Wavelength Swept Photonic Crystal Laser

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Department of Physical Sciences

Wavelength Swept Photonic Crystal Laser

by

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A thesis submitted for the degree of Doctor of Philosophy

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Thesis prepared in association with

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Declaration

This thesis is entirely the candidate’s own work, except where otherwise accredited.

This thesis has not been submitted for an award in any other institution.

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Journal Papers - Published


Journal Papers - In Preparation


Conference Proceedings


- Anton V. Kovalev, **Sharon M. Butler**, Andrei P. Bakoz, Stephen P. Hegarty, Liam O’Faolain, and Evgeny A. Viktorov, “Relaxation oscillations suppression and undamping in a hybrid photonic crystal laser,”
Publications


Conference Oral Presentations


Conference Poster Presentations


• Sharon M. Butler, Andrei P. Bakoz, Alexandros A. Liles, Ben O’Shaughnessy, Evgeny A. Viktorov, Liam O’Faolain, and Stephen P. Hegarty, “Frequency modulated hybrid photonic crystal laser using a microheater,” presented at 3rd European Summer School on PICs for Optical Interconnects 2018, Thessaloniki, Greece
Abstract

Photonics has become integral to society, based on its ability to sense the environment, to manipulate materials and to transport information. The dominance of silicon electronics has made silicon photonics a compelling vision, but difficulties with light emission have caused delays in implementation and an enduring role for III-V materials.

The research conducted in this Ph.D. thesis involves study and utilisation of a combination of the optical gain of Indium Phosphide with the precision and energy of silicon nanophotonics in a novel family of lasers. A continuously tunable akinetic reflective filter is exploited to obtain a wavelength swept laser.

The akinetic reflective filter comprises a 2D silicon photonic crystal cavity providing wavelength selectivity at the resonance wavelength realised by means of lithographically controlled design. At the resonance wavelength, the photonic crystal cavity provides narrowband reflectance which acts as the output coupler of an external cavity laser. The reflectance band is tuned by the thermo-optic effect in silicon in order to sweep the lasing wavelength and allowing for laser frequency modulation.

Two laser configurations are examined, namely: a short cavity single mode laser and a long cavity multimode Fourier Domain Mode Locked laser. The characteristics of these lasers are examined and the effects of tuning the novel photonic crystal resonant reflector in both laser configurations are explored.
# Contents

1 Introduction

1.1 Wavelength swept and tunable lasers ........................................ 1
    1.1.1 Practical applications ........................................... 1
    1.1.2 Laser geometries and tuning mechanisms .......................... 5

1.2 Silicon photonics platform ................................................ 9

1.3 Thesis outline ......................................................................... 10

2 State of the Art

2.1 Monolithic semiconductor laser devices ................................. 14
    2.1.1 DFB lasers ................................................................. 14
    2.1.2 DBR lasers ................................................................. 22
    2.1.3 VCSELs ................................................................. 26

2.2 Wavelength swept lasers ..................................................... 28

2.3 Hybrid III-V/silicon lasers .................................................. 34
    2.3.1 Integration methods .................................................... 35
    2.3.2 Hybrid integrated III-V/silicon lasers .............................. 38

2.4 Summary ............................................................................. 41

3 Tunable Photonic Crystal Laser Theory and Simulations .......... 43

3.1 Laser cavity ......................................................................... 43

3.2 PhC cavity resonant reflector .............................................. 46
    3.2.1 Vertical coupling to PhC cavity ...................................... 51
    3.2.2 PhC cavity resonance modes ....................................... 54
    3.2.3 Resonance wavelength tuning ...................................... 57
## Contents

3.3 Single mode laser tuning theory .......................... 58
3.4 Single mode laser tuning simulations ....................... 61
  3.4.1 Model description .................................. 62
  3.4.2 Reflector bandwidth and FSR ratio .................... 64
  3.4.3 Influence of alpha-factor ............................ 66
  3.4.4 Hysteresis behaviour ................................ 68
  3.4.5 Optimisation of pump parameter for low IM .......... 70
3.5 Summary .................................................. 74

4 Single Mode PhC Laser Characteristics ...................... 76
  4.1 Laser configuration and experimental setup ............... 77
  4.2 RSOA characterisation .................................. 81
  4.3 PhC cavity fabrication and characterisation ............... 86
  4.4 Laser characterisation .................................. 91
    4.4.1 Operation with varied RSOA bias current ............ 93
    4.4.2 Optimisation of cavity length for extended mode-hop free operating regime ..................... 94
  4.5 Bistable operating regimes ................................ 98
    4.5.1 Single longitudinal mode ............................ 101
    4.5.2 Longitudinal mode-hopping .......................... 103
    4.5.3 PhC resonance hopping .............................. 105
  4.6 Summary .................................................. 107

5 Single Mode PhC Laser Wavelength Tuning and Frequency Modulation ...................... 109
  5.1 PhC cavity resonant modulators .......................... 111
    5.1.1 SiN waveguide with p-n junction ..................... 112
    5.1.2 SU-8 waveguide with microheater .................... 114
  5.2 Laser wavelength DC tuning .............................. 117
    5.2.1 SiN/p-n junction .................................. 117
    5.2.2 SU-8/microheater .................................. 120
  5.3 Laser frequency modulation .............................. 124
Chapter 1

Introduction

1.1 Wavelength swept and tunable lasers

The basic components of a tunable laser are a broadband optical gain medium, an optical cavity, and a wavelength selective element. A swept source laser produces a time varying optical output ideally of narrow instantaneous spectral width to give a periodic swept wavelength.

For diode lasers, tuning of the laser wavelength is realised by altering the gain and/or wavelength selective element, either separately or simultaneously. The gain section can be modified by electrical or thermal application. Depending on the laser configuration and wavelength selective element which is employed (some of which are outlined below), this can again be modified electrically, thermally, or by means of mechanical actuation.

The ability to tune the instantaneous wavelength of a laser has several useful applications which will be discussed in the next section. Due to the many practical, scientific, and industrial applications of tunable lasers, extensive research has accelerated their development and improvement of performance.

1.1.1 Practical applications

Tunable Diode Laser Absorption Spectroscopy (TDLAS) utilises the tunable output wavelength of a laser to exploit the principle of light-matter interac-
1. Introduction

As different gases absorb at different wavelengths, the laser wavelength can be tuned to the absorption band of interest. Then the wavelength is precisely scanned across the absorption band revealing the concentration of the gas. This is based on the Beer-Lambert law, for a monochromatic laser beam with frequency $\omega$, the transmitted intensity $I(\omega)$ through a gas cell is [1]:

$$I(\omega) = I_0(\omega)e^{-\sigma(\omega)LN}$$  \hspace{1cm} (1.1)

where $I_0(\omega)$ is the intensity without absorption, $L$ is the optical path length of the cell, $\sigma(\omega)$ is the absorption coefficient and $N$ is the concentration of the absorbing substance.

![Figure 1.1: Principle of TDLAS and WMS redrawn from [2].](image)

A further application of TDLAS is a technique referred to as wavelength modulation spectroscopy (WMS) or frequency modulation spectroscopy (FMS), which is used for detection of low concentration gases (Fig. 1.1). WMS works
1. Introduction

on the principle that a frequency modulated (FM) signal applied around the absorption band of interest produces harmonics and by using phase sensitive detection, low concentration gases can be detected [3]. FMS is applied in a similar fashion but at a higher modulation frequency around the absorption band which generates sidebands for detection. These methods benefit from a laser which can produce a narrow spectral output that can ideally be modulated at high-speed (for FMS while WMS uses a lower modulation frequency). In order to detect unknown gases, a wavelength scan across a larger range is needed therefore, widely continuous swept lasers are more suitable for that function.

In the optical communications field, a high-speed modulated laser can provide high bit rate data transfer. This can be achieved with an intensity modulated (IM) signal by modulating the gain current which also produces a simultaneous FM. For higher bit rates a method of FM-to-IM conversion with an optical filter on the output can be employed as will be discussed in Chapter 2. The modulated light is transmitted via optical fibers and is the basis for many modern high bit rate data transfer applications today, such as datacentres and broadband internet technology. A widely tunable laser is required for wavelength division multiplexing (WDM) for channel discrimination. The modulated signals are transmitted simultaneously through the same optical fiber permitting the transfer of a large number of data streams.

FM lasers have also proven useful for applications such as Frequency Modulated Continuous Wave (FMCW) Light Detection and Ranging (LiDAR). Given that LiDAR is analogous to Radio Detection and Ranging (RaDAR) technology (but using transmitted light instead of radiowaves), much of the same principles apply. FMCW LiDAR operates on the time-of-flight principle but instead of using a pulsed source to measure the time taken of the reflected pulse, a continuous FM laser beam is transmitted. The returned signal from a moving target is Doppler shifted and mixed with the original signal (acting as a local oscillator) resulting in two beat frequencies which are detected at the receiver. This technique is used for range-finding of a moving target which can also determine its velocity.
1. Introduction

The FMCW principle is illustrated in Fig. 1.2, where the difference of the two beat frequencies, $f_{IF1}$ and $f_{IF2}$ is twice the Doppler shift as [4]:

$$f_{IF1} - f_{IF2} = 2f_{Doppler} \approx 2\frac{v f_0}{c} \quad (1.2)$$

where $v$ is the velocity of the target, $f_0$ is the frequency of the input light, and $c$ is the speed of light. The time-of-flight distance to the target is the average of the two beat frequencies:

$$\frac{f_{IF1} + f_{IF2}}{2} = f_{Dis} \quad (1.3)$$

Detection of the beat frequencies allows for the simultaneous measurement of both the distance and velocity of the target. As the shift of the returned signal can be quite small, a narrow linewidth laser with moderate modulation speed capability and continuous tuning is most suitable for this application.

Optical Coherence Tomography (OCT) is a medical imaging technique analogous to ultrasound which uses interferometry to determine distance information between a fixed width reference arm and a sample arm. The reflected light from the depth varying interfaces on a sample is mixed with the reflected light from a fixed mirror on the reference arm and sent to a balanced photodetector. Swept source (SS)-OCT utilises a swept laser
1. Introduction

to scan the wavelength with a time varying function (ideally linear) and generates an interferogram from the sample and reference arm as a function of time (Fig. 1.3). The Fourier transform of this signal produces frequency components as a function of depth of each reflected interface. Scanning the beam of the swept wavelength across a sample generates a map which can then be constructed as a 3D image. A wide spectral sweep is required for this application in order to achieve a high resolution image while a faster sweep speed allows for faster image acquisition rates. The advantages of this non-intrusive imaging approach have increased research efforts to improve the performance of many swept laser sources and development of new geometries and operating regimes.

![Figure 1.3: Principle of SS-OCT from [5].](image)

1.1.2 Laser geometries and tuning mechanisms

The configuration of swept laser and optimal parameters are determined by the intended application. Parameters for optimisation include: sweep range, sweep speed, instantaneous spectral width, device size/footprint, and complexity. Therefore, there are trade-offs between these parameters and the swept laser can be optimised for the specific application. This section gives
1. Introduction

an overview of some of the various types of laser configurations and tuning mechanisms which have been employed to realise wavelength tuning. Chapter 2 will further discuss these with a view towards the up-to-date technologies and their performance.

Many laser geometries have been established for specific applications where a wide continuous tuning range and as high of a sweep speed as possible are necessary attributes such as SS-OCT. The types of laser configuration which generally provide this tend to be relatively larger in size (compared to integrated structures) therefore, multiple longitudinal modes lase simultaneously at any given instant as the wavelength selective element is swept. Many swept laser sources implement tuning of the emitted wavelength by employing a tunable filter (Fig. 1.4). The swept instantaneous spectral width is therefore dependent on the transmission bandwidth of the filter.

![Diagram of wavelength tuning with swept filter](image)

**Figure 1.4:** Concept of wavelength tuning with swept filter from [6].

A fiber ring cavity laser enforces uni-directional lasing using isolators within the cavity and a swept wavelength can be achieved by an intra-cavity tunable filter (Fig. 1.5). As the filter is swept, the transmission window of the filter sets the output wavelength range. One of the most commonly reported filter types in ring lasers include a fiber Fabry-Perot filter [6–8] as this has a wide tuning range with moderate repetition rates. The filter has
1. Introduction

two high reflection coated facets which can be moved rapidly by electrostatic forces or a piezo-electric actuator to tune the transmission band. Another approach uses a grating filter type [9] which the output coupled beam is reflected to and from the grating and tilting the mirror deflects the beam at a varying angle to enable wavelength scanning. A polygon scanning mirror has also been reported as a method of beam scanning on a grating [10–12].

![Figure 1.5: Ring cavity with intra-cavity tunable Fabry-Perot filter from [6].](image)

The Fourier Domain Mode Locked (FDML) laser [13] is a type of ring cavity laser with a tunable Fabry-Perot filter that has a fiber delay line placed in the cavity. This operating regime was introduced to maximise the laser output power while sweeping to enhance imaging for OCT applications. The regime is achieved by synchronisation of the filter sweep period with the light roundtrip time of the cavity and allows for continuous wavelength sweeping with improved laser output power.

Fabry-Perot filters have also been reported in a linear laser geometry with bi-directional lasing in a short cavity configuration (Fig. 1.6). Johnson et al. [14] reported a short cavity laser using an external Fabry-Perot filter as a retro-reflector with tuning by means of a micro-electromechanical system (MEMS) mirror. Tilting the reflected beam on the mirror changes the angle
1. Introduction

of incidence and hence, the reflected wavelength allowing wavelength scanning. The scanned grating type filter has also been employed as an external tunable mirror for an extended cavity semiconductor laser to provide tunable selective feedback [15].

