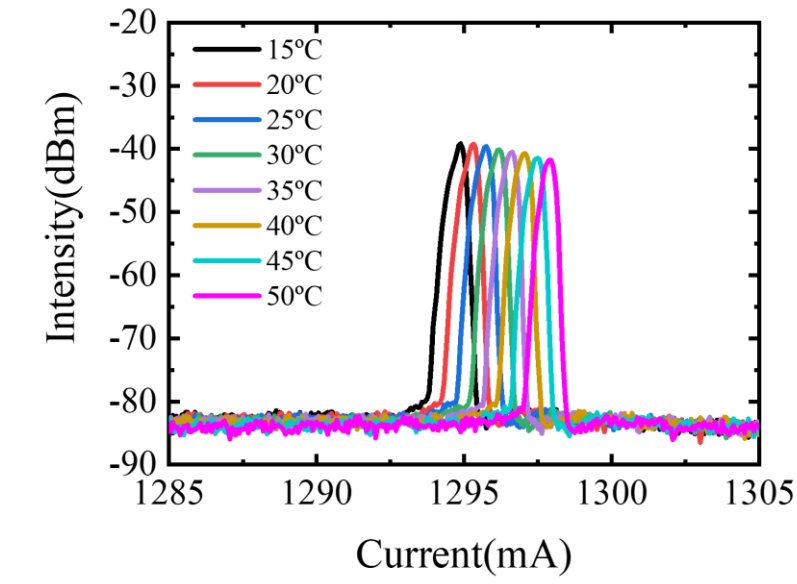


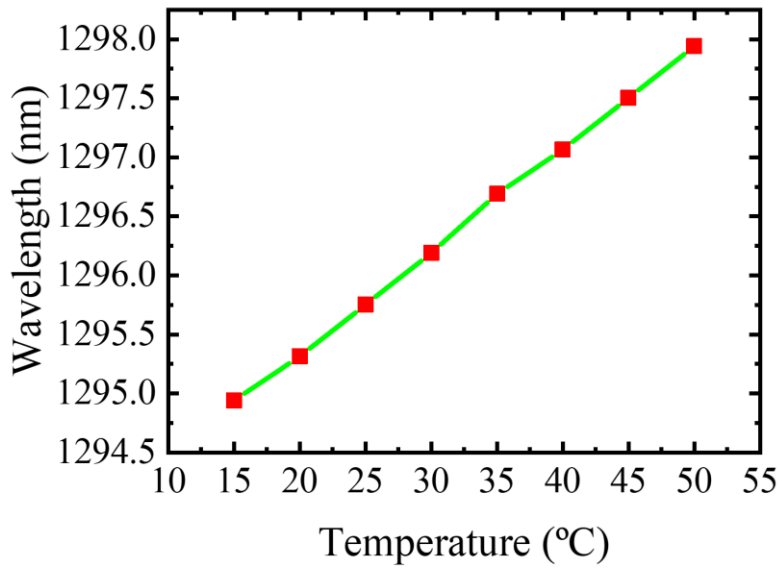
Fig. 4.17: Slope efficiency of a 200 μm REPCSEL as a function of temperature, measured from 15 $^{\circ}\text{C}$ to 50 $^{\circ}\text{C}$ in 5 $^{\circ}\text{C}$ increments.

The spectral characteristic of the 200 μm REPCSEL is shown in Fig. 4.18, with temperature controlled from 15 $^{\circ}\text{C}$ to 50 $^{\circ}\text{C}$ in steps of 5 $^{\circ}\text{C}$. The results show that a single lasing peak is observed over the whole temperature range. The peak wavelength is 1294.9 nm at 15 $^{\circ}\text{C}$ and redshifts to 1297.9 nm at 50 $^{\circ}\text{C}$ in steps of 0.085 nm/ $^{\circ}\text{C}$. The reason for the lasing peak tending to redshift is contributed to the refractive index of the material changing with temperature [23] [24] and thermal expansion [23] also changing the lattice constant of the photonic crystal, the peak wavelength red shifts. [24].

The linewidth increases from 0.38 nm at 15 $^{\circ}\text{C}$ to 0.44 nm at 50 $^{\circ}\text{C}$. This broadening is primarily attributed to enhanced refractive index variations and gain-cavity detuning with increasing temperature. In PCSELs, temperature-dependent changes in the refractive index modify the photonic band structure and can reduce modal discrimination, thereby increasing the likelihood of mode competition and spectral instability. In addition, the redshift of the QW gain spectrum with temperature, governed by bandgap shrinkage, leads to a mismatch between the gain peak and the cavity resonance. This detuning can reduce the effective feedback for the dominant mode and broaden the lasing spectrum. Furthermore, increased carrier-phonon interactions at higher temperatures enhance homogeneous broadening of the gain medium [15], which contributes to linewidth expansion. These combined effects—refractive index variation, gain cavity detuning, and increased scattering processes—lead to the observed increase in linewidth with temperature.



(a)



(b)

Fig. 4.18: (a) Spectral characteristics of a 200 μm REPCSEL at temperatures ranging from 15 $^{\circ}\text{C}$ to 50 $^{\circ}\text{C}$ in 5 $^{\circ}\text{C}$ increments. (b) The corresponding peak wavelength as a function of temperature.

4.7 Photonic Band-Structure Characterization:

Figure. 4.19 presents the measurement apparatus for the band structure of the REPCSEL, which is based on the apparatus as that used for characterizing its spectral properties in Fig. 4.3(b). The difference is that Lens 4 has been removed during the measurement process. The sample is positioned at the focal point of Lens 1. A multimode optical fiber with anti-reflection (AR) coating and a core diameter of 62.5

μm is utilized for band structure measurement. The measurement of the band structure of the PCSEL is an angle dependent measurement, the optical fibre is systematically moved to record spectra at different angles. The movement direction is parallel to the photonic crystal plane. The scan begins at the gamma point (Γ) of the device and moves along the Γ -M and Γ -X directions, with the Γ -X direction representing a 0° orientation in the X-Y plane and the Γ -M direction representing a 45° orientation in the X-Y plane. The fiber is moved in $100\ \mu\text{m}$ steps, which corresponds to an $\sim 0.29^\circ$ angular step size, and the corresponding spectra are recorded using an optical spectrum analyzer (OSA) to generate the band structure. This approach allows characterization of the band structure of a PCSEL. [25][26][27][28]

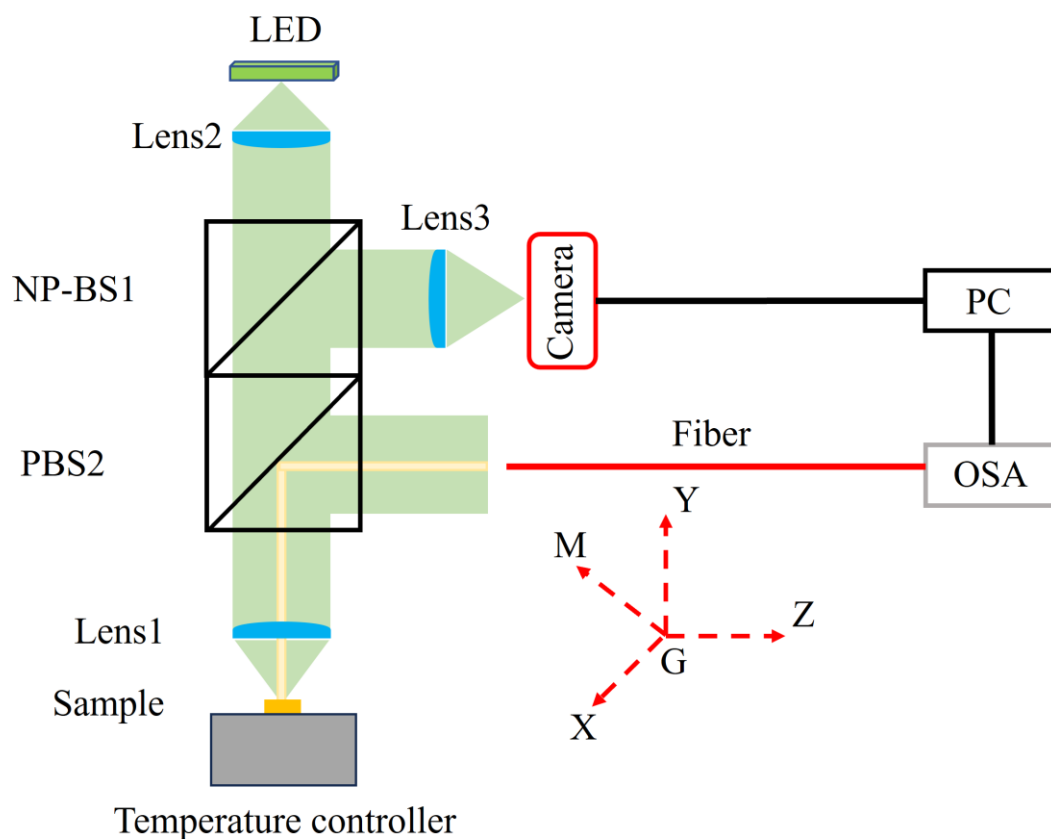


Fig. 4.19: Schematic illustration of measurement apparatus for band structure measurement.

Figure. 4.20 illustrates the band structure and in-plane electric field distribution of the fundamental mode within the unit cell for a PCSEL with a square lattice and circular atom shape, without the perimeter DBR, after Sakai *et al* [25]. The “leaky” mode or “non-leaky” mode is determined by the in-plane electric field distribution within the unit cell of the atom. Since the electric field distribution of the band edge A&B is anti-symmetric with respect to the atom, light emission in the vertical direction is consisted of two out of phase and will tend to be cancelled out. This destructive interference, and low emission rate, is the reason why it is called non-leaky mode [29] [30] [31] [32] [33]. In an ideal device with square lattice and circular atoms, the out of plane emission should be zero as perfect symmetry of the fundamental mode is expected. However, in

real-world devices, the circle shape may be imperfect, resulting in a disruption perfect symmetry, and the device size is finite, resulting in a slight shift of the electric field with respect to the location of the circular atom. [11]. In contrast, since the electric field distribution of the band edge C&D is symmetric with respect to the atom, the electric field distributions will not be cancelled out, leading to constructive interference and higher diffraction in the vertical direction. Consequently, at the gamma point, the spontaneous emission light intensity is higher at the band edge C&D. This is observed experimentally in Fig. 4.20(a). The leaky mode has higher loss in the vertical direction and lower Q-factor compared with non-leaky modes, these higher losses result in a higher threshold current for leaky mode, and non-leaky mode lases first [25]. By changing the radius of the circular atom, the primary lasing mode for either mode B or A can be selected [34][35].

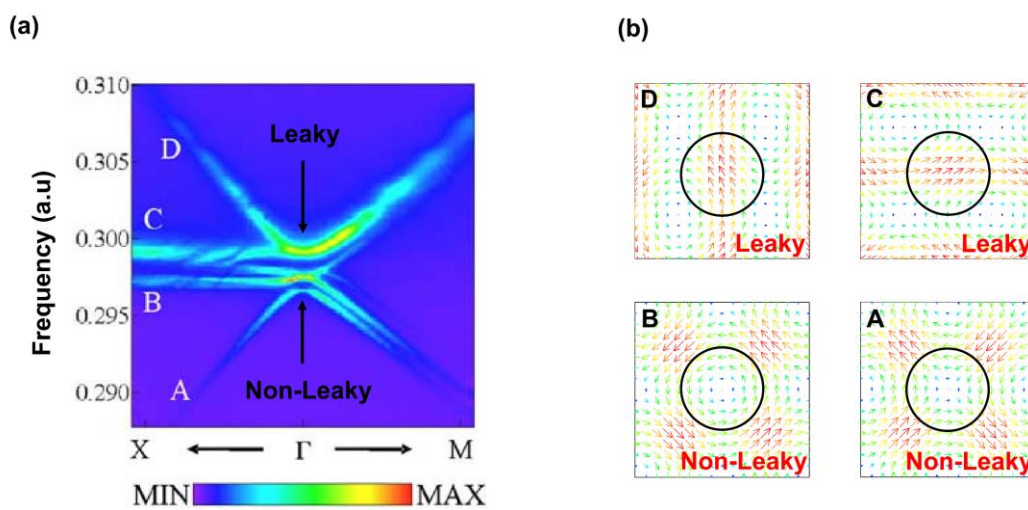


Fig. 4.20: Schematic illustration of the band structure of PCSEL without DBR design around the Gamma point. (a) The measured band structure of PCSEL below threshold. (b) The simulated in-plane electric field distribution for each band at the Gamma point by plane wave expansion (PWE), the arrows represent the electric field vectors in the photonic crystal plane, and the black circles represent the positions of circular atoms at $0.23r/a$ [25]. The circle radius is denoted by r , and the lattice period is denoted by a .

As explained above, due to the in-plane electric field distribution of the non-leaky mode, it leads to lower vertical emission for non-leaky modes and higher vertical emission for leaky modes. However, the situation is expected to change after adding a perimeter DBR.

Figure 4.21 presents the electroluminescence spectra collected at different displacements that give corresponding angles with respect to the surface normal around gamma point, and hence momentum for 200 μm REPCSEL. The measurement apparatus is based on the band-structure measurement method as shown in Fig. 4.19. The raw spectrum is collected with 100 μm ($\sim 0.29^\circ$) step size with an MMF (multi-mode fiber), with a sampling interval of 0.038 nm and a spectral resolution of 1 nm.

Four band edge modes around the gamma point were labeled A, B, C, and D in order of decreasing wavelength. To clearly display the spectrum as a function of angular, Fig. 4.21 only displays every second spatial (angular, momentum) step.

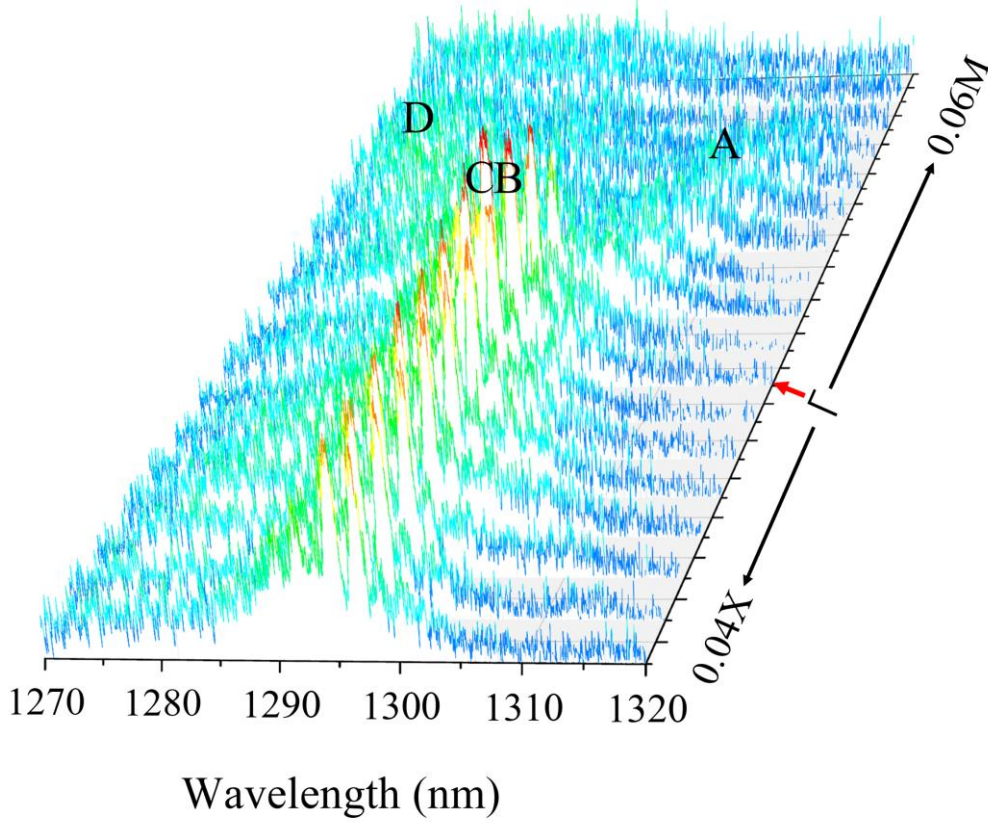


Fig. 4.21: Schematic illustration of the electroluminescence spectra corresponding to current at $0.4I_{th}$ under pulsed condition, which collected at different angles around gamma point with respect to surface normal.

Figure. 4.22(a) presents the band structure of the 200 μm REPCSEL at $0.4 * I_{th}$. The choice of such a low current is to make sure the cavity is “cold” and to reduce the contribution from amplified spontaneous emission. Fig.4.22(b) shows the measurement spectrum at the gamma point at $0.4 * I_{th}$. The result shows that the spontaneous emission of the leaky mode and the non-leaky mode have almost identical vertical emission intensities. This is in stark contrast to band-structure from standard PCSELs where 655 nm AlGaInP [36] 965 nm GaAs [25] 980 nm GaAs [27] 985 nm GaAs [26] 1300 nm InP [35] 1580 nm InP [37] 1950 nm GaSb [38]. The band edge modes C and D are anti-symmetric with respect to the atom, leading to destructive interference and the formation of non-leaky modes. Compared with Fig. 4.20, A and B modes become leaky modes because of the crossing accidental Dirac point [41] induced by increasing the atom radius from $0.23r/a$ to $0.4r/a$. The circle radius is denoted by r , and the lattice period is denoted by a .

The result indicates that the non-leaky mode is selectively enhanced by the surrounding

DBR. Otherwise, the vertical emission intensity should be lower due to the aforementioned reasons.

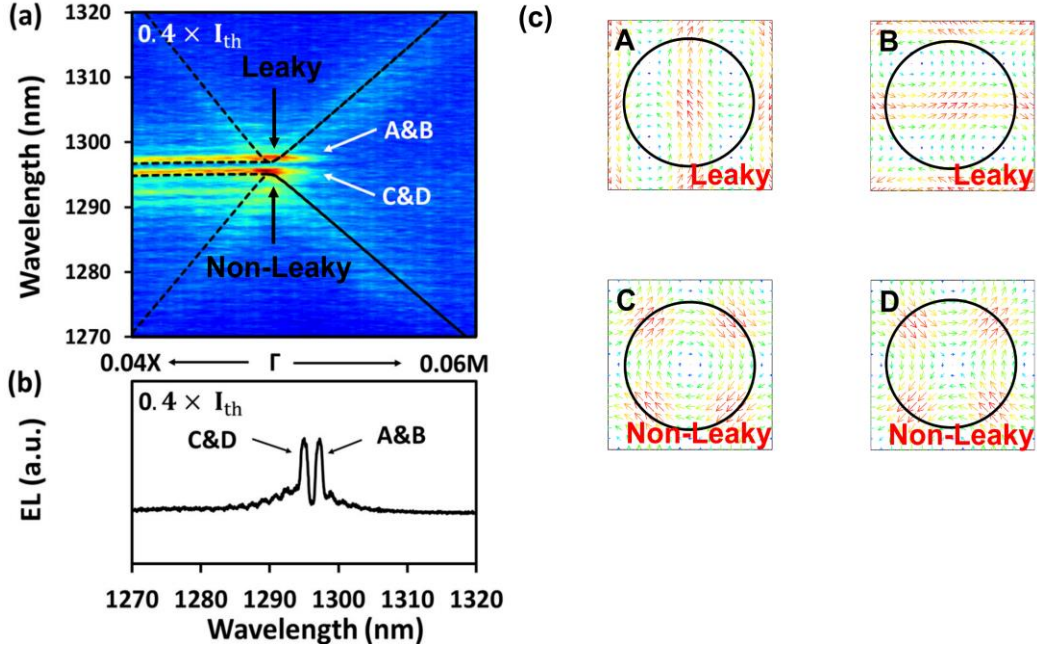


Fig. 4.22: Schematic illustration of the band structure of PCSEL with DBR design around the gamma point. (a) The measured band structure of REPCSEL at the 0.4 threshold under pulsed conditions, the simulation result is represented by black dotted lines. (b) The measured EL spectra at the gamma point and at the 0.4 threshold, with similar emission intensity for leaky mode and non-leaky mode. (c) The simulated in-plane electric field distribution for each band at the gamma point without the influence of the surrounding DBR at $0.4r/a$ [13].