![Figure 1.6: Short cavity with Fabry-Perot retro-reflector with MEMS from [16].](image)

Another type of short cavity swept laser is the vertical cavity surface emitting laser (VCSEL) which operates on a single longitudinal mode due to its ultrashort cavity length giving a large Free Spectral Range (FSR). The laser emits vertically with wavelength selectivity provided by a Distributed Bragg Reflector (DBR) mirror and tuning is achieved by means of mechanical movement of this mirror with a MEMS. These provide large tunability ranges and have been implemented in many SS-OCT applications. By virtue of their wide single mode continuous tuning range, MEMS-VCSELs have also been utilised for optical communications applications and optimised for high bit rate data transfer [17].

Tunable diode lasers are commonly single frequency lasers which operate on a single longitudinal mode as is the case of the VCSEL. The single longitudinal mode can be modulated, tuned continuously, or else discretely stepped to adjacent longitudinal modes, depending on the cavity FSR and the required application. In all the configurations described above, the filter is tuned by means of mechanical movement and this is one of the limitations of the maximum sweep speed achievable. For this reason, such solutions employing an akinetic tunable filter have been reported. A type of DBR laser that operates on the principle of Vernier Tuning (VT) has DBR sampled gratings with different periods on each end facet [18]. Single mode lasing
1. Introduction

is achieved when one reflection peak of the grating overlaps with another. Tuning of the single mode frequency is realised by thermal or electrical application to the DBR gratings to change their refractive index and hence, their reflectivity.

Many solutions to realise a tunable single mode laser have been demonstrated in the past decades, and some of the monolithic state of the art solutions are outlined in Chapter 2, these include: Distributed Feedback (DFB) lasers, DBR lasers, and VCSELs. An advantage of the monolithic approach is the compact size resulting in a small device footprint hence, these lasers are most commonly featured in optical communications technology where small size components are imperative. Since these operate on a single longitudinal mode, they can produce a narrow spectral linewidth as compared to the lasers described above which rely on the filter bandwidth for the spectral width. This also makes them ideal candidates for applications where a swept narrow linewidth is essential such as LiDAR and trace-gas detection as described in Section 1.1.1. However, their continuous tuning range is limited to the cavity FSR therefore, are more commonly utilised as high-speed FM lasers.

1.2 Silicon photonics platform

The main driving force for the research and development of silicon photonics has been the demand for increased bandwidth while keeping energy consumption low for optical interconnects. Given that silicon is the fundamental building block for the electronics industry, compatibility and integration of photonic integrated circuits (PICs) with existing electronic circuitry is the one of the main attractions of this approach. This emergence of silicon photonics for PICs has proven to be one of the leading technologies for high-speed optical interconnects owing to cost effective manufacture and integration with existing complementary metal-oxide semiconductor (CMOS) technologies producing low-cost, high-yield outputs. For this reason, many
optical interconnect components have been developed on silicon such as low-loss waveguides [19] and high-bandwidth photodetectors [20].

To demonstrate ultra-low switching power capability with silicon, many types of silicon based resonant modulators have been developed which will be discussed in Chapter 2. For on-chip optical interconnects, one of the key requirements is an integrated light source which can be modulated for databit communication but simply combining a wavelength selective modulator and laser is problematic due to fabrication imperfections and thermal drift. Integration techniques for III-V and some of the state of the art technologies will be discussed in Chapter 2.

One of the main motivations for the research work in this thesis is the realisation of an efficient modulator/laser configuration on the silicon photonics platform. A wavelength selective element (acting as a narrowband reflector) based on silicon photonics technology is employed inside the laser cavity and will be described in detail later.

1.3 Thesis outline

The research carried out in this thesis is concerned with combining a III-V semiconductor optical amplifier (SOA) with a silicon 2D photonic crystal (PhC) cavity based resonant reflector to realise an external cavity (EC) wavelength tunable laser. Wavelength tuning and FM techniques are explored by directly modifying the reflectance spectrum of the PhC cavity. Firstly, a single mode short cavity laser is realised. Subsequently, wavelength tuning and FM of this laser is demonstrated which is analogous to the tunable diode lasers described above. Further from this, a long cavity multimode laser configuration is demonstrated in FDML operation of which the geometry is related to the wavelength swept lasers described above. The thesis is organised as follows:

Chapter 2 reviews some of the current state of the art III-V monolithic tunable laser diode sources and their specific design and performance. Fol-
1. Introduction

Following that is a review of some of the most recent advances of wavelength swept laser geometries and operating regimes. Finally, a review of the current research which focuses on the integration of III-V materials with silicon based resonators to realise hybrid lasers.

Chapter 3 provides some theoretical background for the PhC laser device in question outlining the theory of the gain and PhC components. Also presented is a theoretical basis for the single mode tuning mechanism and a linear approximation to predict the laser mode tuning with the reflector tuning. A model is utilised for the single mode case and the generated simulation results are presented and analysed.

Chapter 4 describes the experimental work which was carried out to realise the single mode PhC laser. Details of the experimental setup, separate characterisation of the gain section and PhC reflector and subsequently, both components combined to form the laser cavity and examination of the characteristics. Efforts to extend the mode-hop free tuning range are outlined. The laser presents bistable operating regimes which are analysed.

Chapter 5 describes the experimental work which achieved wavelength tuning and FM of the single mode PhC laser. Two resonance tuning approaches for the PhC cavity are presented, namely: a doped p-n junction and a microheater. Analysis of the FM results is given and comparison of the devices is outlined.

Chapter 6 provides a proof-of-concept experimental demonstration of a novel FDML laser. Again, utilising the PhC cavity as the tunable reflector but in this case, extending the length of the laser cavity from the single mode regime to a long cavity highly multimode regime. This extends the continuous tuning range beyond the single mode limitation of the cavity FSR and demonstrates stability in FDML operation over a wavelength swept range.
1. Introduction

Chapter 7 gives a summary of the work detailed in this thesis and suggestions of possible future work which could follow the research efforts described here.

Design and fabrication of the PhC devices was performed by Alexandros Liles in the University of St. Andrews. Finite-Difference Time-Domain (FDTD) simulations in Chapter 3 were undertaken by Praveen Singaravelu in CIT and Tyndall. Laser dynamical modelling and initial simulations in Chapter 3 were undertaken by Ben O’Shaughnessy and subsequent simulations were performed by myself in Tyndall. The experimental and analysis work in Chapter 4 was performed by Praveen Singaravelu and myself in CIT. The remaining experimental and analysis work in Chapters 5 and 6 was carried out by myself in CIT and Tyndall.
Chapter 2

State of the Art

This chapter gives an overview of the latest technology and research to date of wavelength tunable semiconductor diode lasers, FM lasers, hybrid III-V/silicon lasers, and other swept wavelength sources.

While there are a wide range and many variations of tunable lasers available today, this chapter mainly focuses on tunable semiconductor diode lasers as it is most relevant to the work in this thesis. The type of diode lasers discussed in this chapter will be monolithic devices such as: DFB lasers, DBR lasers and VCSELs. Other wavelength swept sources are outlined and subsequently, a review of some hybrid III-V/silicon lasers. While monolithic lasers have been extensively researched in the last few decades owing mainly to their compact size, more recently hybrid III-V/silicon lasers have gained a lot of attention. The main reason for this is the ability to customise independently the design and fabrication of the active and passive components and the accessibility of integration with existing silicon circuits. The III-V device acts as the dedicated active gain material and silicon as an optical filter or reflector in an external cavity configuration. Silicon has been the preferred material for photonic applications as it can be readily integrated with existing electronic circuit technologies and the fabrication process is well established leading to reduced manufacturing costs and the possibility for mass production.
2. State of the Art

Other swept wavelength sources which consist of bulk components are typically not integrated structures but rather have been developed to obtain wide sweep ranges for SS-OCT applications, some of which are described below.

2.1 Monolithic semiconductor laser devices

Monolithic laser devices offer a solution on a single integrated platform with much of the research focus on III-V materials. One of the main advantages of this approach is the compact size of the overall structure resulting in a small footprint which is ideal for optical interconnect applications. Other advantages include reduced packaging costs and complete control over the fabrication process. Research in the last several decades has been productive with this approach owing to these advantages and some of the resulting laser technologies are discussed below. However, one of the main downsides to the monolithic approach is usually the fabrication complexity. Nevertheless, many solutions have been provided and some further research attention has been paid to reducing fabrication complexity as discussed below.

2.1.1 DFB lasers

DFB lasers have a grating along the axial direction of the active layer that distributes the light fed back into the cavity providing single mode operation at a wavelength depending on the grating period (Fig. 2.1(a)). The tuning mechanism is so-called direct modulation by control of the bias current to the diode which changes the refractive index of the material and changes the operating laser wavelength. The operating wavelength can also be controlled by the changing the overall device temperature (Fig. 2.1(b)). Electro-optic (EO) and electro-absorption (EA) modulators have also been incorporated as an external modulation scheme realised by modulation of the bias current on the external modulator.
DFB lasers have historically been one of the most widely used solutions for FM and tunable laser sources. This is due to single mode narrow linewidth output and the simplicity of realising FM by modulating only the injection current to the active section based on thermal expansion in the cavity to change the single mode frequency. Many of the DFB lasers available to-
day show a wide tunability range over a range of wavelengths however, the
continuous tuning range (mode-hop free) is relatively narrow and generally
limited to the cavity FSR. The wide tunability range (beyond the FSR) is
desirable for WDM links and is referred to as quasi-continuous tuning in the
literature.

With regard to sensing applications, the direct modulation produces si-
multaneous large IM combined with FM which affects the sensitivity of the
measurements over the frequency scan range. Numerous methods have been
established to address this by extracting the frequency scan information such
as second harmonic detection and subtraction techniques [23, 24]. Bjorklund
in 1980 [25] first described the techniques of WMS and FMS by means of
modulating the laser frequency across an absorption feature for sensitive de-
tection as described in Chapter 1. Recently, Li et al. [26] presented a method
to measure the phase difference between the FM and IM output to calibrate
for the IM over a frequency scan. They used the time difference of absorption
peaks, taking advantage of the asymmetry of forward and backward wave-
length sweeps. In any case, the post processing of the signal information
to account for the IM adds extra processing complexity therefore, a pure
FM laser can be more favourable for sensing applications as they eliminate
the need for further calculations and processing of the frequency scan signal
information.

A pure FM DFB laser was first demonstrated by Yoshikuni et al. in 1987
[27] with a multielectrode DFB laser by electrically isolating three sections to
control carrier density in part of the active region. This modulated only the
laser frequency and this had little to no effect on the output power indicated
by an almost flat frequency response with increasing modulation frequency.
Recently, Chu et al. [28] reported a device with a separate phase grating
section and applying modulation only in this region to realise pure FM. The
authors presented this as ultrafast wavelength switching for multi-channel
ultra-dense WDM. An alternative method was reported by Tian et al. [29]
demonstrating pure FM by a combination of optical injection and current
tuning based on non-resonant optical coupling. More recently, Shehzad et
al. [30] have realised both pure IM and pure FM individually in a DFB quantum cascade laser. By applying modulation to an integrated heater on the active region and simultaneously applying modulation to the gain current, the FM or IM was suppressed.

The optical communications field has been the driving force for the majority of state of the art solutions in recent years. For this reason, direct modulation of the injection current to modulate the output intensity has been employed with a focus to suppress the accompanied frequency chirp as this broadens the pulse width exacerbated by dispersion in the fiber which limits the transmission distance. The Chirp Managed Laser (CML) by Finisar [31, 32] exploited the effects of frequency chirp by incorporating FM-to-IM conversion in a directly modulated laser and used this for extended transmission distance. While this approach uses a monolithic DFB laser, further components are required such as an optical spectrum reshaper filter for FM discrimination on the optical output. This comes as a butterfly packaged laser but not as an overall monolithic solution. Nevertheless, this laser has been one of the leading solutions for state of the art optical communications devices with applications in numerous modulation formats [32]. However, the requirement for a monolithic solution remains and more recently, Pan et al. [33] proposed a monolithically integrated CML with etched slanted double trenches on the output to act as the optical filter integrated on one platform. This type of monolithic resonant tunneling filter was first introduced by Li et al. [34].

Recent reports show monolithic devices of a DFB laser incorporating a DBR as a reflective element. Recently, the Finisar group developed a device which uses both a DFB and DBR type laser on a single platform with 55 GHz modulation bandwidth [35]. These devices have lately been referred to as a distributed reflector (DR) laser in the literature. Optical feedback is given by the DBR which also enhances the coupling strength of the grating allowing for a shorter cavity. However, in order to integrate the active and passive components, the fabrication process can be complicated. Mao et al. [36] recently developed this structure with a more simplified fabrication
2. State of the Art

process by the identical active layer approach to avoid integration of different epitaxial structures. This also had the same grating structure on the DFB and DBR section to further simplify the process.