To explore loss mechanisms of the lasing mode, the current dependence of the REPCSEL band-structure was investigated. Fig. 4.23 shows the band structure of the 200 μm REPCSEL device under different pulsed currents measured at a temperature of 15°C. The colour scale is varied as the current is changed. Ranging from Fig. 4.23(a) at $0.4I_{th}$ to Fig. 4.23(h) at $1.2I_{th}$. At $0.4I_{th}$, the leaky mode and non-leaky mode shows a similar emission intensity at the gamma point. As the injection current is increased, the emission intensity of the leaky mode and non-leaky mode increase similarly. The emission intensity of the non-leaky mode shows a similar intensity from $0.4I_{th}$ to $0.75I_{th}$, but from $0.77I_{th}$ a strong increase of the non-leaky mode intensity is observed. See Fig. 4.23(f). The apparent disappearance of the leaky mode is due to the colour palette scaling. Fig. 4.23(h) shows lasing occurring for the non-leaky mode after reaching the threshold current.

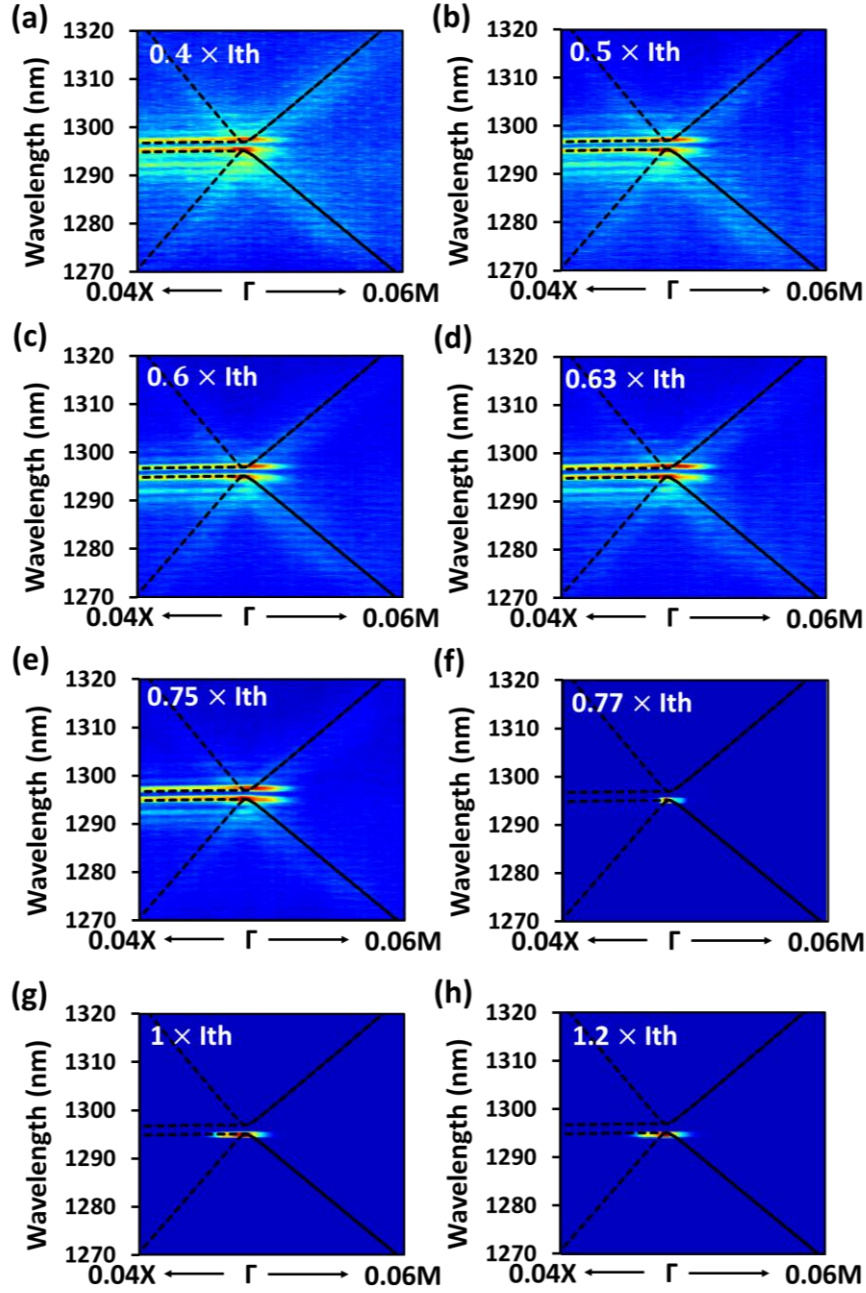


Fig. 4.23: Schematic illustration of the band structure near the gamma point under varying drive currents, with black dotted lines indicating simulation results [13].

Figure. 4.24. Plots the peak intensity of the A&B and C&D bands as a function of current (fraction of I_{th}). The intensity of leaky mode and non-leaky mode are very similar and comparatively small from $0.4 \times I_{th}$ to $0.7 \times I_{th}$. The intensities increase linearly with current. From $\sim 0.8 \times I_{th}$, the intensity of non-leaky mode starts to increase superlinearly while the leaky mode keeps increasing linearly. The superlinear behaviour is attributed to superluminescence [39]. Superluminescence is observed when the parasitic losses of a laser are overcome, but the total losses (parasitic + output) are not yet overcome. The observation of a different behaviour for the leaky and non-leaky modes indicates that their parasitic losses are very different. At $\sim 0.9 \times I_{th}$, the non-leaky

mode are undergoing regenerative amplification and super-luminescence, whilst the leaky modes are not.

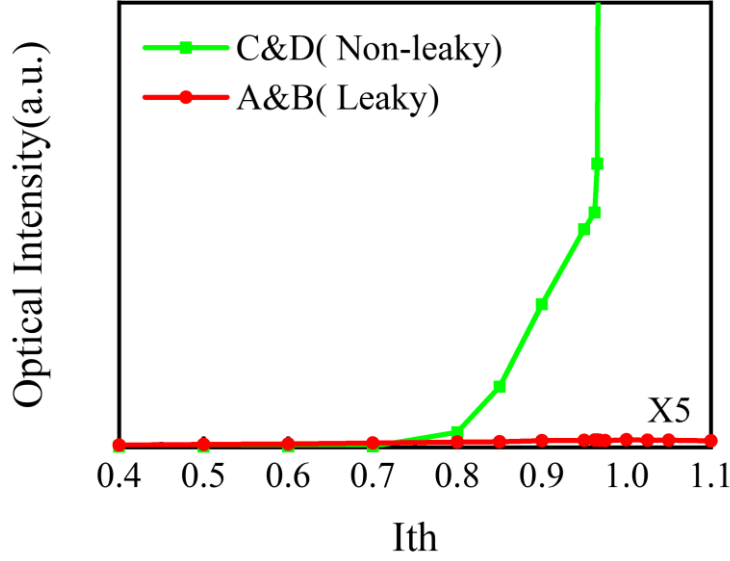


Fig. 4.24: Illustrates the optical power intensity of leaky modes A&B and non-leaky modes C&D under various pulsed injection currents at 15°C, with the intensity of leaky modes scaled by a factor of five for easier comparison [13].

To further understand how mode selectivity of DBR works in the REPCSEL structure, simulation from colleagues (Zijun Bian, Jingzhao Liu) is presented. Fig. 4.25(a) shows the simulated reflectance of the Fabry-Perot resonator (blue line) and the simulated band structure (black dotted line) for a 200 μm x 200 μm REPCSEL device. The band structure and reflectance spectrum of the REPCSEL, with the target wavelength centered at 1297 nm, achieved through a deliberately designed perimeter DBR. The PC region contains 500x500 periods under the P-contact, and 100 DBR pairs are fabricated surrounding the PC region but outside of the P-contact covered area. The simulated resonator reflectance result shows a good match with the PC band structure simulation result at the gamma point. Leaky modes A&B at 1297 nm are located close to the troughs, and non-leaky modes C&D at 1295 nm are located at the peaks of the resonator reflectance.

Figure. 4.25(b) shows the simulated IREF (Internal Resonance Enhancement Factor) value (red line) at different wavelengths around the gamma point region and the corresponding band structure (black dotted line). Fig. 4.25(a) and (b) are courtesy of Dr Zijun Bian. The simulated IREF values show a peak closely aligned with the non-leaky mode at the lasing wavelength of 1295 nm, highlighting the enhanced resonance effect.

The reflectance and IREF are influenced by the number of DBR pairs, a large in-plane loss parameter difference between leaky modes and non-leaky modes was required to demonstrate the mode selectivity concept. Fig. 4.25(c) shows the simulated in-plane loss for the same 200 μm x 200 μm REPCSEL device with different numbers of DBR

pairs, courtesy of Jingzhao Liu. A probabilistic Markov chain [5] model is applied using the boundary reflectivity for the leaky and non-leaky modes as a function of DBR number.

Without the influence of the DBR, the in-plane loss is the same for leaky and non-leaky modes (52 cm^{-1}). As the number of DBR pairs increases to 100, the in-plane loss decreases for non-leaky modes and remains relatively stable for leaky modes. After 100 DBR pairs, the in-plane loss starts to converge for non-leaky modes and decrease for leaky modes. In the end, both in-plane losses tend to converge ($\sim a \text{ few cm}^{-1}$) at large numbers of DBR pairs. The result shows that the best choice for a large difference in in-plane loss is located at the middle position, where the in-plane loss parameter difference between leaky modes and non-leaky modes reaches the highest value. 100 DBR pairs are adopted in this work to give a $\sim 79\%$ difference in resonator reflectance.

I now return to my previous results, and discuss them in the light of these simulations. Fig. 4.25(b) shows that the leaky modes A&B are aligned with the troughs of IREF, and the non-leaky modes C&D are located at one of the peaks of IREF with a value of ~ 200 . This explains why the non-leaky modes have similar vertical emission intensity at $0.4 \cdot I_{th}$ as leaky modes as shown in Fig. 4.23. The almost identical emission rates for the two sets of modes are happenstance.

As C&D are almost degenerate ($< 0.15 \text{ nm}$ splitting), both will be enhanced similarly. The lasing mode (either C or D) will be determined by the precise details of the band-structure and its alignment with the curves in Fig. 4.25(a) and (b). In this work, the first lasing mode happens at mode D.

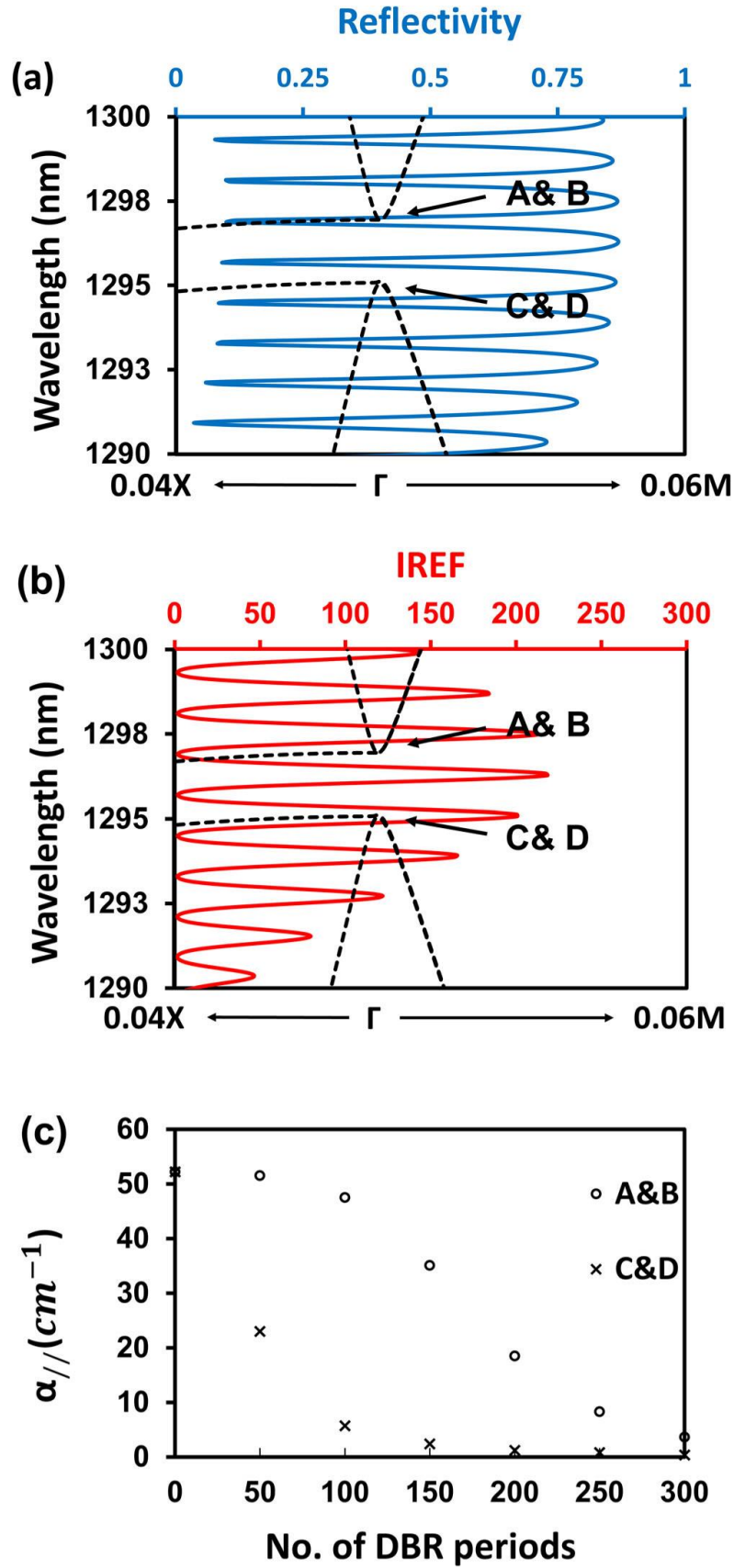


Fig. 4.25: Simulated resonator reflectivity, band structure, IREF, and in-plane loss for the REPCSEL design.

The above measurement result means that the in-plane loss parameter of leaky mode and non-leaky mode is selectively changed by the perimeter DBR. This agrees with the prediction of a reduced in-plane loss, yet equivalent radiative coupling and internal loss for the non-leaky modes.

This is attributed to the vertical scattering being equal for leaky and non-leaky modes at the gamma point, without differences in other loss parameters, mode competition would occur between the leaky mode and non-leaky mode, leading to multi-mode lasing. However, the carefully designed alignment of the surrounding DBR reflectance spectrum makes the in-plane loss parameter have a difference for the leaky mode and non-leaky mode. The in-plane loss is deliberately reduced for non-leaky mode, leading to a similar peak intensity for leaky and non-leaky mode in Fig. 4. 22(b). These results agree with another detailed study of PCSEL structures where the DBR period (and hence target wavelength) were systematically modified is shown elsewhere [13].

4.8 Conclusion:

In this chapter, the detailed characterization of a range of REPCSELs and associated PCSELs was presented. It was shown that for a REPCSEL with square lattice with circular atoms, the in-plane optical loss can be deliberately changed by DBR designs, which further influence the out of plane scattering intensity. For $400\text{ }\mu\text{m} \times 400\text{ }\mu\text{m}$ REPCSELs, the effect of varying the PC and DBR period, and hence detuning with respect to the gain spectrum, on threshold and slope efficiency was presented. Single wavelength peak behaviour is demonstrated for a $200\text{ }\mu\text{m} \times 200\text{ }\mu\text{m}$ REPCSEL (period = 400 nm) with near field images show a flat-top profile. Then, the temperature dependent current power characteristics and spectral measurements are explored in detail.

Band-structure measurement of the REPCSEL at low injection current showed that the scattering intensity of the non-leaky and leaky modes is almost equal at the gamma point. Then, the band-structure measurement as a function of injection current was presented, and the analysis of scattering intensity of the non-leaky and leaky modes at the gamma point showed that the in-plane loss was higher for leaky modes. This was achieved by carefully aligning the envelope of the resonance peak with the non-leaky mode and the trough with the leaky mode. This allowed the engineering of an in-plane optical loss difference between different wavelengths can be achieved. This occurs for a given device size and suitable number of DBRs, to match the zone-centre splitting.

This novel wavelength selectivity mechanism offers a promising new approach to surface emitting laser diode engineering. One promising application of REPCSELs is their potential to reduce the size of PCSELs to enable high speed direct modulation. A major challenge for small scale PCSELs lies in the high in-plane optical loss, which leads to high threshold currents. The wavelength selectivity mechanism inherent to REPCSELs offers a solution by minimizing in-plane optical loss, thereby improving

performance in compact designs. Additionally, REPCSELs hold significant potential for applications requiring high power laser arrays, where their ability to provide efficient, high quality emission and scalable designs makes them highly advantageous. These characteristics position REPCSELs as a key technology for advancing both high speed communication systems and high power laser applications.

4.9 Discussion &Future work:

Since the REPCSEL has shown reasonable efficiencies using a square lattice and circular atoms future work can be expanded to design asymmetric atom shapes such as triangular or double lattice designs to reduce the electromagnetic destructive interference and further increase the out of plane scattering efficiency.

Moving away from the square lattice, the concept of REPCSEL can also be applied to triangular lattice structures. Since the application of the REPCSEL requires relatively low κL to maintain a suitable internal effect, the combination of high refractive index contrast, such as air void atoms, with the REPCSEL can be used to further reduce the size of the device compared with all semiconductor atoms for high speed modulation applications. There are still some challenges remaining, since the effective wavelength selectivity relies on precise alignment between the photonic crystal band structure and the DBR reflectance spectrum. Any misalignment can reduce mode selectivity, increase in-plane losses, and degrading device performance. So, the performance of REPCSELs heavily depends on the precise design and fabrication of DBRs and photonic crystal structures. Achieving the necessary alignment and structural integrity at nanoscale tolerances is technically demanding and costly. So, the future task will be to further optimize the fabrication process to improve DBR quality and make alignment more precise to the target wavelength.

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Chapter 5. Spatially Resolved Band-Structure for the Quantitative Analysis of PCSELs

5.1 Introduction:

Band-structure measurements are often presented in studies of PCSELs [1-33]. Such measurements provide a fingerprint of the PC structure. Whilst they are often presented in PCSEL publications, their use to provide quantitative information is limited. Akin to the analysis of the sub-threshold spectra of a DFB laser [34] [35] [36], the frequencies of the zone-centre peaks can be used to extract the coupling coefficients of the PC [2], and this has been used in a handful of these reports [8] [16] [27].

One report by Sakai *et al* [1] has shown their use in estimating the cavity Q-factor, which is based on the observation of resonance coupling of spontaneous emission to the bands of the photonic crystal. Here, the analysis is conducted of the zone centre emission spectrum at $0.9 \cdot I_{th}$, stating this is “well below lasing”. The author does not investigate the effect of current to confirm that they are indeed measuring a cold cavity. Sakai *et al* quotes a ~ 0.2 nm spectral resolution, but this does not appear to have been considered in their estimate of Q-factor, leading to a ~ 5 -10% under-estimation of the Q-factor.

Furthermore, there is no consideration of the wavevector (Δk) resolution of the measurement apparatus on the measured spectrum. Their system relies upon the device under test being mounted on a goniometer with a lens (unknown distance, unknown size) allowing collection of the light into a fibre-optic cable (unknown type).