![Diagram of DFB-DBR laser](image)

**Figure 2.2:** (a) Cross section of DFB-DBR laser and (b) tuning on DBR mode for various THz outputs from [37].

In a similar novel structure of a DFB-DBR monolithic laser shown in Fig. 2.2(a), Kim et al. [37] reported this as an optical beat source for continuous wave THz technology. This operates in dual-mode operation in which one mode can be tuned (via a phase shifter or heating of the DFB or DBR region) which changes the output beat frequency for sweeping THz wave generation (Fig. 2.2(b)). The same group have also presented another type of dual-mode laser with two $\lambda/4$ phase-shifted DFBs for THz wave generation.
A similar approach using dual-DFBs integrated on an InP platform was demonstrated by van Dijk et al. [39]. This included integrated multimode interference couplers, EO modulators, SOAs and high speed uni-traveling carrier photodiodes which generated optical beat tones for wireless communication. The heterodyne frequency is detected on-chip by the photodiodes converting the optical signal into a high speed electrical signal output resulting in 100 MBit/s data rate wireless transmission over a 90 GHz carrier.

In an effort to extend the mode-hop free tuning range of DFB lasers in a monolithic device, while keeping a small device footprint and using a simple one electrode tuning current, the Tunable Distributed Amplification DFB Laser Diode (TDA-DFB-LD) was first introduced by Ishii et al. [40]. This novel structure has alternating grating sections throughout the cavity. Current injection to a single electrode changes the refractive index of the cavity (consequently the longitudinal mode) and synchronously the Bragg wavelength shifts with the longitudinal mode providing extended mode-hop free tuning. An additional electrode to a grating section provides further tuning by the Vernier effect. This design was later adapted by Nunoya et al. [41] on a pure III-V platform in an asymmetric structure (Fig. 2.3(a)) to further extend the mode-hop free range by elimination of the super-modes (existing from Bragg reflection peak tuning) resulting in an 8 nm continuous tuning range. The super-modes did not coincide as per design of the separate gratings structures illustrated in Fig. 2.3(b). More recently, Onji et al. [42] used this structure to demonstrate accurate wavelength switching at high-speed with 3.2 nm range in less than 100 ns while also applying a feedforward controller to stabilise the wavelength. More recently, a DFB-DBR design has been reported with sampled gratings by Chung et al. [43]. They presented a device of this geometry with sampled gratings of different periods on the DFB section and DBR section which allows for wide wavelength tuning by the Vernier effect. Yagi et al. [44] at the same time also presented a similar device but instead using chirped sampled gratings on the DBR section. This further eliminates side modes for better Side-Mode Suppression Ratio (SMSR) which results in a device suitable for coherent transmission for optical interconnects.
Figure 2.3: (a) Cross section of TDA-DFB laser and (b) illustration of Bragg reflection, longitudinal mode synchronous tuning, and super-mode suppression reproduced from [41].

EO and EA modulators are used as an external method of modulation
while keeping the bias to the active material fixed and modulation is applied to the current on the EO or EA modulator. This approach aims to suppress the frequency chirp and hence increase the bandwidth and transmission reach for optical communications realised with a lower modulation voltage than direct modulation. Hasebe et al. [45] have demonstrated a DFB and integrated EA modulator in a novel structure of a lateral p-i-n diode with 50 Gb/s operation. This lateral structure is an attractive approach for large scale PICs. In a simple linear geometry, Kobayashi et al. [46] used an integrated SOA with an EA modulator and DFB to suppress the chirp and hence improve transmission distance while keeping the overall power consumption low. Similar to this, Chu et al. [47] presented a DFB and integrated EA modulator on the same active layer. This device has a dual output acting as both a transmitter and local oscillator as a coherent source with a small device footprint ideal for ultra-dense WDM systems.

Rapid sweeping of the DFB lasing wavelength was obtained with a method described by Njegovec et al. [48] with a standard telecom DFB laser. The authors presented a novel method of rapid heating and cooling of the laser with pulsed operation with a sweep of 10 nm in 150 ns with repetition rates of tens of kHz. The standard telecom laser is not optimised for the rapid sweeping conditions however, the method showed promise for further development of DFB lasers to operate in this regime.

An application example of a DFB laser applied to FMCW reflectometry was presented by Qin et al. [49] aiming to improve the coherence of the laser by using a composite feedback loop. One element of the feedback loop went to the injection current to control the linear frequency sweep of the laser and another to an acousto-optic frequency shifter to compensate for broadband stochastic frequency noise. This method resulted in an improved coherence and for the FMCW application showed 2 mm and 3 cm spatial resolution for a 50 m and 250 m range, respectively.

Finally, it is worth considering the fabrication compatibility of the aforementioned devices. While these are reports of high performance and innovative structures, the fabrication process can be difficult to implement
2. State of the Art

and CMOS compatibility is an important consideration for mass production. Recently, Magden et al. [50] reported fabrication of a CMOS compatible monolithically integrated DFB laser. This was fabricated on a newly developed gain material: amorphous aluminium oxide. Although the results are presented for an optically pumped laser, it is a promising step towards mass production of DFB monolithic devices.

2.1.2 DBR lasers

DBR lasers employ a grating mirror as the mode selective element and the Bragg wavelength determines the operating lasing wavelength. The grating is in-plane with the active region in a Fabry-Perot type configuration. In general, wavelength tunability is achieved by applying current to the grating section which changes the optical length of the grating period and hence the lasing wavelength.

The structure is usually in a three section configuration (Fig. 2.4) where there is separate current control to the gain, phase and grating section. Control of the current to any of these sections can provide wavelength tunability. Adjustment of current to the gain section or the overall system temperature achieves coarse tuning while more fine tuning is given by control of the Bragg wavelength by the current to the DBR section and finest tuning is realised by current control to the phase section.
Advancements in design led to sampled grating (SG) DBRs which have been frequently reported in the literature and first demonstrated by Jayarajan et al. in 1993 [51]. The SG in a laser geometry has been previously discussed in Section 2.1.1 where it is combined with a DFB. In this section however, they are considered as a DBR laser as the grating is absent in the active region therefore, it is a simpler laser geometry design.

The SG is a grating with a pitch periodically sampled which produces multiple periodic reflection peaks. In a laser geometry of an SG on the front and rear (with slightly different periods) of the Fabry-Perot cavity, single mode lasing occurs with an overlap of the peaks. Broad tunability is realised by applying current to the gratings, changing the reflection peaks overlap position by the Vernier effect as illustrated in Fig. 2.5.

Around the same time the first SG was reported, a super structure grating (SSG) was also developed by Tohmori et al. [53] which is a periodically chirped grating with varying pitch. The advantage of this design is the reflection peaks have equal magnitude as opposed to a decreasing magnitude in the SG, which allows for wider wavelength tuning ranges with the SSG. However, fabrication of the SSG can be more difficult to implement and the same group demonstrated an improved fabrication procedure [54] soon after their first report. Both SG and SSG DBR lasers incorporate a phase tuning

Figure 2.5: SG-DBR reflectivity spectrum showing Vernier tuning concept. Tuning of one SG changes overlapping reflection peaks position, from [52].
2. State of the Art

section for fine tuning and this later led to the development of FM employed with these lasers.

As discussed in Section 2.1.1, a pure FM laser can extend the bandwidth and transmission distance for optical communications. A three section multielectrode DBR laser was first introduced by Ishida et al. in 1989 [55] with the concept of modulating the laser frequency by control of current in one region of the active material, similar to the approach by Yoshikuni et al. for a DFB laser [27].

An FM laser in an SG-DBR configuration with a phase tuning section was reported by Johansson et al. [56]. This was fully integrated with an amplifier and Mach-Zehnder modulator on the output on a single InP substrate. In that report, the authors demonstrated phase modulation by current to the phase section and subsequently realised FM-to-IM conversion by incorporating the Mach-Zehnder modulator on the output. This gave a greater FM bandwidth than by phase modulation alone but with a trade-off of FM efficiency.

Similarly, Matsuo et al. [57] have demonstrated pure FM with an SSG-DBR multi-section laser (Fig. 2.6) in a high performance example showing extended transmission reach. Modulation to the phase tuning section gave pure FM therefore, the modulation speed was not limited by relaxation oscillations, (a limitation of direct modulation). Optically filtering the output light enabled conversion from FM-to-IM with a high extinction ratio. The authors reported a 20 Gb/s NRZ (non-return-to-zero) signal achieved over a 60 km transmission distance.

The advantage of both these schemes is that a wide wavelength tunability range can be achieved by means of tuning the gratings which is attractive for application in a WDM system. While this is quasi-continuous tuning, the phase tuning section allows for FM with high efficiency within the active wavelength region determined by the grating.

The demand for narrow linewidth lasers in coherent systems is ever increasing. In order to reduce the linewidth, further optical components are required and not typically available as a monolithic device. However, Sivanan-
2. State of the Art

![SSG-DBR Laser Diagram](image)

**Figure 2.6**: SSG-DBR laser consisting of a gain section, phase section, and an SSG mirror on the front and rear. Optical filter at the output for FM-to-IM conversion from [57]

than et al. [58] reported a linewidth narrowing technique incorporated into a monolithic structure in an SG-DBR laser. This consisted of an electronic integrated circuit and loop filter as a feedforward frequency lock system enabling linewidth reduction from 80 MHz to 3 MHz. A recent report by Matsui et al. (Finisar) [59] demonstrated a narrow linewidth DBR laser in a conventional grating design (as opposed to SG and SSG). The DBRs on the front and rear of the laser cavity are suspended in an air gap for efficient thermal tuning. The DBR design was optimised for a waveguide with reduced loss for a further filtering effect giving a linewidth of 80 kHz.

Further applications for the DBR laser have been reported for SS-OCT. O’Connor et al. [60] reported the use of an SG-DBR in an SS-OCT application with 100 kHz axial scan rate. Three separate waveform generators on the front and back mirrors and the phase tuning section were used to generate a 47 nm continuous sweep range and an increased repetition rate of 1 MHz with a sweep range of 3.2 nm. Later, Choi et al. [61] demonstrated an SS-OCT application using an SSG-DBR laser with two Vernier-tuned lasers using look-up tables to determine the current to control the output frequency sweep. The frequency was scanned stepwise with a sweep range of 75 nm.
2. State of the Art

Bonesi et al. [18] utilised the commercially available Vernier Tuned (VT)-DBR laser from Insight for OCT imaging with 40 nm sweep range and 200 kHz repetition rate at 1550 nm and 30 nm and 102 kHz at 1310 nm. Song et al. [62] demonstrated a similar laser from Insight with an extended sweep range of 100 nm.

Most recently, an application for FMCW LiDAR was presented by Isaac et al. [63] in a PIC using an SG-DBR laser fully integrated with a Mach-Zehnder interferometer as a frequency discriminator, including photodiodes and couplers. The frequency discriminator on-chip was used for frequency-locking and modulation in a LiDAR application. The laser showed a continuous tuning range of 40 nm with 30 GHz modulation.

### 2.1.3 VCSELs

VCSELs emit light in the vertical direction as opposed to edge emitting like the DFB and DBR lasers discussed in the previous sections. Although they do employ a DBR mirror for wavelength selectivity, this is in a stacked structure.

![Cross-section of Cantilever type VCSEL from [64].](image)

**Figure 2.7:** Cross-section of Cantilever type VCSEL from [64].

Fig. 2.7 shows a commonly reported tunable VCSEL based on a cantilever configuration. The top DBR mirror stack is suspended over an air gap over the active region. Tuning is realised by a change in the physical position of
2. State of the Art

this mirror, changing the length of the cavity. For this reason, it is referred to as a MEMS-VCSEL as the top DBR is actuated electrically for tuning. This idea to obtain a wide tuning range from an electrically pumped VCSEL by means of a MEMS was pioneered by C. J. Chang-Hasnain’s research group in the mid-90s [65, 66] reporting 7 nm tuning range. This was the first time an electrically pumped VCSEL was reported with a wider tuning range, up until then tuning relied solely on the traditional approach of current injection to the active region or DBR to induce refractive index change. This approach had limited tuning capability because of the small size of the active region with typical ranges of ∼1.5 nm in the earlier reports.

Since the demonstration of the first MEMS-VCSEL, many efforts to extend the tuning range and increase the modulation speed have been reported in recent years. Gierl et al. [67] demonstrated a MEMS-VCSEL with a 102 nm continuous tuning range. The group drastically reduced the length of cavity to give the large FSR of 102 nm for mode-hop free continuous tuning, this being the main advantage VCSELs have over edge-emitting lasers. Another advantage is the low threshold current of typically <5 mA. The trade-off is limited maximum output power showing 3.5 mW in that report. The same group later reported this device optimised for high-speed modulation [17], demonstrating 10 Gb/s data rate with a bandwidth of 7.05 GHz and tuning range of 47 nm. The entire device footprint was 470 x 470 µm making VCSELs an attractive solution for high-speed optical interconnects.

The complexity of the fabrication of VCSELs remains to be a drawback. Due to the vertical structure of the device, several epitaxial layers are grown to form the DBR stacks and laser cavity. Efforts to reduce the fabrication complexity have been reported with an aim to eliminate the complicated step of formation of the top DBR stack and replace with a high contrast grating (HCG) which dimensions are defined by optical lithography. One such device was reported by Rao et al. [68] demonstrating high-speed modulation of 10 Gbps with 7.8 GHz bandwidth. In order to extend the wavelength tuning range, a MEMS was attached to the HCG giving a tuning range of 26.3 nm at a central wavelength of 1550 nm. More recently, Li et al. [69, 70] reported
a similar device using a HCG MEMS-VCSEL (Fig. 2.8) with an extended tuning range at 1060 nm central wavelength. They successfully achieved a continuous tuning range of 40 nm with this structure, with 36 nm from the MEMS and 4 nm from thermal tuning of the cavity.