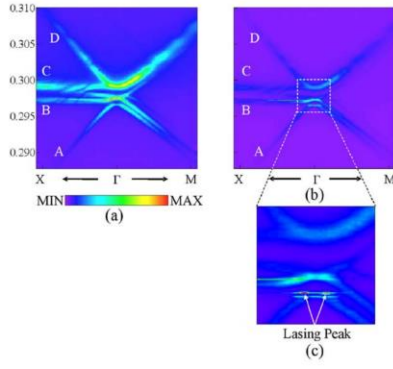
In this chapter, an investigation of spatially resolved band-structure as a function of drive current is presented. The effect of k-vector resolution and injected current (cavity gain) on the measurement is explored and the spatial-spectral characteristics of the PCSEL with the onset of lasing are elucidated.

The result indicates that by using spatially resolved band-structure measurement, the influence of inhomogeneity of the PCSEL in conventional band-structure measurements process can be minimized. At low currents, the optical loss of the different modes is shown to be as expected, with the lasing mode having the highest Q-factor. The lasing mode is observed to narrow for currents $> \sim 125$ mA (threshold=188 mA), providing an estimate of the transparency current. This narrowing highlights the need for careful analysis as a function of current to ensure threshold gain is not underestimated.

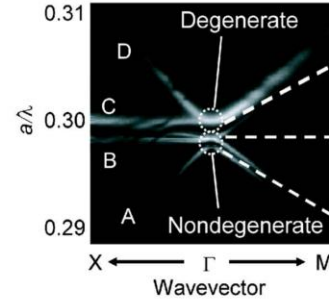
5.2 Gaps in Knowledge:

Figures. 5.1, Fig. 5.2, Fig. 5.3, Fig. 5.4 Fig. 5.5 reproduce the current results of the band-structure for PCSELS. To the best of the author's knowledge this covers all PCSEL band-structure reports at the time of submission. Table. 5.1 presents the analysis conducted in these reports. Whilst many band-structure measurements have been reported, almost no information about the estimation of the Q-factor or threshold gain has been given from the band-structure measurement process. The influence of drive current also has not been considered if quantitative information needs to be extracted. Many previous reports have indicated that the lasing band exhibits a higher emission intensity than other zone-centre bands [10,11,16,20,21,24,26-28]. In the case of a cold cavity, the lasing non-leaky mode is expected to present the lowest emission intensity of all modes. The details will be explained later in section 5.5. The influence of collected wavevector Δk and inhomogeneity of PCSEL also has not been discussed in previous reports. A detailed study of band-structure measurement apparatus and procedures for quantitative analysis is timely and therefore required.

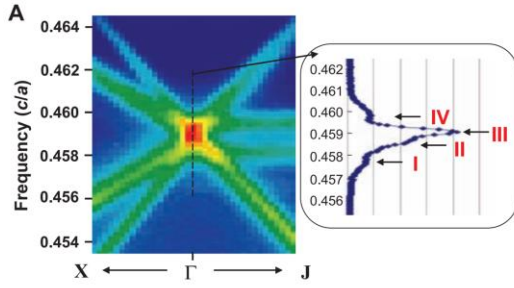
To the best of the author's knowledge, previous studies on band-structure measurements have not reported a detailed investigation of the effects of PCSEL inhomogeneity, collected wavevector (Δk), current, and polarisation. This work presents the first systematic study of spatially resolved band-structure measurements, including the influence of collected wavevector variation, current dependent behaviour, and polarisation properties.



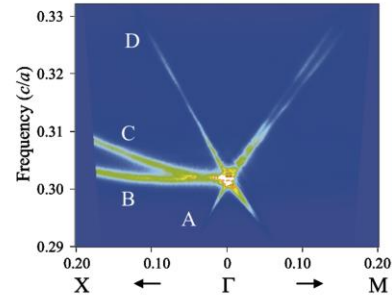
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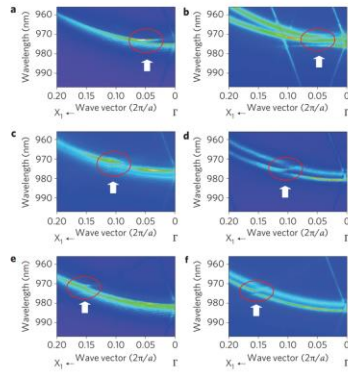
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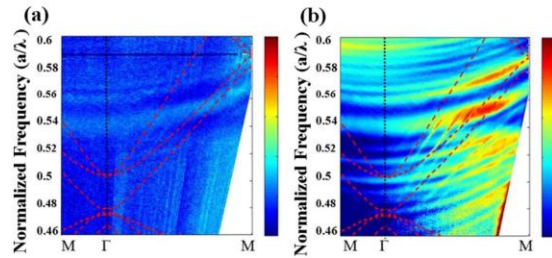
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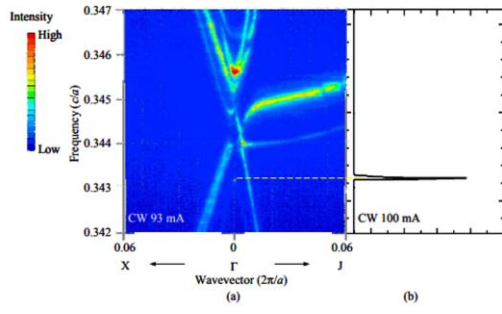


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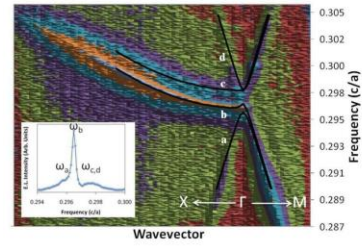


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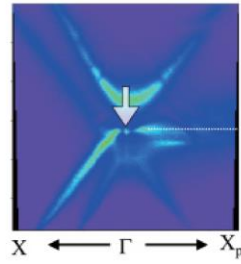
Fig. 5.1: The experimental band-structure of PCSELs reproduced from references [1-6]. InGaAs/GaAs based material system with square lattice [1]. Material system reminds unknown with square lattice [2]. AlGaIn/GaN based material system with hexagonal lattice [3]. Material system reminds unknown with square lattice [4]. Material system reminds unknown with deformed square lattice [5]. AlGaIn/GaN based material system with triangular lattice [6].



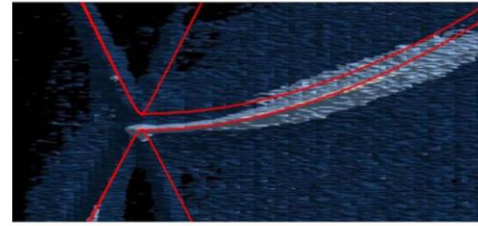
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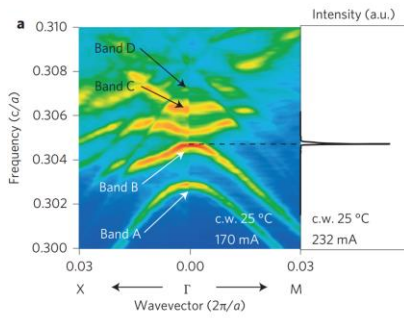
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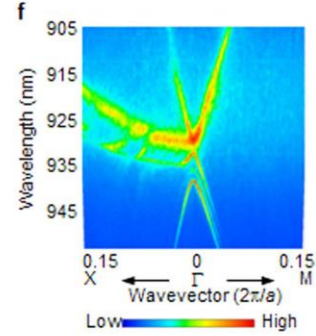
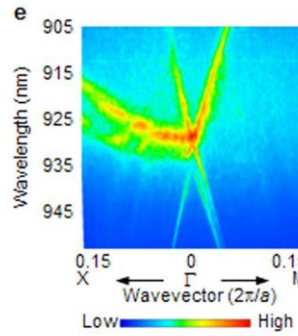
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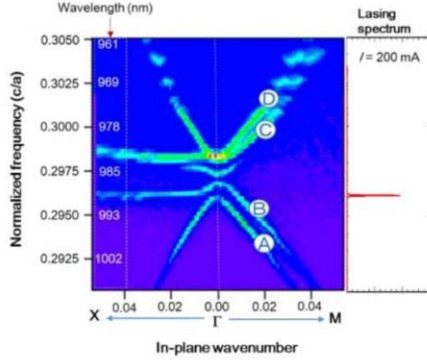


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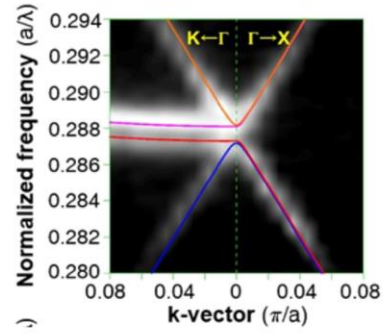


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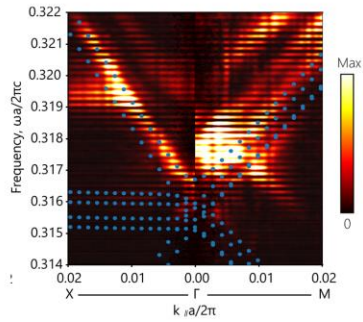
Fig. 5.2: The experimental band-structure of PCSELs reproduced from references [7-12]. Material system reminds unknown with triangular lattice [7]. InGaAs/GaAs based material system with square lattice [8,10,11]. InGaAs/GaAs based material system with centred rectangular lattice [9]. Material system reminds unknown with deformed square lattice [12].



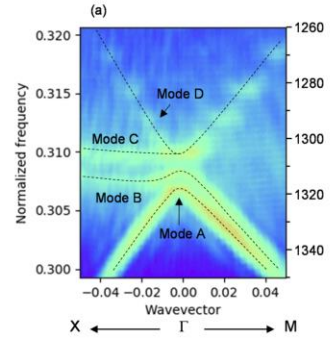
[13]



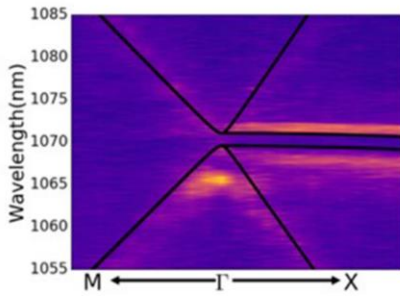
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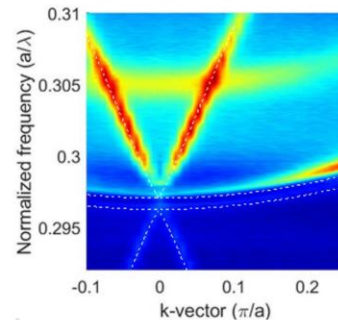
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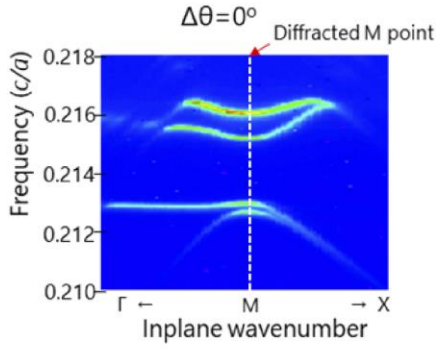


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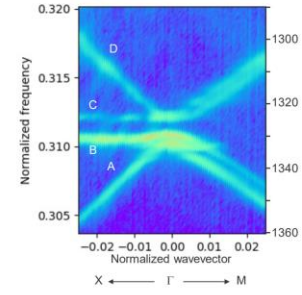


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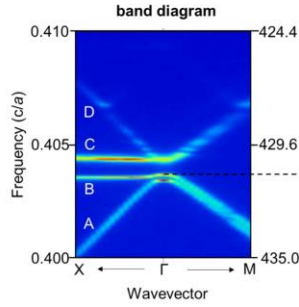
Fig. 5.3: The experimental band-structure of PCSELs reproduced from references [13-18]. InGaAs/GaAs based material system with square lattice [13,14,17]. InP based InGaAs/AlInAs material system with square lattice [15]. InGaAsP/InP based material system with square lattice [16]. Material system reminds unknown with square lattice [18].



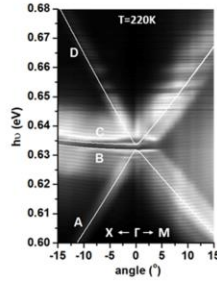
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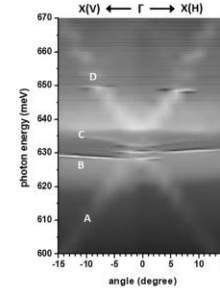
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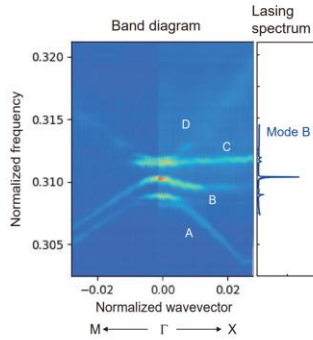
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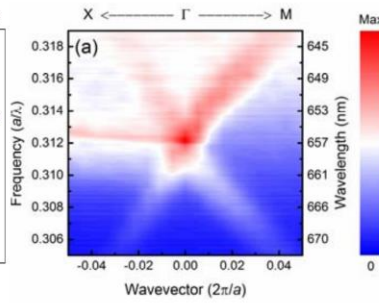
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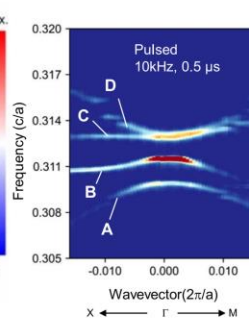
[23]



[24]



[25]



[26]

Fig. 5.4: The experimental band-structure of PCSELs reproduced from references [19-26]. Material system reminds unknown with deformed square lattice [19]. InGaAsP/InP based material system with square lattice [20,24,26]. AlGaIn/GaN based material system with square lattice [21]. GaSb based AlGaAsSb/GaInSb material system with square lattice [22]. GaSb based AlGaAsSb/GaInSb material system with square lattice [23]. AlGaInP/GaAs based material system square lattice.

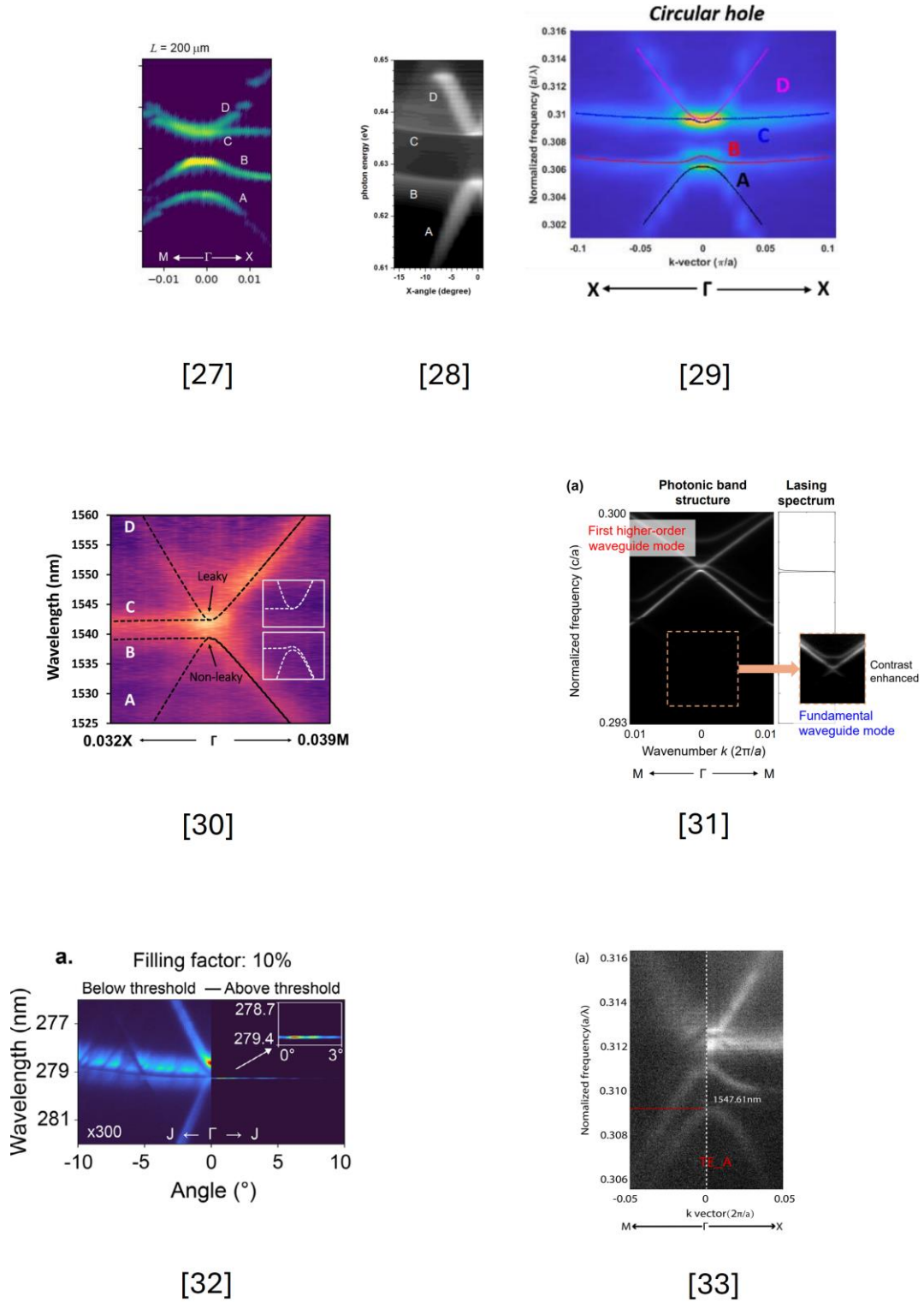


Fig. 5.5: The experimental band-structure of PCSELs reproduced from references [27-33]. InGaAsP/InP based material system with square lattice [27,29,30]. GaSb based III-V-Sb cascade diode material system with square lattice [28]. InGaAs/GaAs based material system with square lattice [31]. AlGaIn/GaN based material system with hexagonal lattice [32]. InP based III-V/Si heterogeneous PCSEL platform with square lattice [33].

Table. 5.1: The corresponding parameters involved in the band-structure experiment process.

REF	Zone Centre SE - K1d, K2d extraction	Spectral Resolution $\Delta\lambda$ (nm)	Angular Resolution Dtheta (degrees)	High K collection Effects	Current Dependence	Q Factor / threshold gain	Collection of lower ΔK effects	Spatial Resolution	Polarization
[1]	No	0.2	0.1°	No	No	Estimate only /No	No	No	No
[2]	Yes	No	No	No	No	No	No	No	No
[3]	No	No	No	No	No	No	No	No	No
[4]	No	No	No	No	No	No	No	No	No
[5]	No	No	No	No	No	No	No	No	No
[6]	No	0.7	0.5°	No	No	No	No	No	No
[7]	No	No	0.1°	No	No	No	No	No	No
[8]	Yes	No	No	No	No	No	No	No	No
[9]	No	No	No	No	No	No	No	No	No
[10]	No	No	No	No	No	No	No	No	No
[11]	No	No	No	No	No	No	No	No	No
[12]	No	No	No	No	No	No	No	No	No
[13]	No	No	No	No	No	No	No	No	No
[14]	No	No	1°	No	No	No	No	No	No
[15]	No	No	No	No	No	No	No	No	No
[16]	Yes	No	No	No	No	No	No	No	No
[17]	No	No	No	No	No	No	No	No	No
[18]	No	No	No	No	No	No	No	No	No
[19]	No	No	No	No	No	No	No	No	No
[20]	No	No	No	No	No	No	No	No	No
[21]	No	No	No	No	No	No	No	No	No
[22]	No	No	No	No	No	No	No	No	No
[23]	No	No	No	No	No	No	No	No	No
[24]	Yes	No	No	No	No	No	No	No	No
[25]	No	1	No	No	No	No	No	No	No
[26]	No	No	No	No	No	No	No	No	No
[27]	Yes	No	No	No	No	No	No	No	No
[28]	No	No	No	No	No	No	No	No	No
[29]	No	No	No	No	No	No	No	No	No
[30]	No	No	No	No	No	No	No	No	No
[31]	No	No	No	No	No	No	No	No	No
[32]	No	No	No	No	No	No	No	No	No
[33]	No	No	No	No	No	No	No	No	No
My work	No	0.05	0.1°	Yes	Yes	Yes	Yes	Yes	Yes

5.3 Contents of This Chapter:

This chapter begins with an introduction to the different methods for PCSEL band-structure measurement that will be used in this chapter. The LIV characteristics of the devices are explored first.

The details of measurement apparatus for band-structure measurement are then introduced. Then, efficacy of band-structure measurement below and above threshold current for a commercial PCSEL is assessed, and the simulated band-structure around the gamma point with the 2D PWE for TE modes is presented. The details of current dependent measurement at the gamma point with multimode fibre (MMF) being used to collect the signal. The details of current dependent measurement at the gamma point with SMF are then introduced to explore the effect of k-vector resolution. At low current, neither method shows the lasing mode to have the lowest linewidth and highest Q-factor.

A spatially resolved band-structure measurement apparatus is then developed to explore the effect of inhomogeneity of the PCSEL, and the details of current dependent measurement at the gamma point with MMF are presented. The result shows the lasing mode has the highest Q-factor at low current, providing confidence that the estimate of threshold gain is more reasonable. Spatially resolved mapping of the emission spectra in the X and Y directions reveal the influence of inhomogeneity of the PCSEL.

The apparatus for the measurement of spatially resolved band-structure using a magnified image is introduced. The details of the current dependent measurement at the gamma point with MMF at 2- and 4-times magnifications are presented. The result shows that the lasing mode has the lowest linewidth at low current up to ~80 mA. The mapping of the 4-times magnified image below the threshold current at different injected currents presents the influence of inhomogeneity of the PCSEL affecting wavelength and linewidth.

Polarisation resolved band-structure measurement apparatus is then introduced, and the details of the polarisation properties of the device are presented.

5.4 Measurement Strategy:

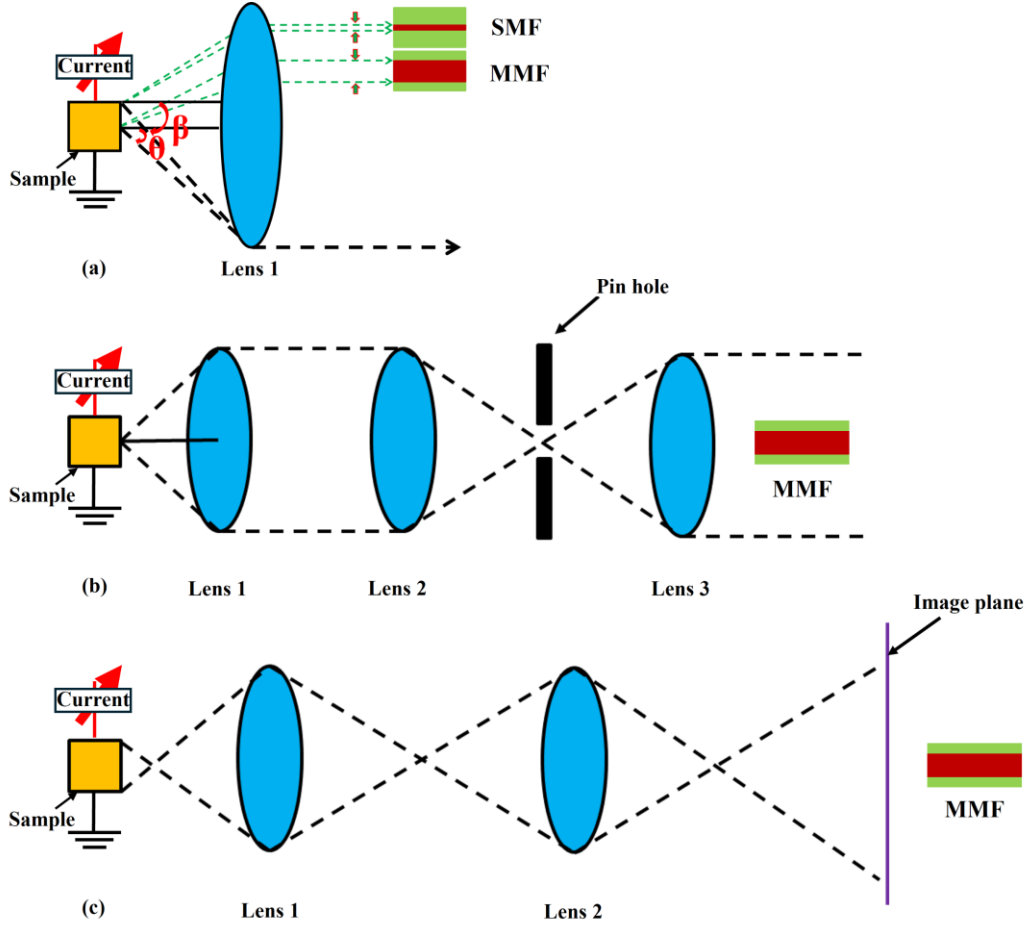


Fig. 5.6: Schematic illustration of three different methods to collect light at different wavevectors: (a) Band-structure measurement method, (b) confocal spatially resolved band-structure measurement method, (c) image plane spatially resolved band-structure measurement method.

The band-structure of the PCSEL is measured from the angle dependent spontaneous emission spectrum below the threshold current [1].

By changing the angle θ (Γ -X to Γ -M) relative to the normal to the PC plane, and measuring the emission spectrum, the band-structure around the gamma point can be obtained.

The in-plane wavevector k is related to the angle θ by the following formula [1].

$$k = 2\pi / \lambda * \sin(\theta) \quad (5.1)$$

Where angle θ is equal to zero (normal to PC plane), and λ is the wavelength in air. Figure 5.6(a) illustrates schematically a method to carry out band-structure measurement. By placing the sample at the focal point of the lens, the angular emission angle (θ) is converted to an x-y position in the collimated beam. The fibre will collect a small fraction of the collimated light corresponding to a particular emission angle.

The finite size of the collection aperture, in this case the fibre core diameter will result in a range of emission angles, $\Delta\theta$, and hence Δk being collected. This Δk will be determined by the lens NA (Numerical Aperture), the diameter of the lens, the fibre NA, and the diameter of the fibre.

For this method, no spatial resolution is involved in the measurement, because the spontaneous emission from the entire area of the PCSEL will be collected during the measurement process. This introduces two linewidth broadening mechanisms. See Figure 5.6. Firstly, the finite chip size can result in higher angular collection from signals at the edge of the chip, as compared to the centre of the chip. Furthermore, inhomogeneity of the PC structure will be included in the standard band-structure measurement.

Figure 5.6(b) is a schematic representation of a spatially resolved band-structure measurement. The sample is placed at the focal point of lens 1 ($f=34.9$ mm), the collimated light will be focused again by lens 2 ($f=34.9$ mm). The pinhole is located at the focal point of lens 2 and lens 3 ($f=49.8$ mm). The Δk will be determined by the NA of lens 3, the diameter of lens 3, the fibre NA, and the diameter of the fibre. Compared with Fig 5.6(a), the PCSEL emission area will be determined by the diameter of the pinhole. Because most of the emission area will be blocked by the pinhole plane, it is expected to achieve a spatially resolved measurement.

Figure 5.6(c) is a schematic representation of image plane spatially resolved band-structure measurement. The sample is placed away from the focal point of lens 1, with magnification depending on the sample position, the distance between the two lenses and the fibre position. Because the fibre is placed at the magnified image plane, the Δk is mainly determined by magnification, fibre NA, and the diameter of the fibre.

Non-normal incidence of the internal beam at the air/semiconductor interface has not been studied. This may be significant for substrate emitting structures with lapped/polished emitting surfaces. However, applying Fresnel's laws to the angular emission indicates that we are able to measure band-structure up to 90° in the air. Practically, the NA of our collection optics limits this to $\sim 31^\circ$ which corresponds to $\sim 30\%$ for Γ to X direction and $\sim 20\%$ to M direction at Brillouin zone [59].

This chapter is based on the measurement of the same device. We expect that the materials are GaAs/AlGaAs but have limited information beyond that.

5.5 Device Operation & Conventional Band-Structure:

Fig. 5.7(a) presents the power-current-voltage (LIV) characteristics of the measured device under continuous-wave (CW) forward bias at 20 °C, and the measurement for this chapter will be operated at CW and 20 °C. The black line represents the current voltage (IV), and the red line represents the current power (LI). The results are reproduced with a V_0 of 1.1V, a shunt resistance of $\sim 1.13 \text{ k}\Omega$ and a series resistance of $\sim 0.45 \text{ }\Omega$.

Figure 5.7(b) presents the emission spectrum at 186 mA (green line) and 190 mA (red line) being just below and just above lasing threshold. Four peaks are observed with the third peak contributing to the lasing power. The third (lasing) peak is observed at 934.16 nm. It exhibits a linewidth of 0.168 nm at both currents. The lasing peak remains at 934.16 nm for both injection currents.

Figure 5.7(c) presents the expanded plot of current power (LI) around threshold current, the green dashed straight line is used to provide visual assistance. The threshold current is determined by the two-segment fit method [37], by using a straight line fit to the approximately linear portions of the L/I curve. The threshold current value is taken as the intercept point where two fitted green dashed straight line meet with each other. For this device it is $188 \pm 1 \text{ mA}$.

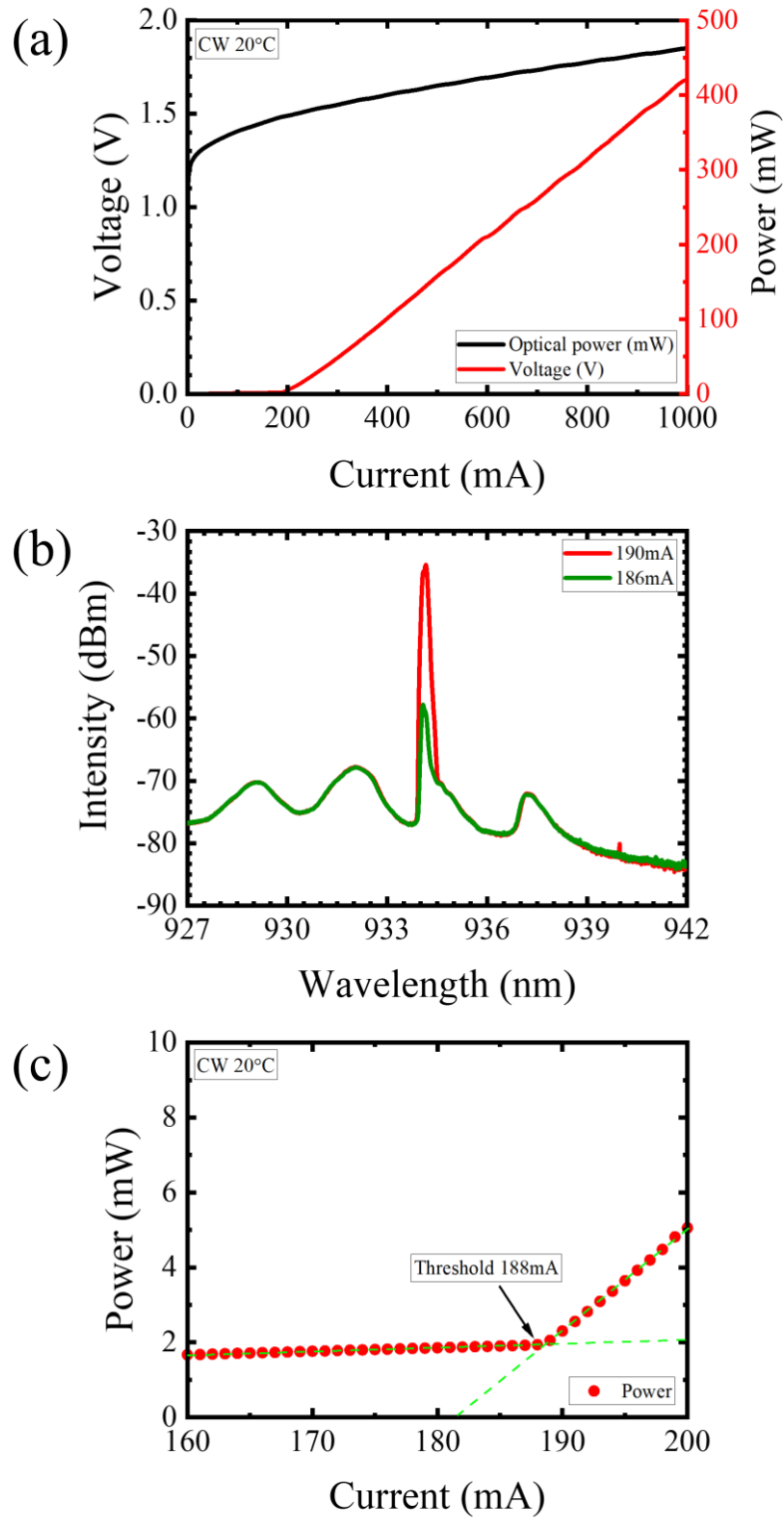


Fig. 5.7: Graph of (a) the LIV characteristics of measured device. (b) The spectrum below and above threshold. (c) The expanded LI around threshold current.

Figure 5.8 presents the apparatus in Fig. 5.6(a) to carry out band-structure measurements. BS1 (Thorlabs BS092) is a non-polarising beamsplitter which reflects $\sim 50\%$ of the collimated light in the perpendicular direction. BS2 (Thorlabs CM1-

BP108) is a pellicle beam splitter which reflects $\sim 8\%$ of the collimated light in the perpendicular direction for imaging. Lens 1 (Thorlabs LA1027-B) is an anti-reflection (AR) coated aspheric lens with a NA of 0.51.

In Fig. 5.8, the blue line represents the LED illumination, and the grey line represents the emission light from the sample. The sample is mounted on a heat dissipation stage. A temperature controller is positioned beneath the stage to control the temperature of the sample. The sample is located at the focal point of Lens 1. Lens 2 is employed to focus the image of the sample onto the camera, providing a view of the sample surface. After the emission passes through two beam splitters, an MMF with a diameter of $62.5\ \mu\text{m}$ and NA of 0.275 collects the collimated light and transmits it to the optical signal analyzer (OSA) to record the spectrum.

During the measurement process, the fibre was moved from Γ -X to Γ -M relative to the normal of the PC plane with $200\ \mu\text{m}$ steps.

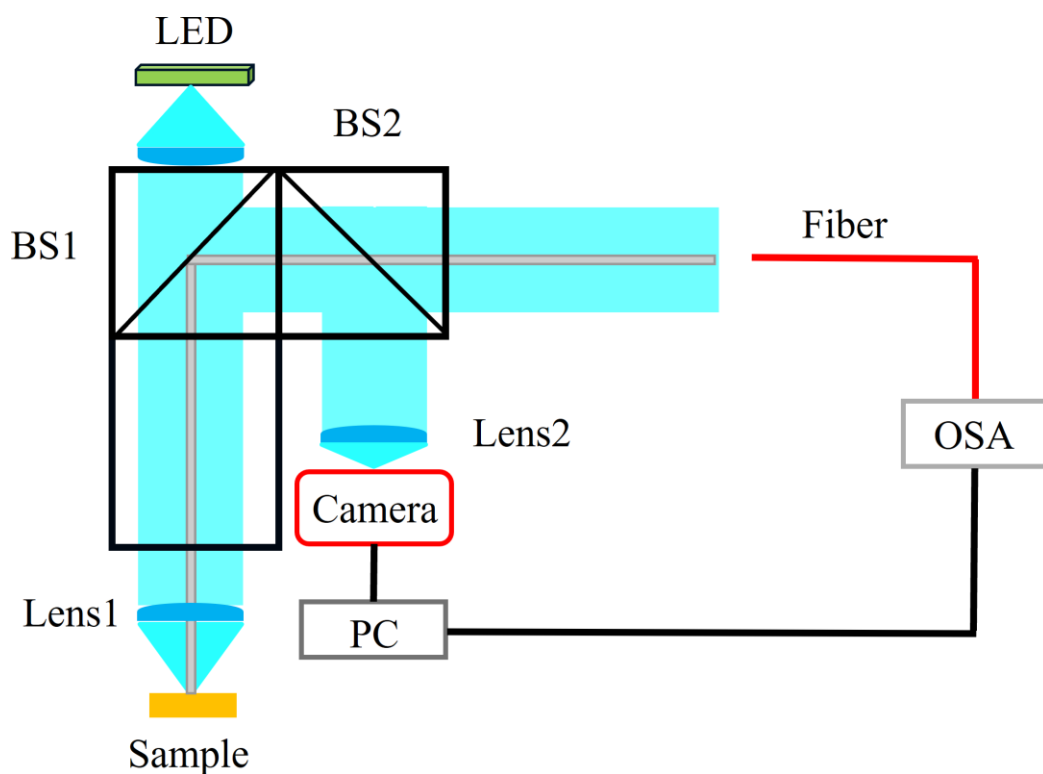


Fig. 5.8: Schematic illustration of the measurement apparatus for band-structure measurement.

Figure 5.9 presents the measured band-structure around the gamma point at $0.8x$ and $2x$ threshold current. With a sampling interval of $0.025\ \text{nm}$ and a resolution of $0.5\ \text{nm}$. The choice of an injection current at 0.8 times threshold current is to copy the measurement conditions used previously [18] [29]. The measurement results indicate that 3^{rd} peak is brighter than rest of the peaks. At 2 times threshold current, a higher scattered intensity of non-leaky mode of 3^{rd} peak is observed after the lasing. At Fig.

5.9(b), the disappearance of the leaky mode is due to the colour palette scaling and lasing occurring for the non-leaky mode of the 3rd peak after reaching threshold.

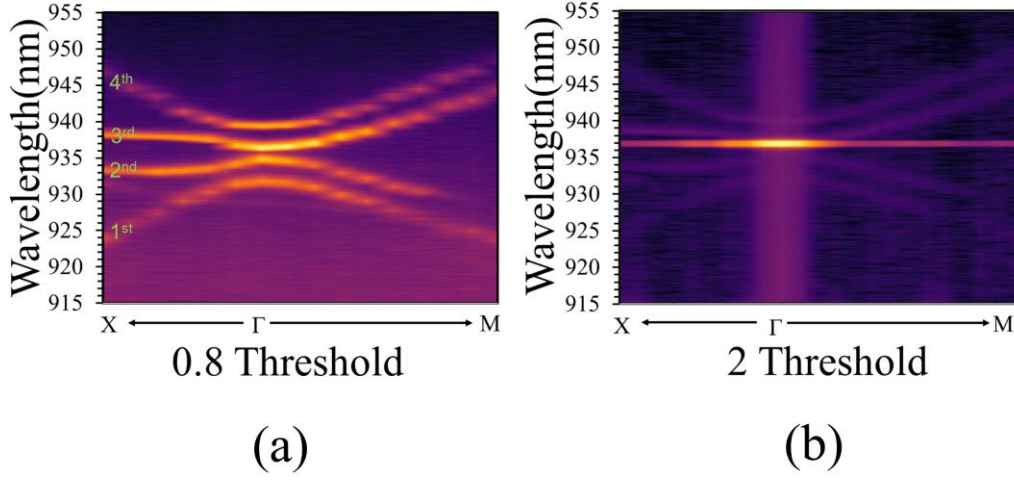


Fig. 5.9: The band-structure at 0.8x threshold and 2x threshold.