![Figure 2.8: HCG-VCSEL from [70].](image)

Owing to their properties of rapidly-swept wide wavelength tuning ranges, VCSELs are an ideal device for use in SS-OCT and imaging applications. Recently, John et al. [71] reported an electrically pumped device operating at 1050 nm for ophthalmic imaging with 63.8 nm tuning range. Another suitable application on account of their wide tuning range extends to FMCW reflectometry and Iiyama et al. [72] presented a high-resolution example with a VCSEL. The frequency was swept by current injection to the active region alone and resulted in a spatial resolution of 250 µm. However, the linewidth of the laser was 80 MHz which limited the measurement range to 1 m.

### 2.2 Wavelength swept lasers

To differentiate from the monolithic lasers described in the previous sections, the wavelength swept lasers described here consist of bulk laser components which are not integrated and have been developed to achieve a large sweep range while also having a fast sweep speed. As described in Chapter 1, their
primary area of application is SS-OCT and have been developed to enhance these attributes for greater image resolution and image acquisition speed. Some of the monolithic lasers described above have also been used for this application such as: the MEMS-VCSEL and VT-DBR laser as they offer a wide sweep range and will be compared to the bulk swept lasers in this section. A comprehensive review of the recent development of light sources for OCT is provided in [73], some of which are outlined below.

In order to achieve a small device footprint, short cavity lasers have been developed in both linear and ring cavity geometries. As shown in Fig. 2.9(a), Jun et al. [8] reported an all-fiber ring cavity laser with a cavity length of $\sim 0.5$ m employing an intra-cavity Fabry-Perot tunable filter. The laser had a sweep range of 125 nm, 240 kHz repetition rate and 75 mW of output power. As described in Chapter 1, a polygon scanning mirror is an alternative filter type used to deflect the beam on a grating to scan a wavelength range which has been reported by Oh et al. [12] with 105 nm range at a rate of 403 kHz with an output power of 32 mW. Okabe et al. [74] also used a deflected beam and grating reflector approach but instead using an EO deflector. Carriers are injected into a potassium tantalate niobate (KTN) crystal in order to deflect the beam by refractive index change (Fig. 2.9(b)) giving 80 nm sweep range at 200 kHz with 20 mW output power. Recently, Johnson et al. [14] reported a linear short cavity laser with a Fabry-Perot retro-reflector tilted by means of a MEMS with 140 nm tuning range but the sweep rate was limited to 100 kHz.

One limitation on the sweep rate is the mechanical speed of the filter. The VT-DBR laser [18] described in Section 2.1.2 has the advantage of tuning by an akinetic (no moving parts) filter therefore mechanically, there is no limitation on the sweep rate. However, there are fundamental limits to the sweep rate to maintain laser operation such as cavity build up time which is an issue for short cavity lasers. This limitation is known as the post-filtering limit, where the filter is swept by more than the filter width during the cavity roundtrip period [6]. In this situation, losses are increased in the cavity, drastically reducing output power eventually stopping laser action entirely.
2. State of the Art

This limitation was overcome by the introduction of the FDML laser by Huber et al. in 2006 [13]. The FDML laser is a ring laser with an intra-cavity tunable Fabry-Perot filter as described in Chapter 1 with the addition of a large fiber delay line placed in the cavity. By sweeping the filter at a period synchronous to the roundtrip time of the cavity, a full sweep is optically stored in the cavity which overcomes the restriction of cavity build-up time as lasing does not need to build up from spontaneous emission. As the post-filtering limit is no longer a first-order limitation, the filter sweep speed is the main limiting factor for the laser sweep rate. A large cavity length is usually required to facilitate synchronisation of the roundtrip time and filter speed but the principle of FDML can be scaled to any cavity length solely depending on the maximum filter speed achievable. This has led to several developments of various FDML configurations to further increase the sweep speed and maximise performance for OCT applications. While a wide sweep range enhances the image resolution, a fast sweep speed provides fast image acquisition rates. Rates of MHz sweeps are essential for applications such as retina scanning and FDML lasers with MHz sweeps have been demonstrated [75–78].

As described in Section 2.1.3, the MEMS-VCSEL operates on a single longitudinal mode and adiabatic tuning occurs due to Doppler shifting of
the photons with changing the resonator length (by movement of the mirror). This adiabatic tuning means there is no fundamental limit on sweep speed however, as wavelength sweeping is realised again by mechanical movement, this remains to be the main limitation. Nonetheless, Tsai et al. [79] demonstrated 1 MHz sweep rate over almost 110 nm wavelength span with 40 mW power. This shows the potential of VCSELs for SS-OCT applications with the advantage of one of the smallest device footprints available.

![Figure 2.10:](image)

**Figure 2.10:** (a) Stretched Pulse swept laser OCT system consisting of a mode-locked fiber laser (MLFL), booster optical amplifier (BOA) and dispersion compensated fiber (DCF) from [80]. (b) Dispersion Tuned swept laser from [81].

An alternative approach to employing a bulk filter element is the Stretched Pulse method (Fig. 2.10(a)) which was first demonstrated by Moon et al. in 2006 [82]. This technique involves using a pulsed laser and temporally stretching the pulses by employing a dispersive fiber. As pulsed lasers can achieve very high repetition rates, this technique offers very high sweep speeds as demonstrated in [80, 83] with 11.5 MHz sweep speed and almost 60 nm sweep range. However, as a highly dispersive fiber is required, this leads to large losses and ultimately low output power of 3.5 mW or less.

Dispersion Tuning is another technique which does not employ tuning of an intra-cavity filter. This exploits chromatic dispersion as opposed to the FDML laser where it is otherwise unfavourable. The cavity gain or loss is modulated synchronously to the roundtrip time and a small wavelength
range is active at any given instant due to the chromatic dispersion. Takubo et al. [84] demonstrated this with 100 kHz sweep rate and 60 nm sweep range. Later, Tozburun et al. [81] dramatically increased the sweep rate to almost 1 MHz by employing two dispersive elements of equal but opposite dispersions to stretch and compress pulses. Modulation is applied to the dispersive element for compressed pulses which are stretched on the output of the opposite dispersive element as shown in Fig. 2.10(b).

Fig. 2.11 provides a graphical comparison of the different types of wavelength swept lasers discussed above from data provided by the review paper in [73] of the latest technologies from 2010-2017. Also added is the most recent advancement for the short cavity laser in 2018 from [14]. It can be seen from this comparison that there are trade-offs between the length of the cavity and the sweep speed due to the cavity build up time as previously discussed. That said, the short cavity lasers have the advantage of a wider sweep range owing to the tuning range of the tunable Fabry-Perot filter employed.

The FDML laser offers a balance between both sweep speed and sweep range attributes and also has the highest output power among the lasers listed here. For this reason, it has been one of the more favoured lasers for SS-OCT applications. The drawback is the requirement of a large cavity length in order to match the roundtrip period to the maximum achievable sweep speed of the filter therefore, do not yet exist as short cavity or integrated lasers.

The various sources listed operate at central wavelengths of 1060, 1310 and 1550 nm. For OCT applications, the choice of operating wavelength will depend on the type of tissue which is being imaged and the required resolution to achieve maximum depth penetration. The absorption of certain types of tissue, which causes attenuation of the reflected signal, needs to be taken into consideration. In general, the spectral bandwidth of the source needs to increase for longer wavelengths to achieve the same axial resolution. This is a similar consideration for LiDAR systems as longer wavelengths can travel further distances. The 1500-2000 nm range of wavelengths are typically used.
2. State of the Art

for Doppler LiDAR and 1040-1060 nm range is used for terrestrial mapping. 1550 nm is the standard datacom wavelength as most optical components (e.g. optical fibers, detectors) operate at this wavelength.

**Figure 2.11:** Comparison of wavelength swept lasers for SS-OCT, data from [73]. Output power value is shown on right in mW. The green category represents the class of short cavity lasers. Abbreviation descriptions and references are provided in Table 2.1.

**Table 2.1:** Descriptions for the swept lasers outlined in Fig. 2.11.

<table>
<thead>
<tr>
<th>Key</th>
<th>Description</th>
<th>Out. Power (mW)</th>
<th>Year</th>
<th>Ref.</th>
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<td>85</td>
<td>2010</td>
<td>[75]</td>
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<td>32</td>
<td>2010</td>
<td>[12]</td>
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<td>2011</td>
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<td>40</td>
<td>2013</td>
<td>[79]</td>
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<td>N/A</td>
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<td>&gt;6</td>
<td>2016</td>
<td>[62]</td>
</tr>
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</table>
2. State of the Art

2.3 Hybrid III-V/silicon lasers

As discussed in Chapter 1, photonic integration on silicon is a promising solution for the mass production of complex photonic elements, due to features such as low-cost manufacture and energy consumption. Silicon has been the preferred material for photonic applications as it can be readily integrated with existing electronic circuit technologies and the fabrication process is well established. The low switching energy demonstrated on silicon has led to the development of silicon based resonant modulators, namely: microdisk [88–90], racetrack [91, 92], microrings [93–98] and 2D PhC resonators [99, 100]. SEM images of these devices are shown in Fig. 2.12 illustrating their \( \mu \)m scale footprint.

![SEM images of devices](image)

**Figure 2.12:** (a) Microdisk resonator from [90], (b) racetrack resonator from [91], (c) microring resonator from [93], and (d) p-n doped 2D PhC resonator from [100]

Silicon has proven to be an efficient low power optical modulator in many
2. State of the Art

of these reports. However, silicon is not an ideal material for light emission/lasing due to its indirect bandgap structure and free-carrier absorption. For this reason, the use of III-V gain materials integrated with silicon has been explored as a solution for use in PICs. The leading motivation for the research discussed below is low power cost efficient optical interconnects and WDM networks hence, the development of devices operating at 1.55 $\mu$m wavelength. Some research groups have explored leveraging silicon photonics technology to further applications such as gas-sensing with absorption bands in or around this wavelength e.g. methane [101–103].

2.3.1 Integration methods

In general, the integration methods are classified as monolithic, heterogeneous and hybrid. Monolithic integration is the direct hetero-epitaxial growth of III-V materials on silicon (Fig. 2.13(a)). However, the fabrication can be challenging due to the lattice mismatch of the materials. Also presenting some challenges is the difference of thermal expansion coefficients of the materials and Wang et al. [104] have used a method of epitaxial lateral overgrowth (ELOG) technology to address this.

The growth of quantum dots on silicon substrates is a viable method due to their lower sensitivity to defects and these have been demonstrated exhibiting low threshold current densities [105–107] but again the fabrication is relatively complicated.

Heterogeneous integration involves the bonding of unprocessed III-V materials to the silicon substrate by means of wafer-to-wafer or die-to-wafer bonding and then addition of a III-V or oxide buffer layer to form the integrated laser (Fig. 2.13(c)). Several laser configurations have been realised with this integration method such as: DFBs [108–110], DBRs [111–113], microrings [114] and microdisks [115, 116].

Hybrid integration involves bonding of the finished and processed III-V gain chip and silicon chip. The gain chip is typically a reflective semiconductor optical amplifier (RSOA) with one highly-reflective facet and one
2. State of the Art

Figure 2.13: III-V/Si laser by (a) monolithic integration by epitaxial lateral overgrowth (ELOG) reproduced from [104]. (b) Hybrid integration by flip-chip bonding, light is coupled to SOI chip through a grating coupler from [117]. (c) Heterogeneous integration by III-V wafer bonding to Si wafer reproduced from [113].

anti-reflective facet and the output light from the RSOA is coupled to the waveguide on the silicon chip which has a reflective element to form the external cavity laser. Light coupling is achieved by either vertical coupling with a grating coupler (Fig. 2.13(b)) or edge-to-edge butt-coupling of the waveguides. The possibility of hybrid integration is the motivation for the single mode laser experimental work in this thesis and some examples with
various silicon based resonators are discussed in Section 2.3.2.

A successful technique for hybrid integration is flip-chip bonding technology demonstrated by Tanaka et al. (Fujitsu) [118] with edge-to-edge coupling. Also demonstrated by Lin et al. (Oracle) [119] employing vertical coupling with grating couplers and the group also reported bonding of an RSOA array with high accuracy passive-alignment [117]. This technique offers improved thermal conductivity between the RSOA and silicon chip with accurate alignment allowing for more flexibility of the design of the active and passive components.

CMOS compatible techniques are an attractive approach as the aforementioned silicon fabrication facilities are well established for mass production. This has been demonstrated by Marchena et al. [120] and Creazzo et al. [121] by metal-bonding unprocessed epitaxial material into the silicon substrate to form an external cavity laser.

The mode coupling efficiency between the RSOA waveguide and the silicon chip waveguide is a consideration for integration. Silicon waveguides are typically used in ring resonator circuits however, silicon has a large mode mismatch with the RSOA waveguide and there are accounts of various methods to address this. One approach is to use a spot size converter to improve the coupling efficiency and Guan et al. [122] and Chu et al. [123] incorporated a silicon nitride (SiN) spot size converter between the RSOA and silicon waveguide. As SiN has better mode matching with the RSOA waveguide, this results in an improved coupling efficiency. Yang et al. [124] adopted an alternative approach by partially etching the silicon layer and creating a tapered waveguide with reduced dimensions. As the tapered waveguide mode is then larger in the vertical direction, this improves the matching to the RSOA waveguide mode. An alternative coupling approach is vertical coupling from the waveguide to the resonator which can be achieved when using a 2D PhC resonator [125]. The waveguide is either SiN or SU-8 material giving improved mode matching to the RSOA waveguide and efficient vertical coupling to the 2D PhC resonator. This is the basis for the work carried out in this thesis and will be further discussed in Chapter 3.
2.3.2 Hybrid integrated III-V/silicon lasers

The use of ring resonators in silicon PICs with an RSOA as the gain medium (Fig. 2.14) has been frequently reported in recent years, the main advantage being their small device footprint and large tunability range due to the relatively large FSR of the microring. Tuning is realised by efficient heating of the microring to change its resonance wavelength based on the refractive index change of the silicon.