Figure 5.10(a) presents the simulation of band-structure around the gamma point using 2D-PWE for TE waves. The PC has a square lattice and isosceles right triangle atoms. This periodic refractive index distribution throughout the entire PC plane causes light waves to undergo in-plane mutual diffraction and 2D standing wave resonances are formed, resulting in the photonic crystal band-structure as shown in Fig. 5.10(a) [10]. At the band edge of the gamma point, high density of light states accumulated due to 2D resonance, and the group velocity of light becomes zero. [38] [39]. On the right side is the corresponding variation in threshold gain which is qualitative, which for each mode is determined by the total cavity loss. The mode with the lowest total loss and highest optical gain tends to have the lowest threshold current [30] [40].

As the wavelength separation of the modes is small in comparison to the gain spectrum width, the lasing mode is generally determined by the mode with the lowest losses. Fig. 5.10(b) presents the simulated in-plane electric field distribution of the fundamental resonant modes within the unit cell. The electric field distributions of the A and B modes are antisymmetric with respect to the atom. The phase of light emission in the vertical direction has a higher degree of partial cancellation with each other, leading to more destructive interference compared with the C and D modes, this cancellation will lead to lower emission intensity before threshold current is reached [41] [42] [43]. This lower loss also leads to non-leaky modes having lower threshold current [42] [44] [45] [46].

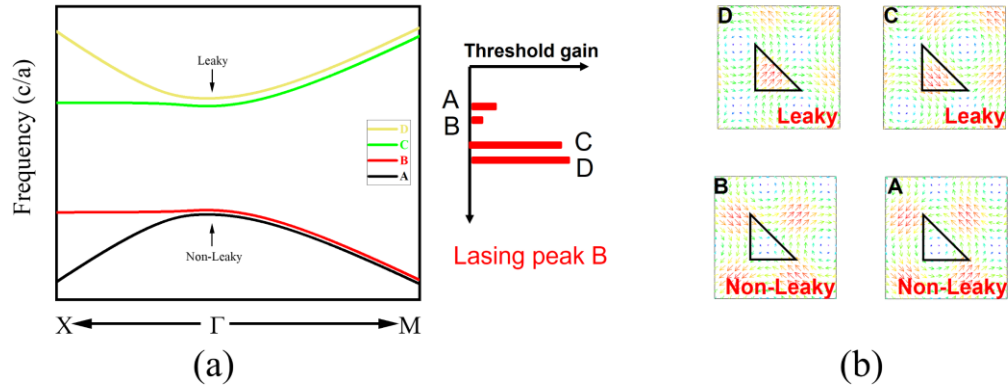


Fig. 5.10: (a) The simulated band-structure around the gamma point of a 2D photonic crystal, and a qualitative representation of their corresponding threshold gain. The band edges are labelled D, C, B and A in order of increasing wavelength. (b) The simulated in-plane electric field distribution for each band at the gamma point by 2D-PWE, the arrows represent the electric field vector in the photonic crystal plane. The length of the isosceles right triangle, denoted as L , is set to $0.2a$, where a represents the lattice period.

5.6 Current Dependent Band-Structure:

Figure 5.11 presents the spectrum at the gamma point as a function of current. The measurement apparatus is based on the band-structure measurement method as shown in Fig. 5.6(a). The raw spectrum is collected as a function of current at 2 mA measurement steps with an MMF at the gamma point, with a sampling interval of 0.008 nm and a spectral resolution of 0.05 nm. Four band edge modes at the gamma point were labelled 1st, 2nd, 3rd, and 4th in order of increasing wavelength. To clearly display the spectrum as a function of current, Fig. 5.11 only displays the spectrum at 10 mA steps. The result shows that the 3rd peak (non-leaky mode) becomes the lasing mode.

At an injection current of 50 mA, the peak intensity of the 3rd peak (non-leaky mode) has the lowest intensity compared with that of the rest of the peaks. As explained above, this mode experiences the lowest total loss at “cold cavity”, which corresponds to the lowest threshold gain and it is the first to reach lasing. The 4th peak (non-leaky mode) has higher intensity than the 3rd peak but lower intensity than the leaky mode. The 1st and 2nd peak are expected to have higher vertical emission intensity due to less destructive interference of the electric field.

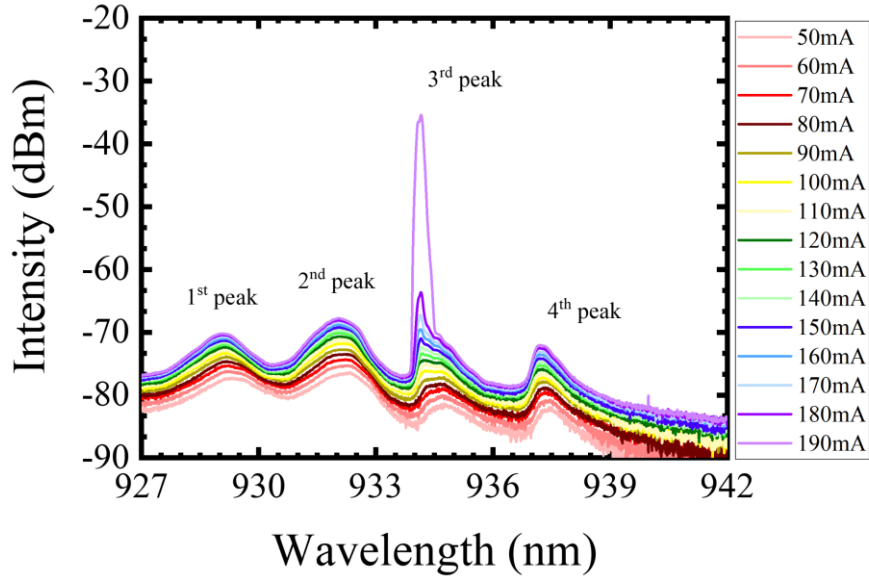


Fig. 5.11: The spectrum at the gamma point as a function of injection current in 10 mA steps.

Figure 5.12 presents the peak intensity as a function of current and the figure is plotted in log scale. The intensity of each peak increases as a function of current. As shown in Fig. 5.12, the peak intensity of the 1st and 2nd peak is higher than the 3rd peak below ~ 150 mA and ~ 168 mA and increases as a function of current. For the 3rd and 4th peaks, initially, similar peak intensities are observed and tend to increase as a function of current. After ~ 100 mA, the peak intensity of the 3rd peak becomes higher compared with the 4th peak and starts to increase superlinearly until it reaches the threshold current.

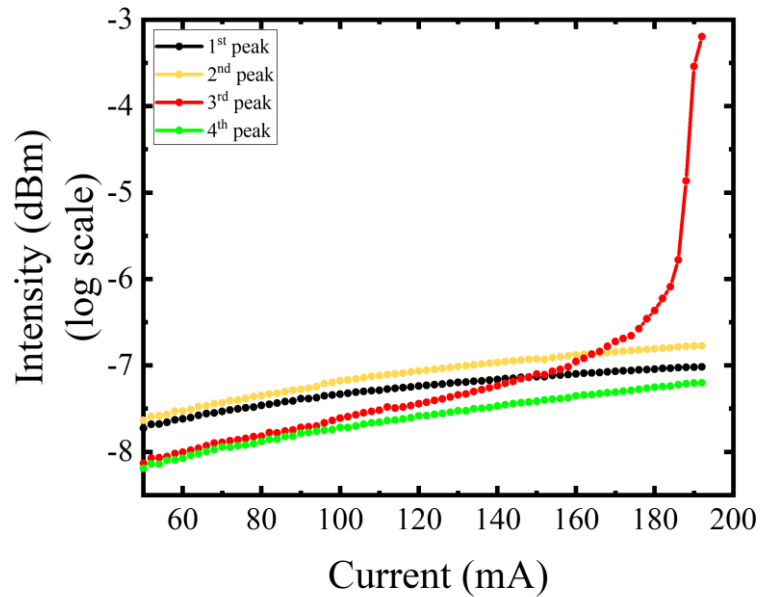


Fig. 5. 12: The graph of each peak intensity as a function of current.

Figure 5.13 presents the measured linewidth, and calculated Q-factor, and threshold of each mode at the gamma point, measured using the MMF as the collection optic, as a function of current.

For Fig. 5.13(a), the result shows that the linewidth of all modes decreases as the injection current increases, and the 1st and 2nd peak have a larger linewidth compared with the 3rd and 4th peaks. The linewidth of the 3rd peak is larger than that of the 4th peak when the injection current is below ~150 mA. When the injection current exceeds ~150 mA, the linewidth of the 3rd peak becomes smaller than that of the 4th peak. A clear change in linewidth for the 3rd peak (lasing mode) when the injection current below ~120 mA is observed. This makes the determination of the Q-factor and hence threshold impossible.

When the injection current exceeds ~150 mA, the linewidth of the 3rd peak exhibits a significant decrease up to ~176 mA and continues reducing until reaching the threshold. The reason for this S-shaped behaviour of the 3rd peak may be mainly attributed to superluminescence (amplified spontaneous emission) [47] [48] [49]. When net modal gain is positive, but below lasing threshold, superluminescence occurs. For such current densities, amplified spontaneous emission at the lasing resonance is preferentially emitted, reducing the linewidth. Figures 5.12 and 5.13 show this correlation between increasing peak intensity and reducing linewidth.

The Q-factor represents the quality factor describing the degree of optical confinement within the cavity [50], and it is given by the following formula [51].

$$Q = \frac{\lambda}{\Delta\lambda} \quad (5.2)$$

λ represents the centre wavelength and $\Delta\lambda$ represents the full width at half maximum of the resonant peak. As shown in Fig. 5.13(b), the 1st and 2nd peaks have the lowest Q-factor, and below ~150 mA, the 4th peak has the highest Q-factor. After ~150 mA, the Q-factor of the 3rd peak has the highest Q-factor. The threshold gains in Fig. 5.13(c) shows a similar trend to Fig. 5.13(a), after ~150 mA, the 3rd peak has the lowest threshold gain.

As mentioned in Fig. 5.10, the lasing mode will have the lowest total loss and the highest Q-factor. It will result in this mode having the lowest threshold gain compared with the rest of the modes, which leads to this mode lasing first. However, the result shows that the Q-factor of the lasing mode is smaller than that of the 4th peak, and the linewidth and threshold gain of the 3rd peak are larger than that of the 4th peak when injecting current below ~150 mA, which does not agree with expectation. It is also difficult to extract g_{th} at low current (less than 100-120mA) because the linewidth shows a slope.

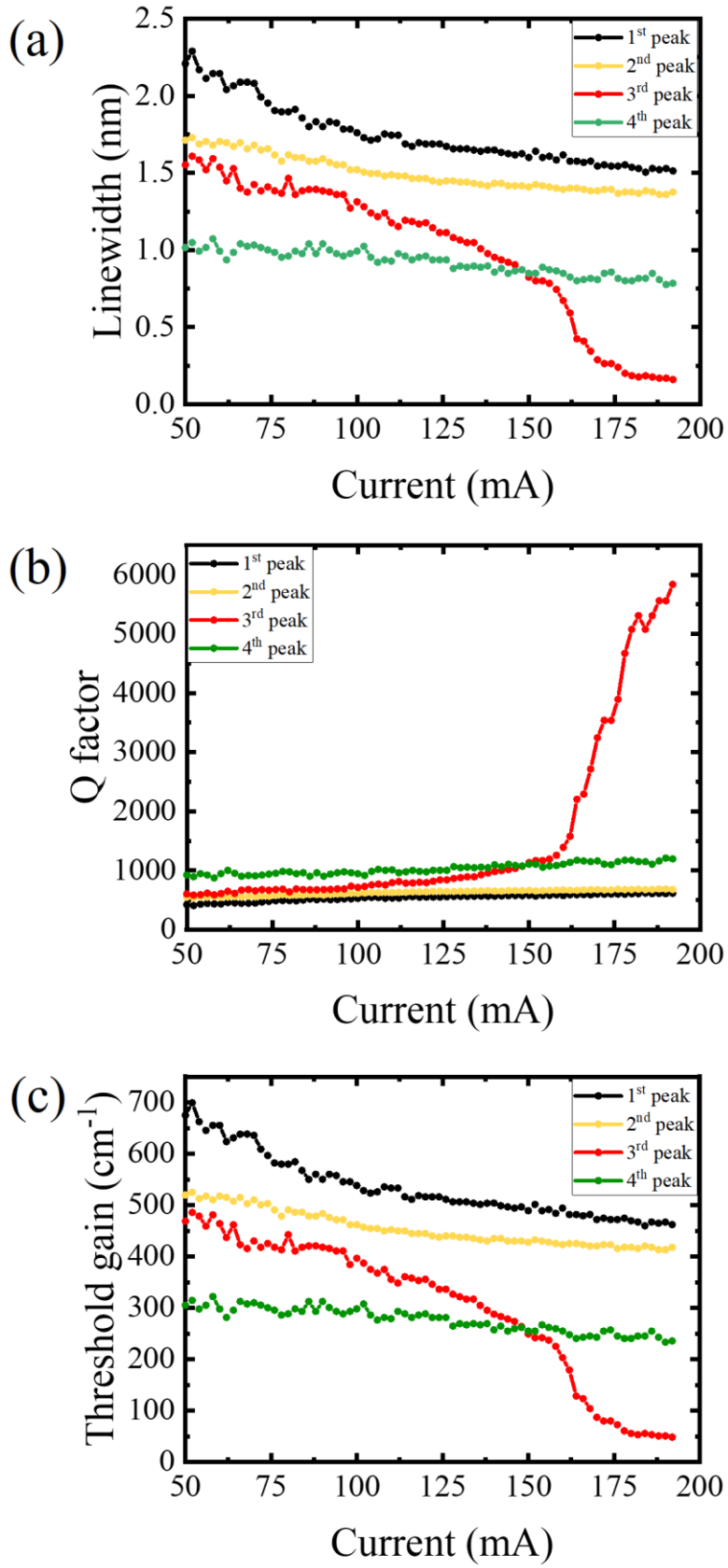


Fig. 5.13: The figure of each peak's (a) linewidth (b) Q-factor (c) threshold gain as a function of current with MMF.

There may be two reasons for the 3rd peak having larger linewidth compared with the 4th peak at “cold cavity” (~ 130 mA) [52] [53]. The first reason may be that during the measurement process, the collected wavevector Δk is determined by the fibre NA and the diameter of the fibre. Since the curvature of the band-structure around the gamma point is not zero, a large fibre diameter leads to higher order wavevectors being collected, which may be one of the reasons why the 3rd peak has a relatively larger linewidth compared with the 4th peak when the injection current is below ~ 150 mA. The details of this will be illustrated later in Fig. 5.14. The second reason may be due to imperfections in fabrication. The fabrication processes such as e-beam lithography, dry etching, and material can all be expected to have a spatial nonuniformity [54]. This can be device to device across the wafer, and within a single device. However, this would require the 3rd peak position to be more susceptible to these manufacturing variations than e.g. the 4th peak. This will be explored later.

Fig. 5.14 presents schematically the band-structure and the effect of different acceptance apertures having different Δk on the linewidth measurement. This can be practically achieved using an SMF to reduce the reception of higher order wavevectors.

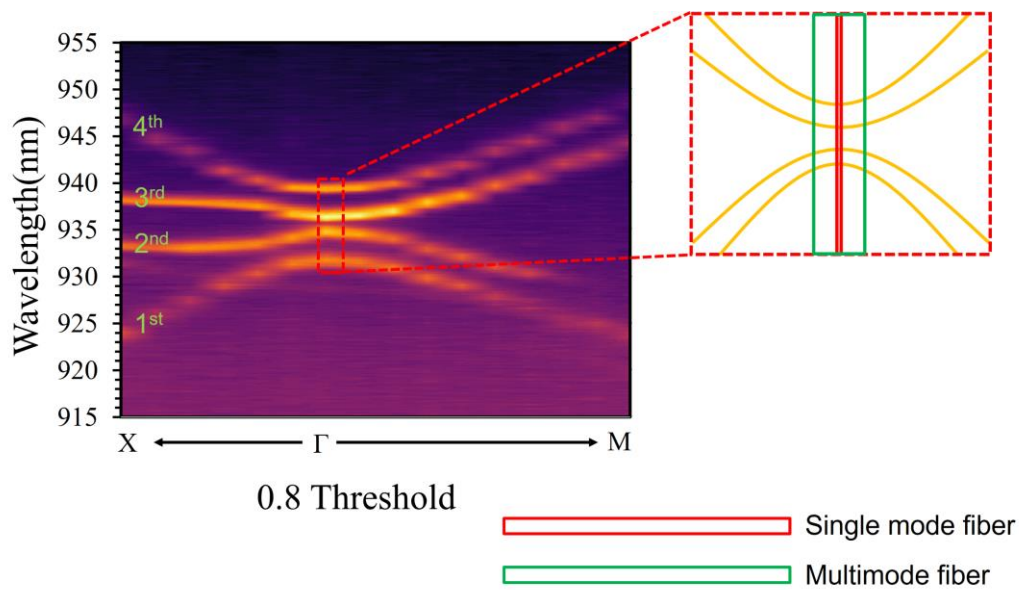


Fig. 5.14: A schematic of the band-structure and inset schematic of the expanded gamma point. Different aperture sizes, and hence spectral broadening are highlighted for the SMF (5 ± 0.5 μm diameter and NA of 0.13), and MMF fibre.

5.7 Current Dependent Band-Structure - Reducing High K

Collection:

Figure 5.15 presents a schematic of the band-structure measurement by replacing the MMF with SMF. Smaller diameters of the fibre core will reduce the collected higher order wavevectors as shown schematically in Fig. 5.14.

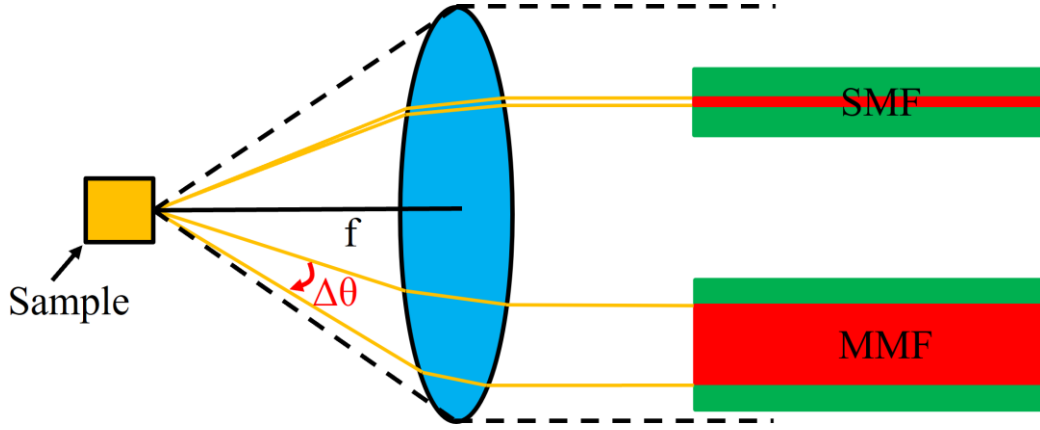


Fig. 5.15: Schematic illustration of the measurement apparatus for band-structure measurement by replacing MMF with SMF.

Figure 5.16 presents the spectrum at the gamma point as a function of current. The raw spectrum is collected as a function of current with 10 mA measurement steps using an SMF at the gamma point. Compared with the result of the MMF measurement, the use of the SMF reduces the collected signal significantly. For injection currents below 80 mA, the collected intensity is too weak to provide a sufficient signal-to-noise ratio, resulting in large error bars in the linewidth measurements. Since the main interest of this study is the linewidth variation in the current range of ~125–185 mA, the signal acquisition settings were not modified, and linewidth analysis below 80 mA was not performed.