Figure 2.14: Vertically coupled hybrid microring laser from [119].

In many reports, the ring resonator acts an optical filter in the RSOA-external cavity configuration and for lasing to occur, a reflective element is required. Previous reports have incorporated a DBR [118] or Sagnac loop mirror [126, 127] as the reflective element to form a Fabry-Perot cavity with a microring as an intra-cavity filter for single mode wavelength selectivity. Wavelength tuning is achieved with an integrated microheater on the microring, changing the refractive index by thermal tuning hence changing the resonance wavelength of the filter. Another approach for single mode selectivity is to use dual-rings with slightly different FSR and tune by the Vernier effect (again by heating) which was recently reported by Guan et al. [122]. Their report showed a quasi-continuous tuning range over 50 nm and an active wavelength stabilisation technique using phase shifters in the cavity.

The use of a directional output coupler and only one microring without an additional reflective element has been demonstrated [119, 128, 129]. The
directional coupler collects the intra-cavity power with reflection from fiber grating couplers at the output ports to form the other facet of the laser cavity. Lin et al. [119] reported such a device with 2.2 nm/mW tuning efficiency and 18 nm tuning range. In a similar optical circuit, an adiabatic microring modulator which has a larger FSR [98] has been reported in an RSOA-external cavity by Yang et al. [124] which showed a tuning efficiency of 1 nm/mW with up to 6 nm tuning range. Lee et al. [130] also used a microring with a directional output coupler with a tuning range of 8 nm for 60 mW heater power and employ an additional dual-ring for Vernier tuning for increased tuning range up to 35 nm for the same applied power.

Figure 2.15: RSOA and silicon PIC including microrings, phase shifters and loop mirrors from [131].

The microring configurations discussed above are optimised for wide quasi-continuous tuning for applications in WDM networks. More recently using an RSOA coupled to a silicon PIC microring configuration, Dong et al. [131] demonstrated a novel tuning mechanism for IM. The PIC comprises two microring filters for increased tunability then 2×2 split to two loop mirrors to close the Fabry-Perot cavity and also contains phase shifters within the cavity (Fig. 2.15). One of the mirrors can be tuned to change its reflectivity and modulation of the output power is achieved via Michelson interferometric modulation. The microrings provide wide tuning range while the phase shifters can fine tune the longitudinal modes. The report showed increased modulation bandwidth beyond the relaxation oscillation frequency realised by modulation of one mirror reflectance highlighting the advantage of this approach over direct modulation (to gain section). The authors demonstrate
40 Gb/s OOK (on-off keying) and 25 Gb/s BPSK (binary phase-shift keying) ideal for applications in coherent optical communications. While this is a high performance example and novel modulation scheme, the drawback is a relatively complex configuration of PIC.

Alternatively, Li et al. [132] have demonstrated a butterfly packaged tunable laser incorporating one microring but the use of an etalon filter is required for single mode wavelength selectivity and includes spot size converters and coupling lenses in the laser cavity. Although the footprint for such a laser is considerably large for use within an optical interconnects circuit, it presents as a useful highly coherent source for applications in optical communication.

Most recently, Zhu et al. [133] have explored using a SiN platform as opposed to Si. SiN offers an advantage of a lower thermo-optic coefficient than Si reducing the need for active cooling. They present a dual-ring configuration for wavelength selectivity and use an InP RSOA for 1.55 µm and a GaAs RSOA for 1 µm wavelength ranges, respectively, allowing for dual-band operation.

As opposed to the microring in an external cavity, a less complex configuration has been explored. Zilkie et al. [134] employ a DBR grating etched into the silicon substrate to act as the reflective element as shown in Fig. 2.16. This is relatively simple in its design in that the main fabrication step is etching on to silicon and the reflected wavelength is determined by the grating period. This laser shows good performance in terms of SMSR and mW
2. State of the Art

output power. However, tuning can only be achieved by heating the system or control of the bias current to the RSOA which exhibits mode-hopping.

The trade-offs for the external cavity configurations are therefore determined as: circuit complexity, tuning range, thermal stability, and device footprint.

2.4 Summary

This chapter gave an overview of the current up-to-date technologies to realise wavelength swept lasers. As can be seen from the review, many solutions are available and the required application will determine which of these is most suitable in terms of the ideal performance, ease of fabrication, mass production and overall cost.

The monolithic approach offers compact devices however, some of these which were discussed have a complicated fabrication process, e.g. VCSELs. Also without the use of an external modulator, the modulation current is typically applied to the entire gain section (e.g. DFB lasers) which consumes larger amounts of power.

The wavelength swept lasers outlined have proven very high performance especially for OCT applications. Currently, most of these swept sources are bulky and expensive and do not exist as integrated solutions. Integration would ultimately bring down the manufacturing cost and the overall device size with the aim of having matched performance to the existing non-integrated devices.

The III-V/silicon hybrid approach has shown to be a good compromise between device performance and cost. By exploiting the broadband gain of III-V materials combined with the high performance of silicon photonics with CMOS processing compatibility makes this an attractive solution for a new class of tunable hybrid lasers. Hybrid microring lasers have shown large SMSR and good tuning ranges with high tuning efficiency as the tuning current can be applied only to the microring component. Bragg gratings also show large SMSR but are relatively longer in length in order to facilitate
2. State of the Art

the Bragg reflectivity. Wavelength tuning can only be realised by current or
temperature change to the entire Bragg section and/or gain section.

The work in this thesis is based on novel 2D silicon PhCs to form the
hybrid laser cavity. These have considerably smaller modal area compared
to microrings, essentially enhancing light matter interaction in the resonator.
This means they have a large Q/V ratio allowing for low capacitance and
better tuning efficiency which will be further discussed in the next chapter.
The vertical coupling scheme (from waveguide to PhC cavity) allows for low
insertion losses and the capability to independently design the waveguide
and PhC cavity for efficient operation. As the PhC cavity is an efficient nar-
rowband optical filter while also acting as a reflector, this allows formation
of a very compact Fabry-Perot laser cavity meaning extended continuous
mode-hop free tuning is possible without any additional elements. This com-
pared to the microring configuration, which requires an additional reflective
element, makes the laser cavities relatively larger thereby increasing overall
device footprint. Similarly for Bragg gratings cavities, the longer length of
these devices will also consequently form a larger laser cavity.

Finally, the novel PhC cavity as a tunable reflector component can be
used in the larger cavity designs in the class of wavelength swept lasers. The
possibility of akinetic tuning of the reflector has the advantage of reaching
sweep speeds of several orders of magnitude higher than the existing typical
mechanical filters. Also having the added advantage of the possibility of
integration to ultimately lead to a highly efficient, compact swept source
laser.
Chapter 3

Tunable Photonic Crystal Laser
Theory and Simulations

The PhC laser presented in the experimental work of this thesis consisted of an optical gain section and a narrowband external reflector. In the single mode configuration, the gain medium was a III-V RSOA and the external reflector was provided by a PhC cavity based resonant reflector. Wavelength selectivity was achieved by the narrowband reflectance peak of the PhC reflector and a short cavity length ensured one longitudinal mode lay within the reflectance band. The characteristics of this type of laser will be examined experimentally in Chapter 4. Tuning of the laser wavelength was achieved by tuning the PhC reflectance band. This chapter aims to give a theoretical description of the laser system and utilising a delay differential equation model to predict laser mode tuning behaviour and output intensity when tuning the reflectance peak which will be explored experimentally in Chapter 5.

3.1 Laser cavity

The optical gain consisted of a multi-quantum well (MQW) SOA (Fig. 3.1). SOAs have been well reported and understood with many references de-
3. Tunable PhC Laser Theory and Simulations

scribing their properties and functionality [22, 135, 136]. Therefore, a brief description of the lasing mechanism is described below and how it pertains to the work in this thesis.

The semiconductor material contains an electron bandgap between the conductance (higher energy level) and valence (lower energy level) bands and when energy is added to the active region, electrons are excited to the conduction band leaving a hole in the valence band. When electron-hole pairs recombine in the active region by radiative recombination, energy is released as a photon with an energy determined by the bandgap (designed for the desired emitted wavelength range). The photon can then stimulate the recombination of another electron-hole pair to release a subsequent photon. The conductivity can be increased by including n-doped and p-doped regions in a separate confinement layer with lower refractive index to confine and increase the number of charge carriers. The quantum wells increase the density of states of carriers which further increases efficiency.

![Figure 3.1: Typical MQW semiconductor optical amplifier from [137].](image)

Spontaneous emission initially occurs from these events and in order for stimulated emission to occur, more electrons must exist in the conduction band than in the valence band referred to as population inversion achieved
3. Tunable PhC Laser Theory and Simulations

by the process of resonating photons through the active region to overcome losses from absorption of photons and non-radiative recombination. This can be realised by formation of an optical resonator surrounding the gain medium to form a laser resonator.

A Fabry-Perot type laser resonator has reflective coated facets enabling photons to resonate through the active region and generate stimulated emission required for lasing action. One facet is required to be partially reflective in order to output the generated laser light. There are a number of factors which govern lasing action such as: carrier lifetime, losses in the cavity and the gain of which their relations are described by the well-known laser rate equations [135, 136].

For this work, we consider a simple Fabry-Perot laser resonator with reflective facets with reflection coefficients, $R_1$ and $R_2$, with an active and passive section (Fig. 3.2). The threshold condition is satisfied when the gain and losses are equal dependent on the reflectivities given by [138]:

$$R_1 R_2 e^{(g - \alpha_i)2L} = 1$$

(3.1)

where $g$ is the modal gain, $\alpha_i$ represents internal cavity losses and $L$ is the length of the cavity including the active and passive sections, $L = L_a + L_p$. The gain threshold condition requires all losses in the cavity to be compensated as:

$$g_{th} = \alpha_m + \alpha_i$$

(3.2)

where $\alpha_m$ describes the mirror loss term [135]:

$$\alpha_m = \frac{1}{2(L_a + L_p)} \ln \left( \frac{1}{\kappa_c^2 R_1 R_2} \right)$$

(3.3)

where $\kappa_c$ is the coupling coefficient ($<1$) between the active and passive sections.

The Fabry-Perot cavity enables longitudinal mode confinement and the roundtrip time of the resonant light determines the FSR i.e. the wavelength separation of the longitudinal modes given by:
3. Tunable PhC Laser Theory and Simulations

Figure 3.2: Laser resonator in 2 mirror configuration with reflectivities $R_1$ and $R_2$. The length of the active section is $L_a$ and the length of passive section is $L_p$. $\kappa_c$ is the coupling coefficient between the active and passive sections.

\[
\delta\lambda = \frac{\lambda^2}{2(n_{ga}L_a + n_{gp}L_p)} \tag{3.4}
\]

where $\lambda$ is the central wavelength, $n_{ga}$ and $n_{gp}$ are the group indices of the active and passive regions, respectively. Solutions to the longitudinal modes are determined by the roundtrip phase condition (discussed in Section 3.3).

3.2 PhC cavity resonant reflector

2D PhCs are realised by the formation of a lattice array of periodic holes in a substrate of a higher refractive index, for example: air holes etched into a silicon substrate. Analogous to semiconductors with different band energies, the differing refractive indices create a photonic bandgap where light of particular optical frequencies are not permitted to propagate. Removing one hole from the periodic structure forms a point defect cavity, and this creates a defect state for an optical frequency in that region. The holes in-plane adjacent to the point defect act as Bragg mirrors and the light of the permitted optical frequency is spatially confined which decays at a rate proportional to the intrinsic quality (Q) factor of the cavity. Given that the PhC cavity confines light highly localised in real space, this results in a broad distribution in Fourier space (k-space) and the strength of optical mode confinement can be interpreted by the spatial Fourier transform. Light with in-plane confinement between two perfect mirrors has a rectangular
function (Fig. 3.3(a)) therefore, the Fourier transform gives two overlapping sinc functions (Fig. 3.3(c)). This abrupt change of the envelope function shows as “leaky” components in k-space equating to losses through vertical radiation ultimately reducing the Q-factor of the cavity.

Figure 3.3: (a) Light confinement in real space between two Bragg mirrors with a rectangular envelope function and (c) corresponding spatial Fourier transform in k-space: two overlapping sinc functions resulting in intensity in the leaky region. (b) Concept of gentle confinement with Gaussian envelope function and (d) corresponding k-space components: two overlapping Gaussian functions achieving significantly reduced intensity in the leaky region.

If the envelope of the field has a less abrupt transition with a gentler profile such as a Gaussian function (Fig. 3.3(b)), the corresponding Fourier transform is a superposition of two Gaussian functions giving significantly reduced intensity in the leaky region (Fig. 3.3(d)). This concept of “gentle confinement” was first proposed by Akahane et al. in 2003 [139] which was a breakthrough in the field to realise high-Q PhC cavities while maintaining a small mode volume (V, i.e. tightly confined electric field spatial distribu-
3. Tunable PhC Laser Theory and Simulations

Reducing the Bragg reflectivity by means of shifting the holes between which the light is confined by precise engineering obtains the Gaussian profile thereby, achieving a high Q/V ratio; a figure of merit with regard to PhC cavities.

Line defect cavities are formed by removing a row of the periodic holes of a PhC to form the resonant cavity [140]. The period of the PhC holes determine the resonant wavelength of the cavity and enhanced control of the resonant wavelength can be realised by shifting of the innermost holes lithographically [141]. The PhC cavities used for the experiments described here were designed as dispersion adapted (DA) cavities as described by Welna et al. [142] where the optical cavity is formed by shifting the innermost holes adjacent to the line defect (Fig. 3.4). These are an extended version of the linewidth modulated cavity for a W1 PhC waveguide [143]. The innermost holes are shifted specifically to match the dispersion curve which creates the Gaussian profile for gentle confinement as described above. The method of hole shift calculation based on the dispersion curve to obtain the Gaussian profile is detailed in Ref. [142]. The design parameters and hole shift positions for the devices used in these experiments are outlined in Table 3.1.

Table 3.1: DA PhC cavity design parameters and hole shift positions. The hole-pair section numbers start with the central hole-pair continuing outwards symmetrically with the shift in x direction (Fig. 3.4(b)).

<table>
<thead>
<tr>
<th>Lattice period (nm)</th>
<th>Hole radius (nm)</th>
<th>Hole shift (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H0</td>
<td>390</td>
<td>40</td>
</tr>
<tr>
<td>H1</td>
<td>90</td>
<td>36</td>
</tr>
<tr>
<td>H2</td>
<td>40</td>
<td>29</td>
</tr>
<tr>
<td>H3</td>
<td>36</td>
<td>22</td>
</tr>
<tr>
<td>H4</td>
<td>29</td>
<td>13</td>
</tr>
<tr>
<td>H5</td>
<td>22</td>
<td>-2</td>
</tr>
<tr>
<td>H6</td>
<td>13</td>
<td>-25</td>
</tr>
<tr>
<td>H7</td>
<td>-2</td>
<td>-6</td>
</tr>
</tbody>
</table>

One of the main advantages DA cavities have over other PhC cavity design approaches [143, 144] is higher coupling rates when employing vertical coupling (see Section 3.2.1). Also, the design permits higher fabrication error tolerances while still achieving a high Q-factor and compatibility with CMOS processing. In the DA cavity, pairs of holes are shifted requiring 10s of nm precision. In comparison to other cavity types where one hole or
3. Tunable PhC Laser Theory and Simulations

Figure 3.4: (a) SEM image of PhC with DA cavity formed by the shifted innermost holes adjacent to the line defect. (b) DA cavity design showing the sections of hole shift pairs with respect to a W1 waveguide configuration. Hole shift values are given in Table 3.1. (c) Isometric drawing of PhC on-chip with the shifted holes indicated in purple.
few holes are removed, shifting of the innermost holes to obtain a high Q-factor generally require single digit nm precision making these incompatible with CMOS processing as photolithography mask grid sizes are in 10s of nm. Although, the smaller cavities have the advantage of a very large FSR and/or often support just one resonant mode.

Given the length of the line defect in DA cavities, higher order resonance modes can be supported in the cavity. Since light resonates in the PhC cavity, it can be considered as a Fabry-Perot resonator where the multiple resonance modes which exist are separated by the FSR of the PhC cavity (see Section 3.2.2). This is one trade-off for DA cavities in comparison to other design approaches with large FSR or which support just one resonant mode however again, DA cavities are favoured for compatibility with CMOS processing and result in high manufacturing yield. Also, the drawback of reduced FSR is outweighed by low insertion loss when employing vertical coupling. The advantage of low insertion loss when using the PhC cavity as a reflector in a laser cavity helps to realise low threshold by providing substantial reflectivity which will be demonstrated experimentally in Chapter 4.

Other silicon based optical filters such as microrings (as discussed in Chapter 2) typically employ a method of side coupling. The coupling efficiency is determined by the gap between the waveguide and the microring. These can operate as “add-drop” filters where the resonant wavelength of the microring determines the filter transmission through the waveguide. Similarly for the 2D PhCs described here, the bandwidth of reflection is proportional to the photon lifetime in the resonator, i.e. the Q-factor. 1D PhCs such as Bragg gratings where in-plane coupling is employed, the reflected wavelength is determined by a defect in the periodic structure. The bandwidth of reflectivity is dependent on the index contrast variation giving constructive and destructive interference of the reflected wavelengths between the gratings.

For the 2D photonic crystals used here, the light at the resonant wavelength of PhC cavity is reflected back to the waveguide and any other light propagating through the waveguide is transmitted (excluding any losses in-
3. Tunable PhC Laser Theory and Simulations

In this respect, the PhC cavity acts as an optical filter [125] and light propagating at the resonant wavelengths will therefore be reflected back hence, the PhC cavity acts as a narrowband reflector with an approximated Lorentzian shape. Thereby, qualifying the term “reflective filter” and also interchangeably referred to as either “reflector” or “filter” throughout this thesis. In order for light to resonate within the cavity, a method for coupling must be employed.

3.2.1 Vertical coupling to PhC cavity

Several methods of coupling to PhC cavities have been demonstrated such as in-plane waveguide coupling or side coupling [145]. These devices show high coupling loss and therefore are not suitable as reflector components for an EC laser. The vertical coupling scheme was originally proposed for a silicon waveguide to a silicon PhC cavity by Qiu in 2005 [146] and has since been utilised for low refractive index waveguides to couple efficiently to a higher refractive index silicon PhC cavity as described by Debnath et al. [125]. This novel vertical coupling approach with two differently index matched materials is realised by a k-space momentum overlap between the waveguide mode (Fig. 3.5(a)) and the PhC cavity mode (Fig. 3.5(b)). On account of the ultra-small mode volume of the PhC cavity, its k-space distribution is expanded and achieves coupling to the narrow distribution of the waveguide optical mode. In terms of real space, light propagating through the waveguide at the resonant wavelength evanescently couples to the PhC cavity (Fig. 3.5(c)). The waveguide is located on a vertical layer above the PhC cavity and usually features an optical buffer layer material (such as oxide) between them (Fig. 3.5(d)).

The transmission (T) and reflection (R) properties of the device depends on the efficiency of light confinement of the PhC cavity and the coupling parameters to and from the waveguide and the PhC cavity. The coefficients
3. Tunable PhC Laser Theory and Simulations

Figure 3.5: k-space distribution (i.e. Fourier transform of spatial mode profile) of (a) waveguide and (b) fundamental PhC cavity mode from [125]. (c) Side view schematic representation of vertical coupling scheme from waveguide to PhC cavity in real space. (d) Isometric drawing of vertically coupled waveguide and PhC cavity system.

for T and R are [147]:

\[
T = \frac{\Delta \omega^2 + (\Gamma^0)^2}{\Delta \omega^2 + (\Gamma^0 + \Gamma^c)^2} \tag{3.5}
\]

\[
R = \frac{(\Gamma^c)^2}{\Delta \omega^2 + (\Gamma^0 + \Gamma^c)^2} \tag{3.6}
\]

where \(\Delta \omega = \omega - \Omega\), with \(\omega\) being the frequency of the incident light and \(\Omega\) is the resonant mode frequency, \(\Gamma^0\) is the intrinsic loss of the resonator and \(\Gamma^c\) is the energy decay rate from the cavity to the waveguide. The quality factor, \(Q\) is commonly used to describe parameters of PhC cavities and its
relationship to the decay rate is $\Gamma = \Omega/2Q$ [148]. Given these relations, then at the resonance frequency i.e. $\omega = \Omega$, the transmission and reflection coefficients can therefore be expressed as a function of the quality factors [125]:

$$T = \frac{Q_t^2}{Q_0^2}, \quad R = \frac{Q_t^2}{Q_c^2}$$

(3.7)

where $Q_0$ is the intrinsic quality factor of the PhC cavity and $Q_c$ is the quality factor of the coupling of the waveguide mode and PhC mode therefore, the total quality factor $Q_t$ is:

$$\frac{1}{Q_t} = \frac{1}{Q_0} + \frac{1}{Q_c}$$

(3.8)

The coupling quality factor is inversely related to the coupling rate: $\gamma = 1/Q_c$ and a larger $\gamma$ means more efficient coupling between the waveguide and PhC cavity therefore, more light is reflected giving higher reflectivity. $Q_0$ is a figure of merit for PhC cavities as it describes the efficiency of light confinement. When light at a resonant wavelength couples from the waveguide to the cavity, it is stored for a period of time proportional to the decay rate and higher $Q_0$ cavities will store the energy more efficiently. This determines important parameters such as the extinction ratio (ER) for modulator design, filter finesse and the reflection bandwidth which pertains to the reflector functionality in an EC laser. The total quality factor can be obtained directly from the transmission spectrum by measuring the full-width half-maximum (FWHM) of the transmission dip and its central wavelength as:

$$Q_t = \frac{\lambda}{\text{FWHM}}$$

(3.9)

hence, the intrinsic quality factor is determined from:

$$Q_0 = \frac{Q_t}{\sqrt{T}}$$

(3.10)

where $T = T_{\text{min}}/T_{\text{max}}$ i.e. the normalised minimum and maximum transmission values obtained from the spectrum. Finally, the coupling quality factor
3. Tunable PhC Laser Theory and Simulations

can be calculated using the relation:

\[ Q_c = \frac{Q_0 Q_t}{Q_0 - Q_t} \]  \hspace{1cm} (3.11)

In the next section, these quality factors and relations are used to establish the reflection properties of the PhC resonance modes.

### 3.2.2 PhC cavity resonance modes

As previously mentioned, the shifted holes adjacent to the line defect of the periodic holes in the PhC structure forms the optical resonator. The length determines the FSR of the PhC cavity resonator and gives the possibility to support higher order resonance modes. Each resonance mode has a different total quality factor, \( Q_t \) given by Eq. 3.8 due to the various coupling rates by the mode area overlap with the waveguide. High coupling rates result in a large ER and a higher reflectivity as the light which is resonant in the PhC cavity is efficiently reflected back through the waveguide. \( Q_t \) also depends on the intrinsic quality factor, \( Q_0 \) which differs for each mode and determines the bandwidth of the reflection peak. The variation in \( Q_0 \) between the resonance modes is attributed to their difference in mode volume.

![Figure 3.6](image)

**Figure 3.6:** FDTD simulation of transmission and reflection spectra of PhC resonances with (a) SU-8 and (b) SiN waveguide. The fundamental mode is at the longest wavelength side and increasing mode order from right to left. (Simulations courtesy of Praveen K.J. Singaravelu.)
3. Tunable PhC Laser Theory and Simulations

A Finite-Difference Time-Domain (FDTD) simulation was implemented to produce the transmission and reflection spectra for a polymer SU-8 waveguide with dimensions of width by thickness \((W \times T) = 3 \times 2 \, \mu m\) (Fig. 3.6(a)) and a SiN waveguide \(W \times T = 1 \times 0.5 \, \mu m\) (Fig. 3.6(b)). Parameter values used in the simulations are listed in Table 3.2. A perfectly matched layer (PML) boundary condition was applied to absorb diffracted light from the PhC cavity and waveguide.

It can be seen that there are variations in the bandwidth and reflectivity for the resonance modes. It must be noted that the simulations are not fully resolved due to computational power limitations. Therefore, both materials in the simulation cannot be accurately compared to each other but instead this gives a comparison between their respective resonance modes.

Table 3.2: Parameters for FDTD simulations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation package</td>
<td>Lumerical FDTD Simulator</td>
</tr>
<tr>
<td>Excitation type</td>
<td>Optical mode source (1.52 - 1.62 , \mu m)</td>
</tr>
<tr>
<td>Monitors</td>
<td>Frequency domain power and electric field</td>
</tr>
<tr>
<td>Run time</td>
<td>50,000 fs</td>
</tr>
<tr>
<td>Mesh grid conditions</td>
<td>(dx = 19), (dy = 16), (dz = 22 , nm)</td>
</tr>
<tr>
<td>SU-8 wg dimensions ((W \times T))</td>
<td>(3 \times 2 , \mu m)</td>
</tr>
<tr>
<td>SiN wg dimensions ((W \times T))</td>
<td>(1 \times 0.5 , \mu m)</td>
</tr>
</tbody>
</table>

Fig. 3.7 shows the lateral view of the FDTD simulated mode field profiles for the fundamental, second and third order resonance modes on coupling from the SiN waveguide in Fig. 3.6(b). The energy density is represented by the colour scale with highest energy density shown in red. The plots indicate the propagation of the waveguide mode and coupling into the PhC cavity mode. The ripple effect is on account of the time averaged electric field of the mode propagation. For the fundamental mode, a large amount of energy is at the centre of the cavity and has a typical Gaussian profile. For the higher order modes, the energy is dispersed and covers a larger mode volume and these have a more complex profile compared to the fundamental mode.
3. Tunable PhC Laser Theory and Simulations

These profiles indicate the reflection properties for each mode where the fundamental mode has the smallest bandwidth value showing a large energy density indicating high $Q_0$. The second mode has a larger bandwidth given by the larger mode area and a high energy density with high reflectivity indicating a high coupling rate. Finally, the third mode has the largest mode area and least energy density resulting in a larger bandwidth and less reflectivity due to lower coupling rates. Again, it must be noted that the simulations are not fully resolved therefore, the finite simulation time gives an initial approximation of these values.