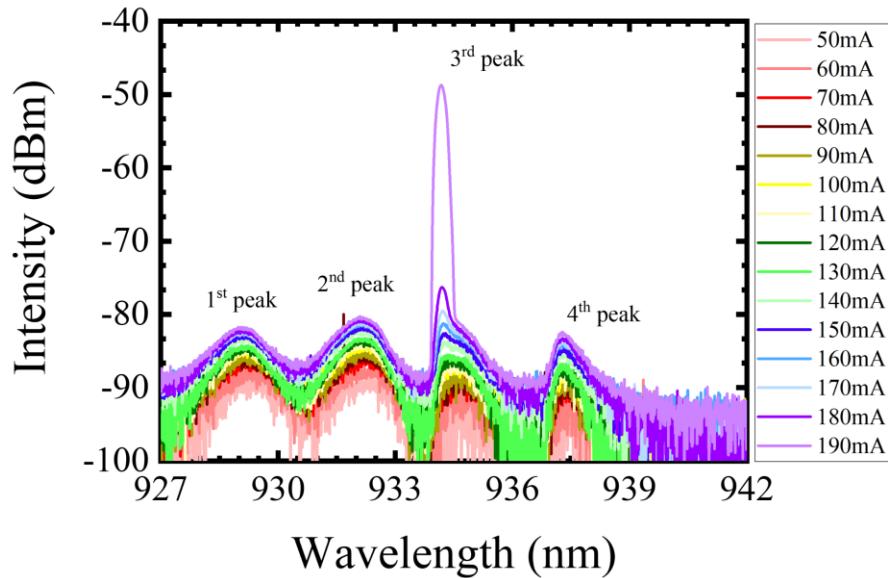


Fig. 5.16: The band-structure was measured by the SMF.

Figure 5.17 presents the result of the comparison between the linewidth using SMF (low Δk) and MMF (higher Δk) collection optics as a function of current. Compared with MMF measurement results, there is a clear difference in the linewidth of each peak.

The reduction of linewidth for each mode is observed in the SMF measurement results. For the 3rd peak of SMF measurement result, this reduction was not as great as that observed in MMF measurements. The result shows the influence of the collected wavevectors and indicates that more collected wavevectors will lead to a broader linewidth.

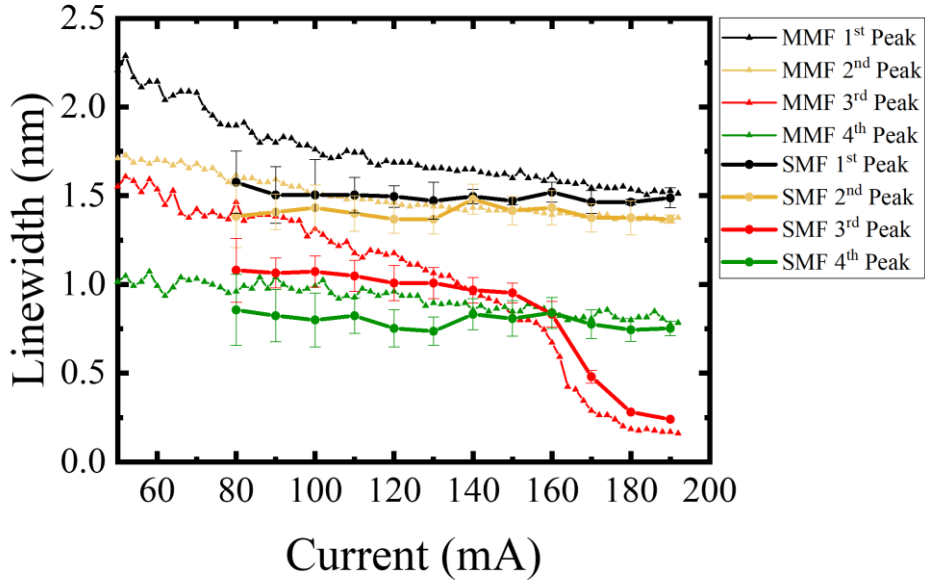


Fig. 5.17: The comparison between the linewidths of SMF and MMF as a function of current.

Figure 5.18 presents the measured linewidth, and calculated Q-factor, and threshold of each mode at the gamma point with SMF collection optics as a function of current. For Fig. 5.18(a), the result shows that the 1st and 2nd peaks have larger linewidth compared with 3rd and 4th peaks during the measurement process, and the linewidth tends to remain essentially constant as the injected current increases. For the 3rd peak, the linewidth tends to remain essentially constant when injection currents are below ~100 mA, and the linewidth will reduce when injection currents exceed ~100 mA. However, the linewidth of the 3rd peak is still larger than the 4th peak when injection currents are below ~160 mA. As superluminescence occurs, and the cavity becomes “hot” (injected current > ~160 mA), the linewidth of the 3rd peak becomes smaller than the 4th peak.

From the SMF collection optics results, different modes exhibit linewidth reduction to different degrees. These varying degrees of linewidth reduction are explained if the $\Delta\lambda/\Delta\kappa$ at the zone center differs among the modes. This variation is observed clearly in the band-structure measurement. However, the low wavevector (Δk) collection results indicate that the linewidth of the lasing mode still does not reach the lowest value of all four modes. This suggests that an estimate of threshold gain from this spectral data would be erroneous. The predicted threshold gain is $\sim 300 \text{ cm}^{-1}$, which is rather large for any GaAs based laser diode. [11] [55] This may indicate that the influence of nonuniformity in the photonic crystal structure should also be considered. To explore this, a spatially resolved band-structure measurement is carried out.

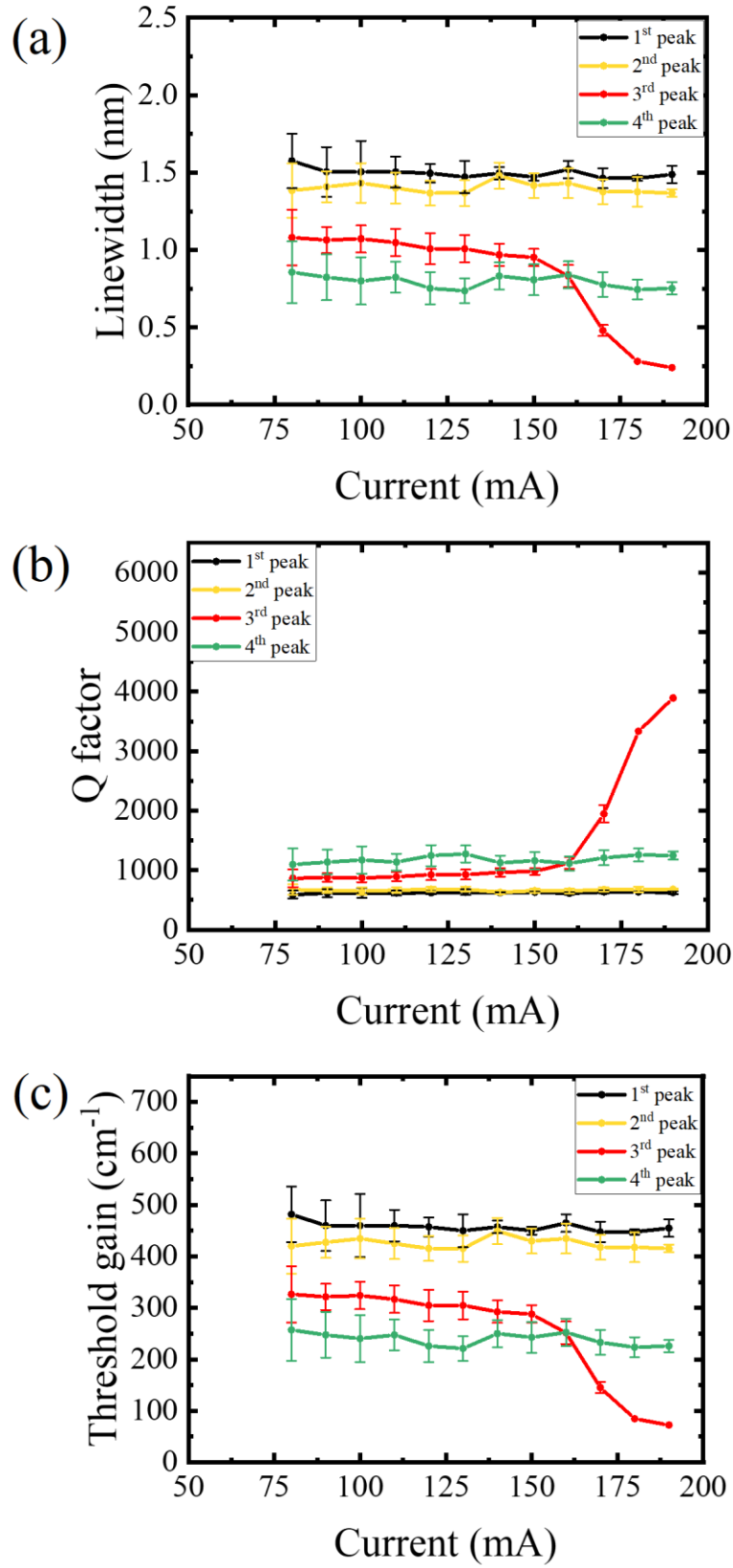


Fig. 5.18: Each peak's (a) linewidth (b) Q-factor (c) threshold gain as a function of current measured with SMF collection optics.

5.8 Spatially Resolved Band-Structure - Confocal System:

Figure 5.19 schematically presents the spatially resolved band-structure measurement method. BS1, BS2, BS3, BS4(Thorlabs CM1-BP108) are pellicle beam splitters which reflect $\sim 8\%$ of the collimated light in the perpendicular direction for imaging. Lens 1 and Lens 2(Thorlabs LA1027-B) are anti-reflection (AR) coated aspheric lenses with a numerical aperture (NA) of 0.51. Lens 3 (Thorlabs LA1131-C) is an anti-reflection (AR) coated aspheric lens with a numerical aperture (NA) of 0.48.

The blue line represents LED illumination, and the grey light represents the emitted light from the sample. The sample is located at the focal point of Lens 1. After the emitted light passes through two beam splitters (BS1, BS2), $\sim 80\%$ will remain, and Lens 2 is employed to focus this collimated light. The camera 1 is employed to give a clear view of sample surface.

The image of the sample is located at the focal point of Lens 2 and is the same size as the sample. A pinhole with a diameter of $\sim 50 \mu\text{m}$ is adopted in this work to achieve spatially resolved function and is placed at the focal point of Lens 2. The pinhole is positioned at the highest intensity of the image and is also placed at the focal point of Lens 3. $\sim 80\%$ of the light will remain after passing through the remaining two beam splitters (BS3, BS4). Camera 2 is employed to gives a clear view of the pinhole surface. A MMF is placed at the highest intensity point of the plane and collects the light into the OSA to record the spectrum.

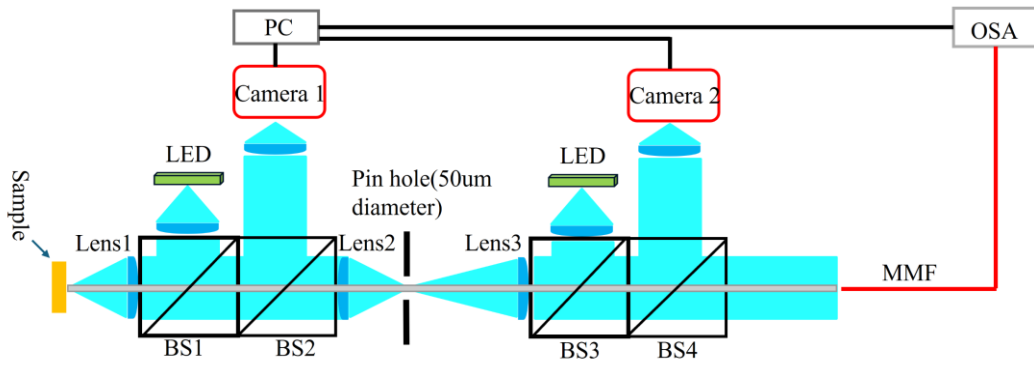


Fig. 5.19: Schematic illustration of the apparatus for the pinhole spatially resolved band-structure measurement.

Figure 5.20 presents a schematic of the sampled area with a microscope image of the PCSEL device. Since the diameter of the pinhole is $\sim 50 \mu\text{m}$, the sampled area will be the same size as the pinhole. The rest of the area will be blocked by the pinhole plane, which is used to achieve spatially resolved measurements. The sampled area occupies $\sim 1.77\%$ of the emission area. The raw spectrum is collected as a function of current.

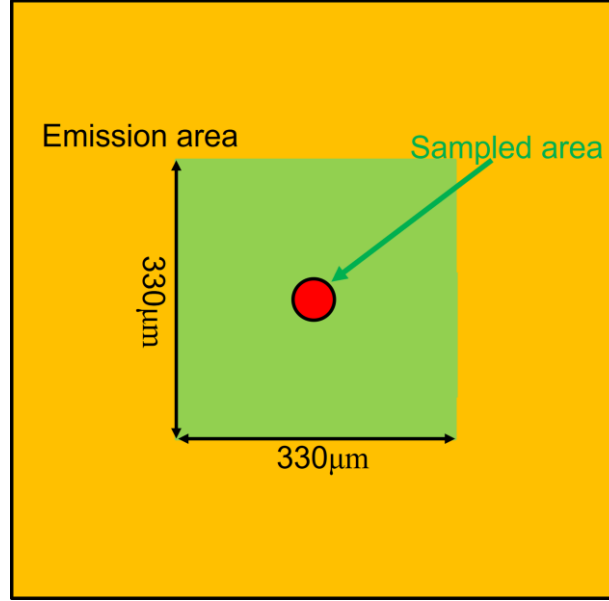


Fig. 5.20: Schematic illustration of sampled area with a microscope image, the emission area is a $330 \times 330 \mu\text{m}$ square.

Figure 5.21 presents the measured linewidth, and calculated Q-factor and threshold gain as a function of current. Since the pinhole will block most of the emission power, the collected power will therefore be reduced. For currents below 80 mA, for which it is hard to effectively measure the emission spectrum, no analysis for the 3rd and 4th peaks is possible. This is also true for the 1st and 2nd peaks at injection current below 135 mA. In Fig. 5.21(a), the 1st and 2nd peaks have larger linewidths as compared with the 3rd and 4th peaks. For 3rd peak, instead of exhibiting a broader linewidth than the 4th peak at currents below ~ 125 mA, the 3rd peak now emerges at the zone center with the lowest linewidth value of all 4 modes. The linewidth is reduced from ~ 125 mA until it gets close to the threshold current at 186 mA. A high rate of linewidth reduction is observed between ~ 125 mA and ~ 160 mA. This change in linewidth has the same impact for the calculated threshold gain, the lasing peak has the lowest threshold gain as expected, and the Q-factor of the lasing peak has the largest value of all 4 modes.

Since the pinhole only allows the emission from the sampled area to pass through, the influence of inhomogeneity on the linewidth is reduced, which in turn reduces the linewidth of the 3rd peak. The linewidth remains essentially constant when injection current is below ~ 125 mA and this provides an estimate of the threshold gain $\sim 110 \text{ cm}^{-1}$. The results show that for this sample, the impact of inhomogeneous photonic crystal structures on the linewidth is a critical factor.

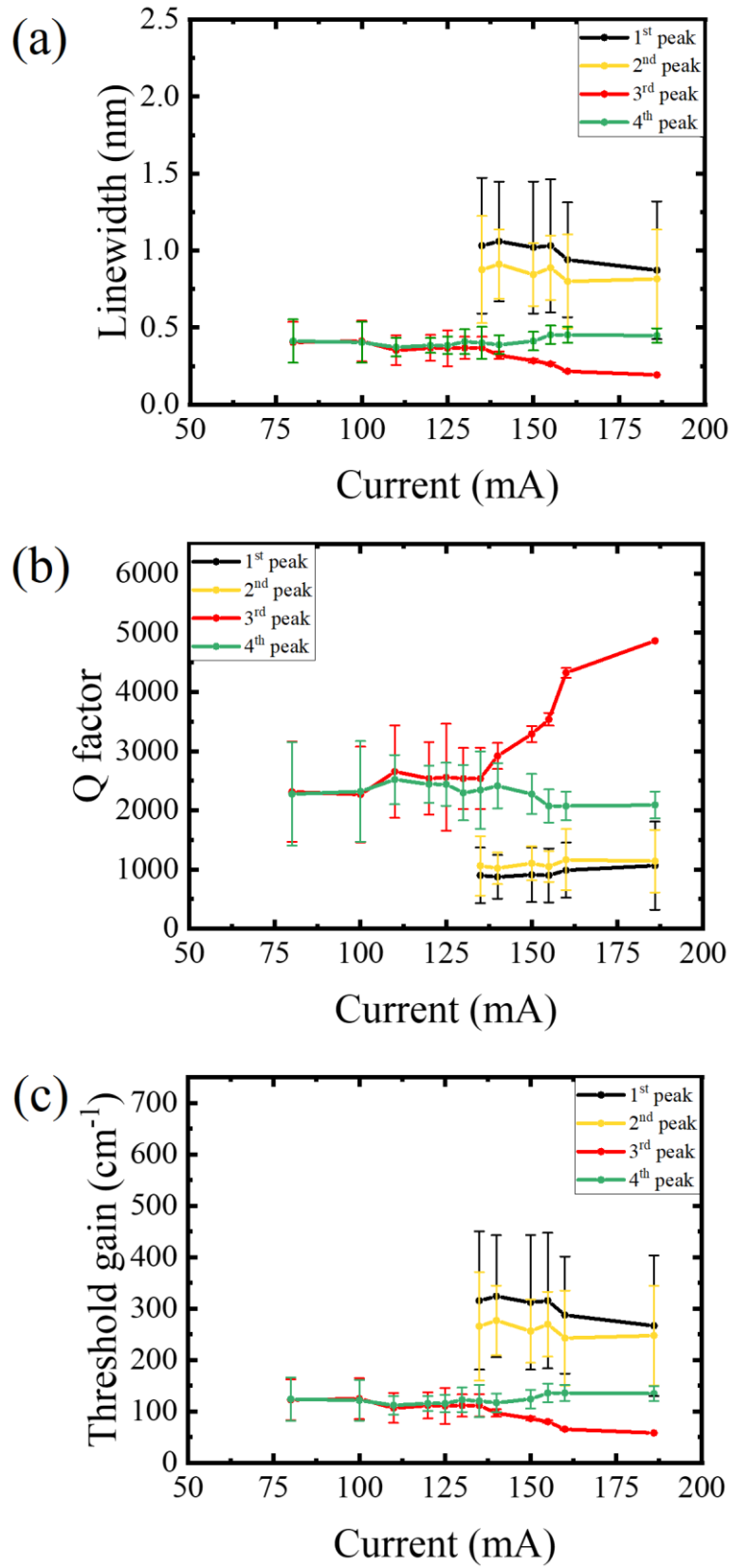


Fig. 5.21: Each modes gamma-centre peak's (a) linewidth (b) Q-factor (c) threshold gain as a function of current using the confocal system with MMF collection optics.

Figure 5.22 presents the comparison of linewidth with different measurement methods. The result indicates that after using confocal system with MMF, the linewidth of each peak gradually declines. Finally, the lasing peak has the lowest linewidth.

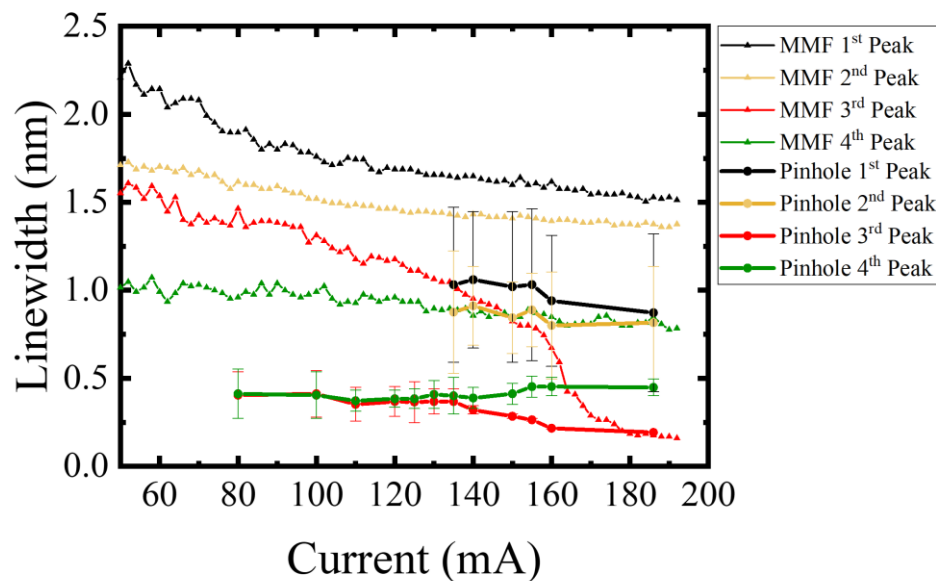


Fig. 5.22: The comparison between the linewidths of MMF and confocal system as a function of current.

Then, to explore the influence of inhomogeneity on wavelength variation, the next step is to map the photonic crystal area through a pinhole at a current just below threshold (186 mA). The resolution of the OSA is relaxed from 0.05 nm to 0.2 nm to allow more rapid data acquisition. The position of the pinhole was moved from -X to +X and from -Y to +Y in 50 μm steps. The center point, where the X and Y scans intersect, corresponds to the highest intensity point after the emitted light is collimated by Lens 3. During the mapping process, the MMF was kept in the same position.

Figure 5.23 presents the mapping process and the corresponding spectrum in the X and Y direction. The result shows that the center point has the highest intensity and tends to reduce when the pinhole moves toward the edge. During this process, the peak wavelengths exhibit shifts, the 1st and 2nd peaks tend to undergo a blue shift, while the 3rd and 4th peaks experience a red shift as the pinhole moves from the center toward the edge of the device.

At the edge of the mapping range, the intensity of the 3rd peak tends to decrease. This can be explained as follows. Conventionally, the in-plane loss can be minimized, and a large portion of light can be confined within the PC region for a high coupling coefficient [30] and a large area [56]. The surface emission intensity will tend to be higher at the center and lower at the edge of the device in the near field [30].

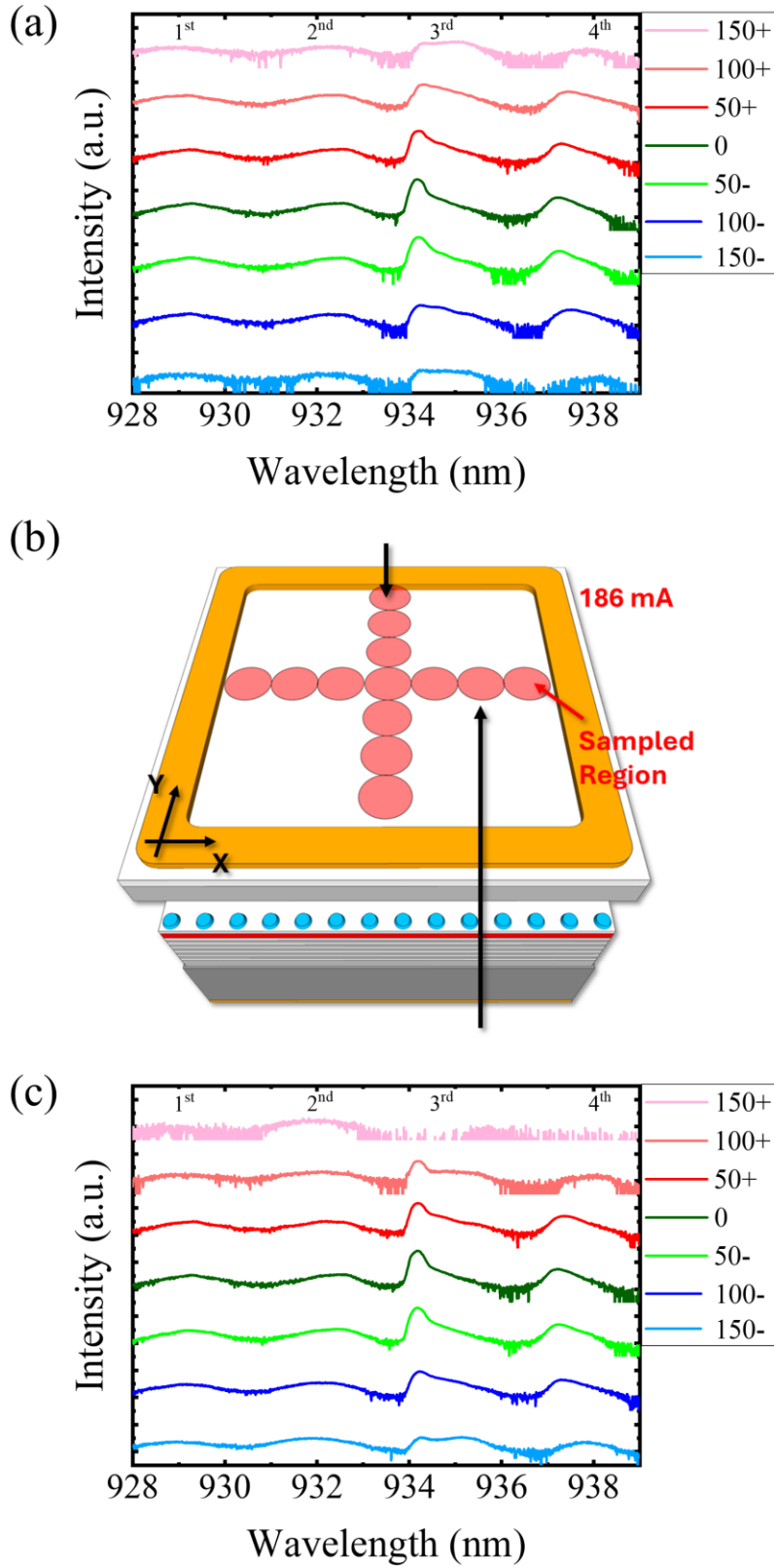


Fig. 5.23: Spatial mapping of PCSEL emission at 186 mA, showing the corresponding spectra in both directions. (a) The spectrum in the Y direction. (b) The red dot represents the position of the pinhole, measured in 50 μm steps. (c) The spectrum in the X direction.

5.9 Spatially Resolved Band-Structure -Image Plane:

An alternative way to implement the spatially resolved band-structure is through the measurement of the magnified image of the sample. Fig. 5.24 presents the apparatus for spatially resolved band-structure measurement for x4 magnification. BS1, BS2, (Thorlabs CM1-BP108) is a pellicle beam splitter which reflects $\sim 8\%$ of the collimated light in the perpendicular direction for imaging. Lens 1 and Lens 2 (Thorlabs LA1027-B) are anti-reflection (AR) coated aspheric lenses with a numerical aperture (NA) of 0.51.

In Fig. 5.24, the blue line represents the LED illumination, and the grey light represents the emitted light from the sample. The apparatus is based on two lens systems to achieve a magnification function. The sample is located away from the focal point of Lens 1. After the emission passes through two beam splitters, $\sim 80\%$ of the power will remain, and Lens 2 is employed to focus the emission light again. A MMF is placed away from the focal point of Lens 2 located at the image plane, where the image of the sample has 4 times magnification. The collected signal will be transferred to the OSA to record the spectrum. Since the MMF is placed directly on the image plane, the fibre only occupies $\sim 0.17\%$ of the sample's emission area. Whilst the area of collection is only a small component of the signal intensity, an increased signal strength can be expected in this case (all light within the NA of the fibre), as opposed to the case for the incident plane wave in the case of the standard measurement (MMF or SMF above). It is also expected that this measurement collects essentially all emitted angles, within the acceptance angle of the fibre (~ 16 degrees).

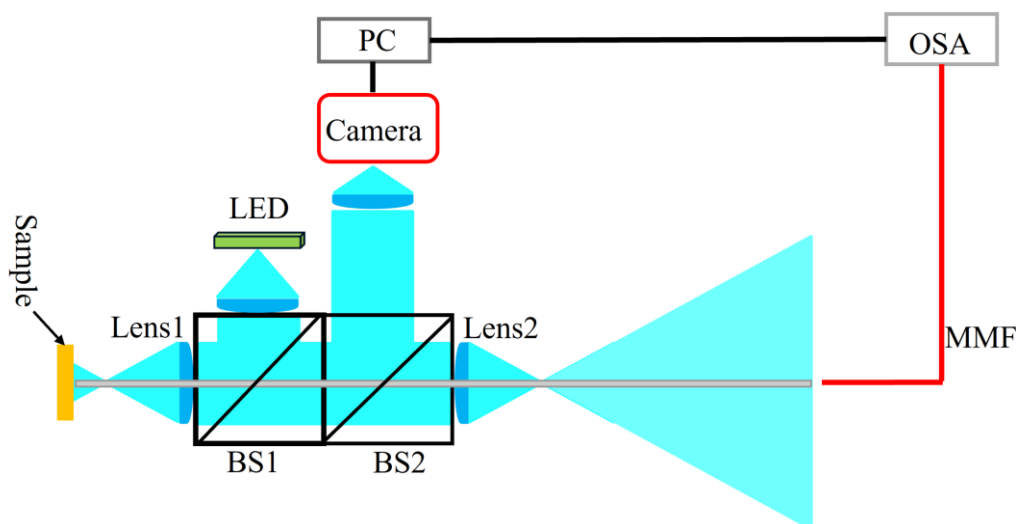


Fig. 5.24: Schematic illustration of the measurement apparatus for spatially resolved band-structure measurement under 4 x magnification using an MMF.

Figure 5.25 presents the spectrum at the highest intensity point as a function of current. The raw spectrum was collected in 2 mA steps. To clearly display the spectrum as a function of current, Fig. 5.25 only displays the spectrum in 10 mA steps. An increased signal intensity was observed, and is discussed later.

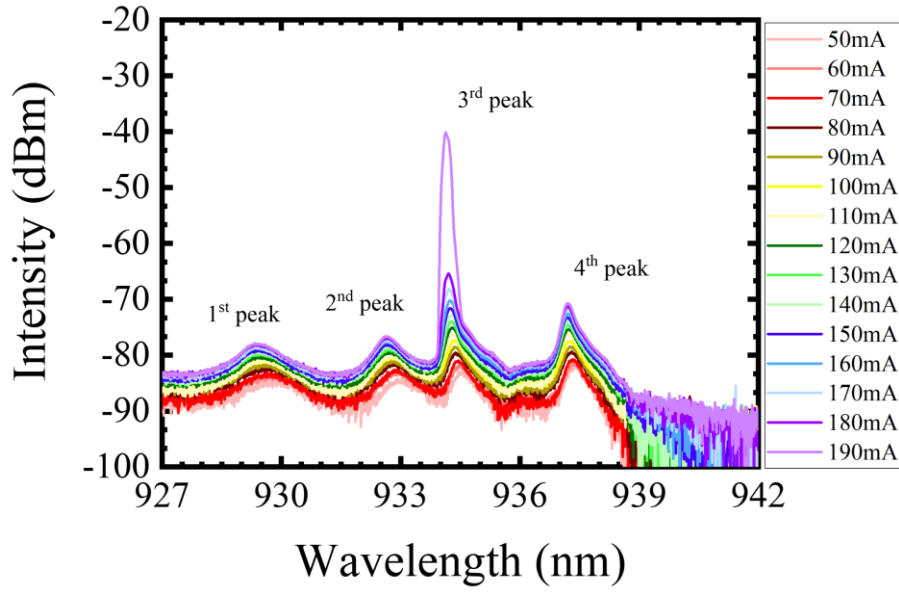


Fig. 5.25: The spatially resolved band-structure spectrum was measured through 4 $\times$ magnification using an MMF.

Figure 5.26 plots the linewidth of each peak as functions of injection current, obtained via spatially resolved band-structure measurements by using an MMF under 2- and 4-times magnifications, measured at the highest intensity point in the image plane. As expected, the higher magnification system has a correspondingly lower power signal. The measured linewidth is not quantitatively useful in this case as a measure of photon lifetime. Referring back to the previous “standard” measurement, some linewidths are reduced, while some remain unchanged or increased. This is attributed to the different curvature of the band-structure. However, the relative change of the spectra elucidates the scale of inhomogeneity within the PCSEL. The linewidths of all bands are essentially identical for all currents, indicating that the characteristic length scale of PC inhomogeneity is less than the areas interrogated here ($\sim <30 \mu\text{m}$). This is in line with the observation for the $50 \mu\text{m}$ confocal system described previously.

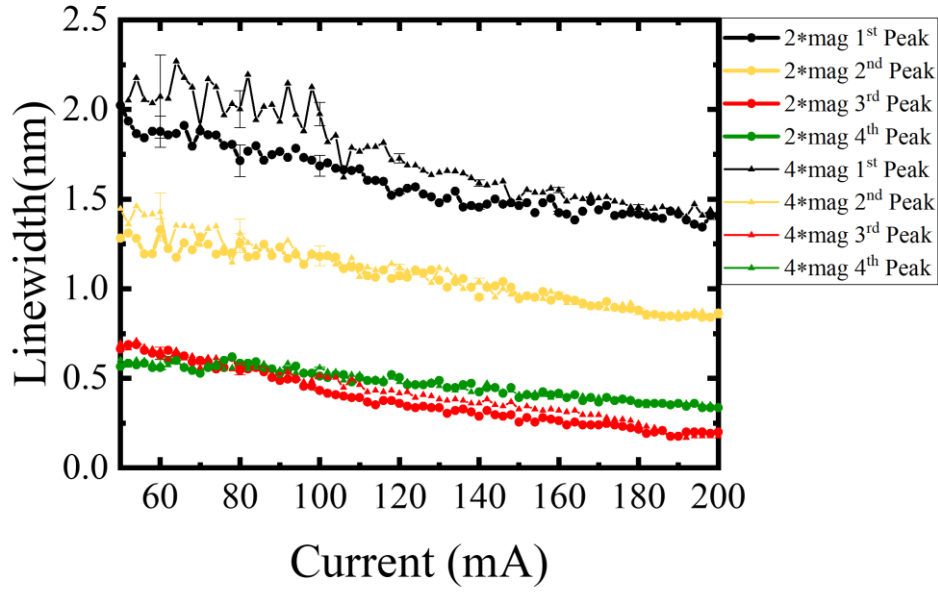


Fig. 5.26: The comparison between the linewidths of $2 \times$ and $4 \times$ magnification as a function of current.

The high throughput (described in the summary section) lends itself to the more rapid mapping of the PCSEL as a function of current.

Figure 5.27 and Fig. 5.28 present spatially resolved mapping of the x4 magnified image of the sample using MMF collection at a series of currents below threshold. The MMF position is scanned from $-X$ to $+X$ and from $-Y$ to $+Y$ in $60 \mu\text{m}$ steps (the fibre diameter). The central point, where the X and Y directions overlap, corresponds to the highest intensity position on the image plane.

As current is increased towards threshold, the lasing mode peak wavelength map indicates a reduction in variation across the PCSEL as lasing is approached. The lasing mode peak wavelength is also shown to reduce as the current is increased. The measured linewidth of the lasing mode is also observed to become smaller and more similar as lasing is approached. This preliminary mapping begins to illustrate the formation of a large area stable mode as lasing begins. As superluminescence occurs, so the PCSEL active element transitions from opaque (no long-range communication) to transparent, where long range communication is possible. This illustrates the change from many isolated microlasers to a single large area stable optical mode.

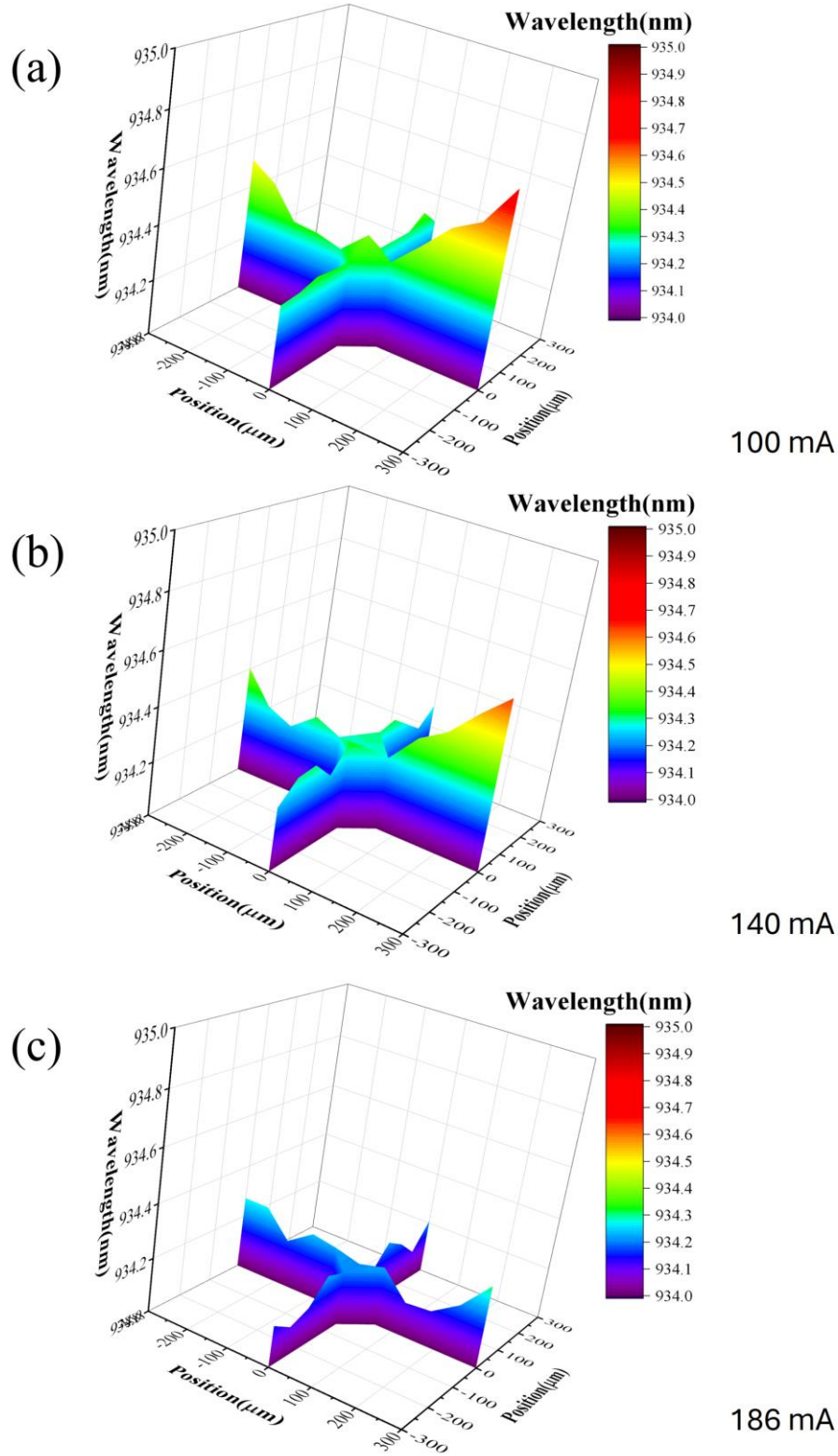


Fig. 5.27: Schematic illustration of the mapping process with MMF. The corresponding wavelength of the 3rd peak in the X and Y directions. (a) 100 mA. (b) 140 mA. (c) 186 mA.