![Figure 3.7: Side view of time averaged FDTD simulated mode field profiles from SiN waveguide to PhC cavity for (a) fundamental mode, (b) second order mode and (c) third order mode. (Simulations courtesy of Praveen K.J. Singaravelu.)](image)

Both the SU-8 waveguide and SiN waveguide were used in the devices for the experimental work. There are trade-off properties for each waveguide such as: SU-8 has a lower effective index relative to silicon therefore, a lower coupling rate to the PhC cavity compared to SiN. Both waveguides confine the fundamental transverse electric (TE) mode efficiently and the larger dimensions of the SU-8 waveguide (in order to ensure mode confinement) achieves better mode area matching for coupling to the RSOA waveguide and lensed fiber. Although SiN has better reflection properties due to more favourable waveguide-to-PhC cavity coupling, SU-8 has the advantage of improved waveguide-to-waveguide coupling to the RSOA. In that respect, there is somewhat of a balance between both waveguides efficiency in terms of the reflection properties in an EC laser configuration.
3.2.3 Resonance wavelength tuning

Utilisation of the PhC cavity as the reflector in an EC laser enables wavelength selectivity owing to the narrowband reflection peak as shown above. By exploiting the electro-optic or thermo-optic effect of silicon, tuning of the reflectance peak can be realised. Doping of the cavity and addition of a p-n junction facilitates injection of carriers into the cavity which will initially decrease the refractive index and cause a blue-shift of the resonance wavelength. Further increase of carriers will locally heat the PhC cavity causing an increase in refractive index and consequently red-shifting the resonance. This can also be achieved by fabrication of a microheater close to the PhC. These methods and experimental results are discussed in more detail in Chapter 5. Carrier depletion will also shift the resonance but this weak effect does not substantially shift the resonance for operation in the laser configuration but has potential with improved fabrication design. Therefore, the focus of the experimental work is on the thermo-optic effect and red-shifting of the resonance wavelength.

The amount of wavelength shift is proportional to the refractive index change of the material with the relationship:

\[
\frac{\Delta \lambda}{\lambda_0} \approx \frac{\Delta n}{n}
\]  

(3.12)

where \(\lambda_0\) is the resonance wavelength, \(\Delta \lambda\) is the change in resonance wavelength, \(n\) is the refractive index and \(\Delta n\) is the change in refractive index. The thermo-optic coefficient of silicon is \(dn/dT = 1.86 \times 10^{-4} \text{K}^{-1}\) (for 1550 nm at room temperature) [149], corresponding to a refractive index change of \(10^{-3}\) per \(6^\circ\text{C}\).

In the laser configuration, tuning of the resonance wavelength results in tuning of the lasing wavelength and enables wavelength sweeping and frequency modulation. The next sections will discuss the tuning of the single mode laser wavelength by tuning the reflectance peak providing an explanation of the mode tuning mechanism.
3. Tunable PhC Laser Theory and Simulations

3.3 Single mode laser tuning theory

As described previously, the emitted wavelength of the PhC EC architecture is defined by the overlap of a longitudinal mode of the laser cavity with the reflection band of the PhC resonant reflector. Later in Chapter 5, FM is demonstrated of this configuration by tuning the reflector resonance via thermo-optic tuning. Refs. [150–152] have measured experimentally the phase change over the reflection band for PhCs. Their results show the reflection phase $\phi_r$ shifts across the stop band of the reflective filter by $0 \leq \phi_r \leq \pi$ which is further illustrated for a PhC cavity in [153].

Assuming a Lorentzian shape for a PhC cavity-based reflector (Fig. 3.8(a)), close to the filter centre the reflection phase (Fig. 3.8(b)) is given by:

$$\phi_r = \arctan\left(\frac{2\pi \nu}{\Gamma}\right) \approx \left(\frac{2\pi \nu}{\Gamma}\right)$$

(3.13)

where $\Gamma$ is half the reflection bandwidth in radians, $\nu$ is the optical frequency and the linear approximation is valid close to the filter center, i.e. where the reflectivity is highest. The propagation phase, $\phi_{prop}$ increases linearly with increasing frequency as given by $2\pi \nu T$, where $T$ is the cavity roundtrip period therefore:

$$\phi_{prop} = \frac{2\pi \nu}{FSR}$$

(3.14)

where FSR is the Free Spectral Range of the laser cavity. The sum of the propagation phase and the reflection phase is the total accumulated phase and the lasing solution is satisfied by:

$$\phi_{prop} + \phi_r = 2\pi m$$

(3.15)

where $m$ is an integer. This is illustrated on Fig. 3.8(c) which shows the solution existing at the intersection of a laser cavity mode and the total accumulated phase, that lies within the reflection band. If the reflection band is tuned by $\Delta F$, the phase at every frequency near the reflection band
3. Tunable PhC Laser Theory and Simulations

Figure 3.8: (a) The reflection peak aligned with the longitudinal mode shifts by $\Delta F$ and (b) the reflection phase, $\phi_r = \arctan(2\pi\nu/\Gamma)$ occurs across reflection peak and shifts by same amount. (c) The total accumulated phase is the sum of the propagation phase, $\phi_{\text{prop}} = 2\pi\nu T$ and the reflection phase. The single mode lasing solution exists at the intersection of the cavity mode, $m$ and the total accumulated phase. The solution shifts by $\Delta \nu$ and exists on the same cavity mode (green points).

centre will change by:

$$\Delta \phi = -\Delta F \left(\frac{2\pi}{\Gamma}\right)$$  \hspace{1cm} (3.16)

To maintain the roundtrip phase condition the lasing mode shifts by $\Delta \nu$, leading to the following relation:

$$-\Delta F \left(\frac{2\pi}{\Gamma}\right) + \Delta \nu \left(\frac{2\pi}{\Gamma}\right) + \Delta \nu \left(\frac{2\pi}{FSR}\right) = 0$$  \hspace{1cm} (3.17)
Re-arranging Eq. 3.17 gives the modal frequency shift needed to retain phase matching as:

$$\Delta \nu = \Delta F \left[ \frac{1}{1 + \frac{\Gamma}{FSR}} \right]$$  \hspace{1cm} (3.18)

This linear approximation shows that the lasing frequency shift $\Delta \nu$ is less than the reflector shift $\Delta F$ (Fig. 3.8), and with a larger FSR to filter width ratio, the laser mode frequency follows the filter centre frequency more closely.

With this approximation, taking a value of a reflector half width $\Gamma = 7.5$ GHz (linear, 47.12 in gigaradians per second) and $FSR = 80$ GHz, a lasing frequency shift $\Delta \nu$ of 5 GHz requires a reflector shift $\Delta F$ of 7.95 GHz. If the initial condition is that the starting mode-reflector detuning is zero i.e. 100% reflectivity, then for a lasing frequency shift of 5 GHz, this will result in a 0.7 dB reduction in the reflectivity which would require a modest 0.35 dB increase in the gain per pass to maintain lasing.

To examine the longitudinal mode tuning range as determined by the filter width and the FSR, we assume an allowed mode-to-filter detuning of one filter half width ($|\Delta F - \Delta \nu| \leq \Gamma/2\pi$) then from Eq. 3.18:

$$\left| \Delta \nu \left(1 + \frac{\Gamma}{FSR} \right) - \Delta \nu \right| \leq \frac{\Gamma}{2\pi}$$  \hspace{1cm} (3.19)

This gives then a maximum laser mode tuning range of:

$$\Delta \nu = \frac{FSR}{\pi}$$  \hspace{1cm} (3.20)

This result shows that the longitudinal mode tuning while remaining close to the filter centre depends only on the value of the FSR and it is independent of the width of the reflector, so for a larger FSR, a wider tuning of the lasing mode can be realised. Narrower values for $\Gamma$ will lead to better mode-to-filter tracking, but the reflector half-width is proportionally smaller also and the two effects cancel (within the limits of the linear approximation).

While this is a reasonable approximation for operation close to the reflectance peak, the various dynamics within the laser cavity are neglected,
3. Tunable PhC Laser Theory and Simulations

such as: carrier density, alpha-factor and losses in the cavity and the effect they have on the mode tuning and output intensity. Therefore, in the following section, the SOA parameters are applied to a model and the system is numerically explored as it undergoes mode tuning.

3.4 Single mode laser tuning simulations

To model the single mode laser numerically, an adapted delay differential equation model for the electric field envelope and the saturable gain of the SOA is used, similar to that used to describe passively mode locked lasers in [154] but without the equation for saturable absorption. This model has been applied for swept source lasers which consist of an SOA and Lorentzian filter and has been used to predict the electric field and temporal dynamics of an FDML laser [155], and short cavity laser [156] with close agreement between theoretical and experimental results.

To apply the model for the single mode laser geometry, the parameters were set to attain $\Gamma < \text{FSR}$. In the simulations, the model was applied by stepping the reflector central frequency, allowing a short wait time for the intensity to stabilise to disregard transient effects, and then calculate the average value of intensity. As the reflector central frequency was stepped, the laser mode frequency was calculated as a function of detuning from the reflector central position. In the model this represents a slowly swept filter in which these conditions are most relevant to the work in Chapter 5.

The system variables were explored in the simulations and subsequent analysis of the effect they have on the laser output intensity and mode frequency detuning. These included: reflector bandwidth to FSR ratio, alpha-factor, analysis of hysteresis behaviour dependent on the reflector tuning direction, and SOA DC bias condition (pump parameter).
3. Tunable PhC Laser Theory and Simulations

3.4.1 Model description

The set of model equations used in the simulations have been derived in [155–158] which define the time evolution of the electric field envelope, $A(t)$ and saturable gain of the SOA, $G(t)$ as:

$$\dot{A}(t) + (1 - i \Omega)A(t) = \sqrt{\kappa} e^{\frac{1-i\omega}{2}(t-T)}A(t-T)$$  \hspace{0.5cm} (3.21)

$$\dot{G}(t) = \gamma \left( g_0 - G(t) - \left( e^{G(t)} - 1 \right) |A(t)|^2 \right)$$  \hspace{0.5cm} (3.22)

respectively, where $\alpha$ is the linewidth enhancement factor, $\kappa$ is the linear attenuation factor, $T$ is the cavity roundtrip time and $g_0$ is the pump parameter. $\gamma$ is the carrier density relaxation rate normalised to the filter half width, $\Gamma$ and $\Omega$ is the filter central frequency, $F$ normalised to $\Gamma$.

In the case of a static reflector, the electric field envelope takes the form $A(t) = A_0 e^{i\omega t}$, where $\omega$ is $2\pi\nu$ and the gain variable is constant as $G(t) = G_0$. Thereby, each mode solution with index $n$ can be satisfied with:

$$\text{arg}(1 + i(\omega_n - \Omega)) = -\frac{\alpha}{2} \ln \left( \frac{1 + (\omega_n - \Omega)^2}{\kappa R} \right) - \omega_n T$$  \hspace{0.5cm} (3.23)

where $R$ is the reflectivity of the output mirror. The intra-cavity intensity of each mode solution is given by:

$$I_{cn} = \frac{\kappa R (g_0 - \ln (1 + (\omega_n - \Omega)^2) + \ln \kappa R)}{1 - \kappa R + (\omega_n - \Omega)^2}$$  \hspace{0.5cm} (3.24)

hence, the transmitted output power for a given mode solution is calculated as a function of the reflected power in the cavity dependent on the mode-to-filter detuning, carrier density, gain and roundtrip losses to obtain:

$$I_{outn} = I_{cn} \kappa R e^{G_0} \left( 1 - \frac{R}{1 + (\omega_n - \Omega)^2} \right)$$  \hspace{0.5cm} (3.25)

Fig. 3.9 shows the position of the lasing mode which is determined by the overlap of the gain spectrum and the reflection peak of one PhC cavity.
3. Tunable PhC Laser Theory and Simulations

resonance which exists at a longitudinal mode solution of the laser cavity. In the simulations below, one reflection band and a flat gain spectrum was considered which was adequate for the small mode tuning ranges demonstrated in the next sections.

Figure 3.9: Lasing mode (red) determined by the overlap of the gain spectrum (blue) and reflection peak of one PhC cavity resonance (black) at a longitudinal mode solution (green).

Investigation of the single mode laser configuration was carried out using the equations above applied to the simulations. By applying the case for the static reflector, the mode solution and output intensity was determined. Then stepping the reflector central frequency resulted in a new mode solution and output intensity. Unless otherwise stated, the parameters in Table 3.3 were applied in the simulations. The linear attenuation factor, $\kappa = 0.2$ was estimated from roundtrip losses in the cavity. The coefficient of reflection from the output mirror was estimated as $R = 0.4$. An estimated value of the linewidth enhancement factor, $\alpha = 3$ was chosen as this is a typical value for standard SOAs although this has not been experimentally measured here. Similarly for the carrier relaxation rate, $\gamma = 1 \text{ GHz}$ is a typical value for these devices but was not experimentally measured. The reflector half width, $\Gamma$
3. Tunable PhC Laser Theory and Simulations

and roundtrip period, \( T \) were values obtained experimentally, although, a range of these values were found for the different devices but these values in particular were closer to ideal conditions. The pump parameter, \( g_0 \) relates to the SOA bias condition and was set to 5.3 (discussed later in Section 3.4.5). In the model, \( g_0 \) is the unsaturated gain per roundtrip and is equal to 0 at transparency therefore, has a particular value representing the threshold current depending on the system and lasing occurs at multiples of that value.