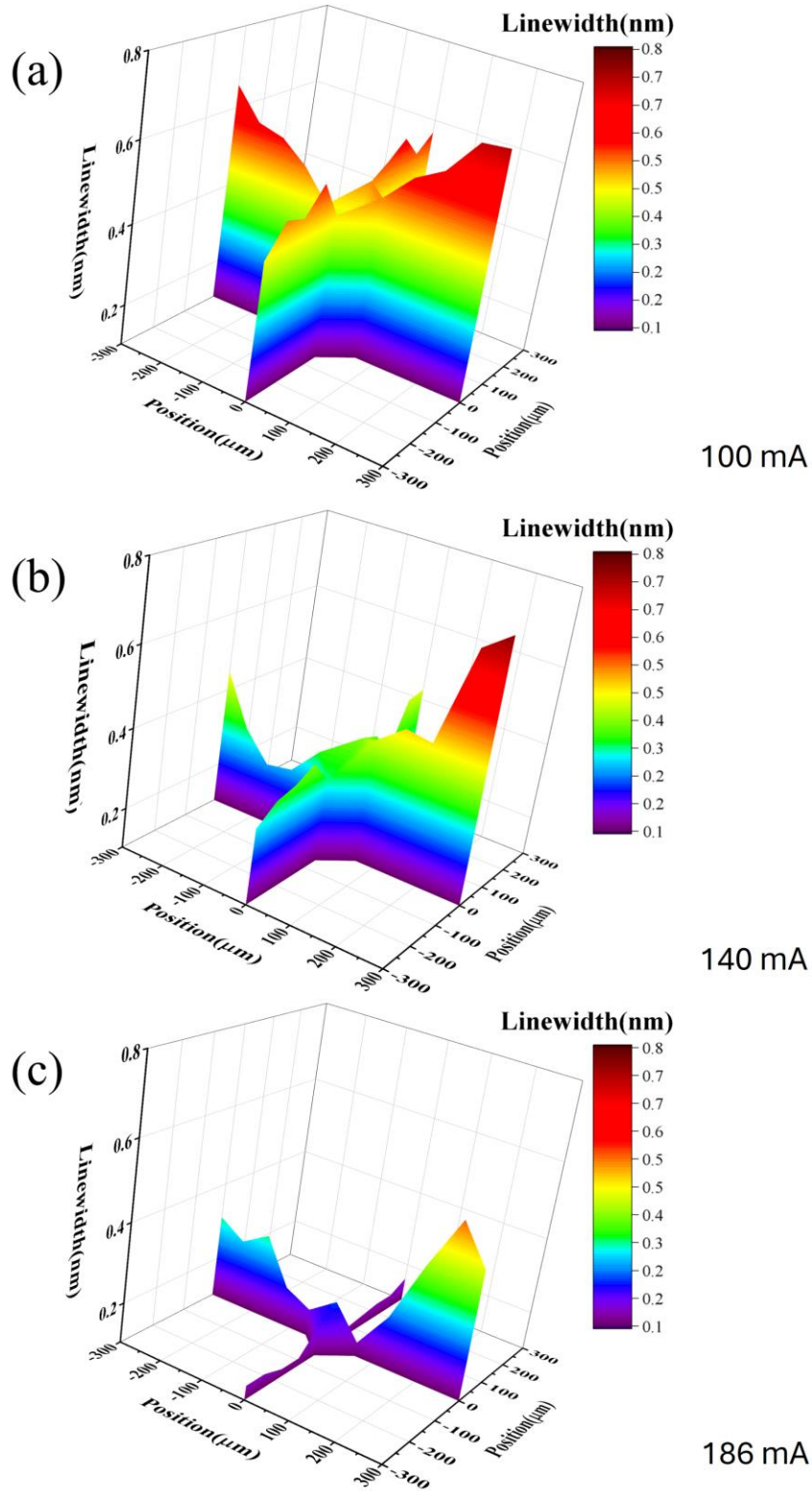


Fig. 5.28: Schematic illustration of the mapping process with MMF. The corresponding linewidth of the 3rd peak in the X and Y directions. (a) 100 mA. (b) 140 mA. (c) 186 mA.

5.10 Polariser Dependent Measurement:

Figure 5.29 presents the measurement apparatus to carry out polarisation dependent measurement. BS1, BS2, (Thorlabs CM1-BP108) is a pellicle beam splitter which reflects $\sim 8\%$ of the collimated light in the perpendicular direction for imaging. Lens 1 (Thorlabs LA1027-B) is an anti-reflection (AR) coated aspheric lens with a numerical aperture (NA) of 0.51.

The blue line represents the LED illumination, and the grey line represents the emitted light from the sample. The sample is located at the focal point of Lens 1, ensuring that the emitted light is collected and collimated by Lens 1. After the emitted light passes through two beam splitters, a polariser (extinction ratio >1000) is placed in front of the MMF to enable polarisation dependent emission spectra to be obtained. The MMF then collects the filtered light and delivers the signal to the OSA for spectral recording.

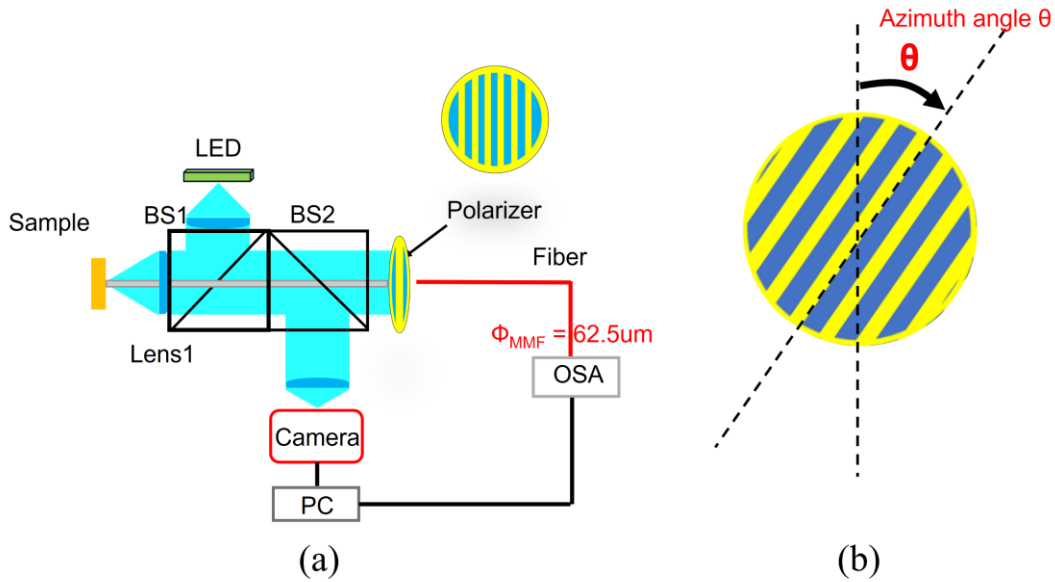


Fig. 5.29: (a) Schematic illustration of the measurement apparatus for polariser dependent measurement. (b) The definition of the azimuth angle θ during the rotation process.

To display the variation of each mode as a function of polariser rotation angle, the MMF was placed at the gamma point. The spectra were measured with a polariser rotated from 0° to 180° in regular angular increments. The injection current was set at 186 mA and increased to 192 mA. The corresponding heat map of the measurement results under 186 mA and 192 mA is shown in Fig. 5.30 (a) and (b).

Since the polariser only allows the direction of electric fields that align with its transmission axis to pass through, the power of the collected signal will be reduced after adding a polariser. When the direction of the main component of the electric field is aligned with the transmission axis of the polariser, the collected signal will reach its

maximum. Fig. 5.30(a) and Fig. 5.30(b) illustrate the variation of each mode with polariser rotation.

The results show that the trend is similar for the 1st and 3rd peak. When the polariser is rotated from 40° to 130°, a sequential increase in the emission power of the 1st and 3rd peaks is observed, with the highest intensity at 130° and the lowest at 40°. The 2nd peak and the 4th peak have similar trends, but they have the highest intensity at 40° and the lowest intensity at 130°. The main reason is that the polarisation direction of each peak in the near field is different, and the far field is the Fourier Transform of the near field. From Fig. 5.10(b), the remaining non-cancelled electromagnetic fields of the D and B peaks within the atom exhibit similar orientations for vertical emission, resulting in the same polarisation direction for both peaks. The result indicates that the angular difference between the highest intensity and the lowest intensity is 90°. When considering the electric field distribution within the unit cell for the 3rd peak in Fig. 5.10(b), only the electric field component oriented at 45° remains uncanceled, enabling emission in the vertical direction. Since the far field is just a Fourier transform of the near field, when the direction of the polariser is aligned with the 45° orientation, the maximum intensity will be detected, and the lowest intensity will be detected when the direction of the polariser is perpendicular to the 45° orientation.

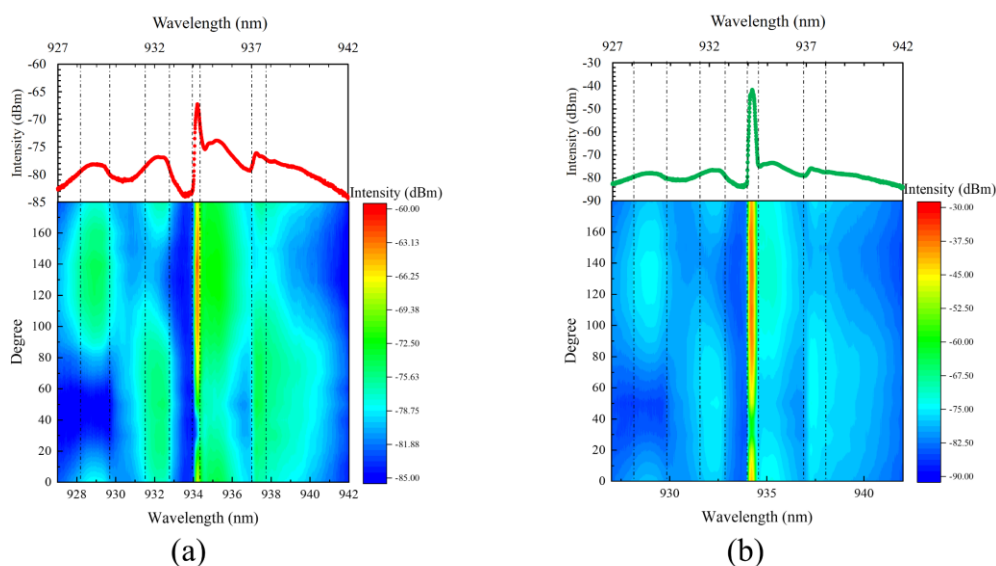


Fig. 5.30: (a) The intensity map of the polarisation dependent emission spectrum as a function of polariser rotation from 0° to 180° at a drive current of 186 mA. The top panel shows the spectrum recorded at 0°. (b) The intensity map of the polarisation dependent emission spectrum as a function of polariser rotation angle from 0° to 180° at a driving current of 192 mA, with the top panel displaying the spectrum at 0°.

5.11 Conclusion:

In this chapter, a brief introduction to different measurement methods was presented, in addition to the LIV characteristics of the devices.

The band-structure measurement apparatus was introduced. The band-structure measurements at 0.8x and 2x the threshold current were presented, and the simulation was also presented. The details of the current-related measurement with high Δk collection (MMF) were presented, and compared with those using very small Δk collection (SMF). The results from both methods indicate that the lasing mode does not have the lowest linewidth and highest Q-factor among all 4 modes, which is contrary to expectation, suggesting the measurement requires more detailed study.

A confocal spatially resolved band-structure measurement setup was introduced, along with current dependent measurement using high Δk collection due to the small signal throughput. These results indicate that the estimated threshold gain is $\sim 110 \text{ cm}^{-1}$. After applying the linewidth ratio between the MMF and the SMF (~ 1.3) previously obtained, it is expected to estimate the threshold gain to be $\sim 85 \text{ cm}^{-1}$. Spatial mapping along the X and Y directions reveals the influence of PC inhomogeneity.

An image plane spatially resolved band-structure measurement setup was then introduced and current dependent measurement with high Δk collection at 2- and 4-times magnifications was presented. As shown in Tables 5.2, the high throughput is beneficial for rapid mapping of the PCSEL, although the measured linewidth is not quantitatively useful in this case as a measure of photon lifetime. Nevertheless, it enables qualitative comparisons, suggesting that the characteristic length scale of inhomogeneity is less than $\sim 30 \text{ }\mu\text{m}$, indicating that the $50 \text{ }\mu\text{m}$ pin-hole measurement may be suitable to eliminate inhomogeneous effects. The mapping results reveal how the PCSEL evolves a large optical mode composed of many small would-be lasers as lasing begins.

Table. 5.2: The corresponding measurement signal strength at the highest intensity point during the band-structure measurement process.

Measurement	Relative Signal Strength
Zone Centre MMF	1
Zone Centre SMF	0.037
Confocal MMF	0.014
x2 Image MMF	1.471
x4 Image MMF	0.717

The polariser-dependent measurement apparatus was introduced, and the polarisation property of the device was presented.

5.12 Discussion & Future Work:

This chapter has focus on gaining quantitative data ($\Delta\lambda$, Q-factor, Gth). It has also looked at collected wavevector Δk effects, finite sample size effects and inhomogeneity effects.

This work showed that the drive current must be carefully considered if quantitative information is to be extracted. Many reports show lasing band to be brighter than other zone centre bands [10,11,16,20,21,24,26-28]. This lowest leakage mode should have the lowest intensity in the case of a cold cavity. The observation of a bright non-leaky band, that will become the lasing band is gain in the cavity leading to superluminescence. Such data therefore invalid for Q-factor or threshold gain estimations.

It has been shown that the collected wave-vector impacts the spectral linewidth and hence quantitative analysis. Table 5.1 indicates the general absence of such details in the literature. Details of the collection of optics and the effects of the collected wavevector Δk on $\Delta\lambda$ need to be considered for the band-structure to have quantitative value.

Finally, for the sample used here, inhomogeneity was shown to have a significant impact which to the best of my knowledge has not been considered in any previous report.

Overall, in future work, the signal collection needs to be enhanced. For example, multi-channel detection can be used, which should allow shorter measurement times and improved signal stability.

For the case of confocal mapping, detailed analysis for the entire area would allow the influence of inhomogeneity to be explored. Samples with a deliberate change in PC shape or period would be interesting to study, and enhanced signal strengths would allow a direct measurement of threshold gain rather than an estimate as the Δk collection area and device sampling area could be made arbitrarily small.

For the image-plane band-structure measurement, the use of an SMF would allow very high spatial resolution but this not expected to provide any benefit in terms of very high Δk collection. As the peak position would be sensitive to temperature and refractive index change in the PCSEL, it may be a very powerful tool in engineering large area PCSELs where differences in local temperature and current injection [54][57][58] may be important.

For the polarisation dependent measurement, some simulation work is required to compare and check the simulation results and measurement results of the far field polarisation. It would be interesting to check samples with different PC designs which may have different polarisation characteristics.

5.13 Reference

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Chapter 6. Conclusion

For this thesis, the main research focus was on the characterisation of photonic crystal surface emit lasers (PCSELs) devices and materials.

Chapter 2 reviewed the basic background knowledge about the laser diode. This was followed by the key definitions of period, filling factor, coupling theory and band structure in photonic crystal. PC engineering is introduced for PCSELs.

Multi-wavelength sources are widely used in many laser applications, such as wavelength-division multiplexing (WDM) in optical communication systems. For multiwavelength PCSEL arrays, the multiwavelength functionality is typically achieved by using a common active region and adjusting the photonic crystal lattice constant. Chapter 3 presented the detailed characterisation of InGaAs/GaAs quantum wells which were grown by 2D SAG. Micro-photoluminescence measurements and white light interferometry profiling were used to analyse the emission wavelength and GRE. The result demonstrated that a total 86 nm wavelength shift and over 100 μm size of uniform area were achieved. The observed symmetric GRE suggests that anisotropic effects in the material growth kinetics are negligible during the growth process. The results showed the potential of application of 2D SAG technology into high efficiency PCSEL arrays.

Chapter 4 presented the detailed characterisation processes for operating parameters of REPCSELs (and their associated PCSELs). The result show that a reduction in threshold current and an increase in slope efficiency were observed for the 400 μm sized REPCSEL. For 200 μm sized PCSELs and REPCSELs, the LI results show that no PCSEL device showed lasing behaviour up to 1.1 A, whilst the REPCSEL demonstrated a threshold of 324 mA (860 A/cm²). Single wavelength peak behaviour was observed for a 200 μm size REPCSEL with near field images showing a flat-top profile. The current dependent band structure measurement further indicates the influence of the DBR region. By precisely aligning the envelope of the resonance peak with the non-leaky mode and matching the trough with the leaky mode, it was demonstrated that the in-plane optical loss is effectively reduced by the perimeter DBR, with distinct loss characteristics observed between leaky and non-leaky modes.

Chapter 5 presented the detailed characterisation of the band-structure process for the quantitative analysis of PCSELs. The current dependent measurement at the Gamma points with different k-vector resolution elucidate the influence of collected k-vector on linewidth. Then, the spatially resolved band-structure measurement showed that the influence of inhomogeneity of the PC in the conventional band-structure measurement process can be minimized. The lasing mode with the highest Q-factor at low current injection was observed, and it became narrower for currents $> \sim 125$ mA, which

provides an estimate of the transparency current. Spatially resolved mapping further reveals the influence of inhomogeneity of the PCSEL on emission wavelength. 4-times magnified image mapping indicates that the characteristic length scale of PC inhomogeneity is less than 30 μm .

Chapter 7. Future Work

Detailed characterisation of photonic crystal surface emitting laser (PCSEL) devices and materials was presented in this thesis. Several areas require further investigation.

For Chapter 3, based on the empirical understanding of indium incorporation in InGaAs quantum wells grown by 2D SAG, future development of 3D models [1][2] for predicting material distribution and wavelength shifts during the 2D SAG process would be valuable. Such models could help achieve more accurate target wavelength matching for future PCSEL designs. Since the flat emission region tends to exhibit a circular shape, circular mask designs are also worth investigating. Furthermore, larger window area designs should be explored, and a higher mask to window size ratio may result in a larger wavelength red shift. The limit of indium composition and thickness that can be grown without inducing strain relaxation should be reached. Since a non-planar semiconductor surface may affect the definition of future PC gratings, its influence on the e-beam lithography process should be further investigated. In addition, this technology may find more commercial applications by being extended to other material systems operating at different wavelength ranges, such as 1310 nm light sources for Si photonics engines.

For Chapter 4, the coupling strength ($\kappa L=2$) is adopted for 200 μm device, in the future, higher $\kappa L \sim 10$ can be used to test the proposed limits to the REPCSEL effect. Void atom designs would allow higher coupling coefficients (κ) allowing smaller device sizes that maintain the required κL . Reducing L brings larger FP mode resonance splitting, allowing finer adjustment of the overlap of the FP resonances with the PC band-structure. This allows careful study of the REPCSEL effect. Rather than circular atoms and square lattices, the concept of the REPCSEL could be extended to triangular atoms or double lattice in square lattices for increasing vertical emission rate. A triangular lattice structure could also be explored due to higher 2D coupling strength which is benefit for low refractive index contrast material system (AlGaIn/GaN) [3]. The influence of current injection in the DBR region is also a worthy research direction since it can reduce the absorption loss and possibly enhance power conversion efficiency.

For Chapter 5, future work could focus on developing a new measurement system with a small collected wavevector range Δk (ideally tuneable) and spatially resolved band-structure measurements with a tuneable spot size. Such measurements would require multi-channel detection to enable longer integration times and improved signal to noise ratio. In addition, inhomogeneity, such as variations in the PC period or hole shape, could be deliberately introduced in bespoke samples to investigate the limitations of coherent 2D lasing in PCSELs. Multi-contact device structures could also be fabricated to locally vary the carrier density and study its influence as the lasing threshold is approached, where some regions of the PCSEL may operate at slightly different

injection currents than others. The polarisation dependent measurements is also worthy of further study. A sample with different PC atom sizes (triangular and/or circular) should show a switch in the polarisation, that would provide a strong link between PC band-structure simulation and this new characterisation method.

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