**Table 3.3:** Default parameters for simulations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \kappa )</td>
<td>Linear attenuation factor</td>
<td>0.2</td>
</tr>
<tr>
<td>( R )</td>
<td>Reflection coefficient</td>
<td>0.4</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>Linewidth enhancement factor</td>
<td>3</td>
</tr>
<tr>
<td>( T )</td>
<td>Roundtrip period</td>
<td>25 ps</td>
</tr>
<tr>
<td>( \Gamma )</td>
<td>Reflector half bandwidth</td>
<td>7.5 GHz</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>Carrier relaxation rate</td>
<td>1 GHz</td>
</tr>
<tr>
<td>( g_0 )</td>
<td>Pump parameter</td>
<td>5.3</td>
</tr>
</tbody>
</table>

The next sections explore variation of these parameters to gain insight to the behaviour of laser system and allowing for optimisation of parameter values depending on the desired output while the single mode laser undergoes tuning with the narrowband reflectance peak shift.

3.4.2 Reflector bandwidth and FSR ratio

For the linear approximation in Eq. 3.18, the ratio of reflector bandwidth to the FSR determines how closely the lasing mode will track the reflectance peak shift. To investigate this approximation and the tuning range dependence on the reflector bandwidth to FSR ratio, a single parameter was varied. All parameters from Table 3.3 were applied and only the reflector bandwidth was varied with \( 2\Gamma = 10 \text{ GHz}, 15 \text{ GHz} \) and 20 GHz. Figs. 3.10(a) and 3.10(b) show the resulting mode tuning and output intensity dependence on the reflector bandwidth for a fixed FSR of 40 GHz.
3. Tunable PhC Laser Theory and Simulations

The approximation in Eq. 3.20 states the frequency tuning range is independent of the filter bandwidth and only depends on the FSR while staying close to the filter centre. While this holds true for the reflector tuning range as can be seen from Fig. 3.10(a) where the reflector tuning range is one FSR for each filter width then a mode-hop occurs outside this range. However, on account of the reflector bandwidth and FSR ratio, the laser mode tracks by a different amount for each width over the reflector tuning range. Since Eq. 3.20 is a linear approximation with an assumed shift of half a filter width then its validity was examined by calculating the mode tuning range from the aligned position of mode and reflector peak at -15.9 GHz (this asymmetry is explored later in relation to the alpha-factor in Section 3.4.3). Taking half

Figure 3.10: Simulation results of reflector shift for a fixed FSR of 40 GHz for reflector widths of 10 GHz, 15 GHz and 20 GHz for (a) laser frequency shift with black cross indicating aligned mode and reflectance peak position at -15.9 GHz and (b) corresponding intensity output. Fixed reflector width of 15 GHz for FSR of 10 GHz, 25 GHz and 40 GHz for (c) laser frequency shift and (d) corresponding intensity output.
the filter width from this point in each direction and determining the laser mode tuning range results in 4.06 GHz, 5.17 GHz and 5.9 GHz for widths 10 GHz, 15 GHz and 20 GHz respectively, which is reasonably close to the linear approximation in Eq. 3.20 in that, the mode tuning range is independent of filter width when operating close to the filter centre within half a filter width tuning range.

Further examination of the tuning range was performed by keeping the filter width constant at 15 GHz and setting FSR = 10 GHz, 25 GHz and 40 GHz (Figs. 3.10(c) and 3.10(d)). Again, mode-hopping occurs when the reflector is tuned beyond one FSR as above and the mode tracking is improved with a larger FSR to reflector bandwidth ratio. Notably, for the smallest FSR value of 10 GHz, there is a very slight mode shift as $2\Gamma > \text{FSR}$, highlighting the significance of ensuring a large FSR to reflector bandwidth ratio to achieve substantial mode tuning with the reflector shift.

The corresponding intensity plots show a small reduction in output power when the mode is aligned with the reflectance peak (Figs. 3.10(b) and 3.10(d)) due to the higher reflectivity giving more reflected power in the cavity (discussed later in Section 3.4.5). This power change tends to curve as the mode tunes around the reflectance peak. The output power then drastically reduces as the detuning between the reflectance peak and mode further increases.

### 3.4.3 Influence of alpha-factor

The alpha-factor or linewidth enhancement factor, describes the change in gain with the change in carrier density and the resulting change in refractive index dependent on carrier density [159]. This produces a phase shift to all the laser wavelengths described by the relation [135]:

$$\alpha = -\frac{4\pi}{\lambda} \frac{dn}{dN} \frac{dg}{dN}$$

(3.26)
where $n$ is the refractive index, $N$ is the carrier density, $g$ is the gain and $\lambda$ is the wavelength.

In the simulations above, a value of $\alpha = 3$ was applied. Asymmetry in the detuning can be seen in that, for zero detuning of the reflector, the lasing mode is detuned from the reflectance peak. To further investigate the detuning relationship and asymmetry, simulations were performed for varying values of $\alpha$ to determine the effect on mode detuning from the reflectance peak.

![Figure 3.11](image)

**Figure 3.11:** (a) Laser frequency shift as a function of reflector shift for alpha values of 0, 1, 2 and 3 with black crosses indicating aligned mode and reflectance peak position. (b) Laser frequency shift (blue) and output intensity (red) as a function of reflector frequency shift for alpha values of 0 (solid lines) and 3 (dashed lines).

Fig. 3.11(a) shows the reflector-mode relationship for $\alpha = 0, 1, 2$ and 3 with the black crosses indicating perfect alignment of reflectance peak and lasing mode. By examining $\alpha = 0$, it can be seen that at zero reflector detuning, the lasing mode is also at zero indicating perfect alignment of the lasing mode with the reflectance peak. As the reflector is detuned by either positive or negative frequency, the lasing mode behaviour is symmetrical. The reflector-mode relationship in this situation for the linear region is solely attributed to the reflector bandwidth to FSR ratio as described above. The slope at the centre where the phase is linear equals the approximation given by Eq. 3.18 with a value of 0.46.
3. Tunable PhC Laser Theory and Simulations

Increasing values of $\alpha$ showed to increase the reflector-mode detuning by shifting all frequencies to higher values. The alignment position shifted to 8.04 GHz, 16.1 GHz and 24.06 GHz for $\alpha$ values of 1, 2 and 3, respectively. The mode tuning range extends for higher $\alpha$ values, within reason in that, for positive detuning of the reflector from the mode alignment position, there is a larger range of mode tuning before mode-hopping to the higher frequency. Although, for negative detuning from the reflector-mode alignment, the range is considerably less until mode-hopping occurs to the lower frequency.

The increase of the mode frequency with increasing $\alpha$ values was expected given the relationship in Eq. 3.26 in that, a larger $\alpha$ value leads to an increase in carrier density, reducing the refractive index essentially reducing the cavity length therefore, reducing the wavelength (blue-shift) i.e. increasing the mode frequency.

In Fig. 3.11(b), $\alpha = 0$ and $\alpha = 3$ are compared for the lasing frequency shift and output intensity. Again, showing symmetric tuning behaviour for $\alpha = 0$ and the reduced intensity at zero detuning indicating the reflector peak position. The comparison with $\alpha = 3$ shows the adjacent lower frequency mode solution which exists in approximately the same reflector tuning region for $\alpha = 0$. Again, the mode tuning range is extended for positive detuning although, consequently there is a larger reduction in output power with further detuning as the mode has moved significantly from the reflectance peak in this region.

3.4.4 Hysteresis behaviour

All the above simulations were performed by stepping the filter from right to left i.e. decreasing frequency, increasing wavelength. To examine the effect on the mode behaviour with tuning direction, the reflector was also stepped in the opposite direction from left to right. Using parameters again from Table 3.3 with alpha = 3 and both tuning directions for filter widths of 10 GHz and 20 GHz are shown in Figs. 3.12(a) and 3.12(c), respectively.
3. Tunable PhC Laser Theory and Simulations

For the 10 GHz filter width, hysteresis behaviour can be seen in the region where the reflectance peak and mode align. With opposite tuning directions of the reflector, bistable states are evident at the point of mode-hopping. A larger hysteresis loop width of 3.22 GHz was observed for the 10 GHz reflector compared to 1.4 GHz for the 20 GHz reflector indicating an increased hysteresis effect with reduced reflector bandwidth. The same effect and loop width was observed on the intensity output. A reduced FSR gave a reduced loop width, similarly for a wider reflector bandwidth as the mode solution exists within a shorter range within the reflector bandwidth then as the reflector shifts, there is less range of bistable states.

![Graphs showing hysteresis behaviour](image)

**Figure 3.12:** Hysteresis behaviour at mode-hopping points for decreasing reflector frequency steps (solid lines) and increasing reflector frequency steps (dashed lines) for (a) reflector width of 10 GHz showing hysteresis loop width of 3.22 GHz and (c) reflector width of 20 GHz showing hysteresis loop width of 1.4 GHz. Corresponding laser frequency shift as a function of the gain variable for reflector widths of (b) 10 GHz and (d) 20 GHz.
The bistable states for opposite tuning directions can be explained by considering the carrier density and refractive index relationship, determined by the alpha-factor (Section 3.4.3). Figs. 3.12(b) and 3.12(d) show the corresponding laser frequency shift as a function of the gain change (which is proportional to the carrier density). The gain is at a minimum when the mode and reflectance peak align as there is more power reflected into the cavity. At the point of mode-hopping, a smaller gain value leads to a larger mode frequency jump as the refractive index change is greater. This can be attributed to the wider reflector bandwidth providing more reflected power in the cavity over a larger range resulting in less gain. The hysteresis presents with tuning of the reflector central frequency in opposite directions showing the difference of gain and carrier density. This is dependent on the previous state in that, the carrier density sets the refractive index determining the phase relationship thereby, the reflector-to-mode position. The solution for those set of parameters then holds until the point of mode-hopping. For the opposite direction, the gain and carrier density are at a different value thereby, setting a different reflector-to-mode position while sustaining the solution for a different range.

Later in Chapter 4, it is shown experimentally the existence of bistable states based on the dependence of the mode solution on the previous solution given by the refractive index change and the relative reflector-to-mode position.

3.4.5 Optimisation of pump parameter for low IM

The laser IM accompanying FM as a function of the DC biasing condition is numerically explored in this section. These are expected to be related, as for a fixed DC bias and a reduced output mirror reflectivity, the intra-cavity laser power will decrease (due to threshold increase), but at the same time a larger fraction of the internal power is transmitted as less power is being reflected back into the cavity. The SOA bias is given by the pump parameter $g_0$. 

70
3. Tunable PhC Laser Theory and Simulations

Simulations were performed with the parameters in Table 3.3 but with $T = 12.5$ ps for an FSR = 80 GHz and with varying values of $g_0$ from 3-8 in steps of 0.01. The IM over a set modulation range was obtained for each stepped value of $g_0$ and was calculated using the equation:

$$ IM_{(dB)} = 10 \log \left( \frac{I_{max} - I_{min}}{I_{avg}} \right) $$  \hspace{1cm} (3.27) 

with $I_{max}$, $I_{min}$ and $I_{avg}$ as the maximum, minimum and average intensity, respectively.

Figure 3.13: Simulations of the IM vs. $g_0$ for modulation range of (a) 5 GHz and (b) 20 GHz. Laser output intensity (red) and laser frequency (blue) as a function of reflector shift (with reflector-mode alignment set at frequency = 0) for modulation range of (c) 5 GHz and (d) 20 GHz. The green dashed line indicates a perfect 1:1 relationship between the laser and reflector frequency, and the purple dashed line is the predicted linear relationship in Eq. 3.18. The solid black lines are the mode tuning range limits of 5 GHz and 20 GHz (8.3 GHz and 27.5 GHz for reflector).
3. Tunable PhC Laser Theory and Simulations

Figs. 3.13(a) and 3.13(b) show the IM as a function of $g_0$. As explained in Chapter 2, a low IM or pure FM laser can be beneficial for communications or sensing applications therefore, the lowest IM for a fixed $g_0$ is taken to be the optimal value. This value of $g_0$ was found to be 4.35 and 5.3 giving an IM of -34 dB and -16 dB for mode tuning ranges of 5 GHz and 20 GHz, respectively.

In Figs. 3.13(c) and 3.13(d) the simulations were performed with the optimal $g_0$ applied. The laser intensity is indicated by the red line as a function of the reflector central frequency shift, which remains almost constant over the modulation range. Also shown is the relationship between the reflector central frequency shift and lasing frequency shift indicated by the blue line with the reflector-mode alignment set at frequency = 0, for clarity. As demonstrated in Section 3.4.2, it can be seen that as the reflector central frequency shifts, the laser frequency follows and the predicted linear relationship in Eq. 3.18 is shown as the purple dashed line in Figs. 3.13(c) and 3.13(d). This shows a close relationship to the linear approximation while tuning close to the filter centre. For comparison, the green dashed line indicates a perfect 1:1 relationship between the laser and reflector frequency. The vertical black lines are the laser mode tuning range limits of 5 GHz and 20 GHz (in the range which gives the lowest IM value). These results indicate the dependence of the IM on the DC biasing condition for a given tuning range and show that an optimal value can be obtained to achieve a low IM.

As these results show a low IM accompanying FM, a small change in the bias current simultaneous with reflector tuning would be required to further reduce the IM and a pure FM laser can be realised. This was investigated in the simulations by applying a simultaneous tuning function to $g_0$ accompanying the reflector tuning.

In the simplest case, this involved applying modulation to $g_0$ in the opposing direction to the reflector modulation, while tuning within a small range close to the edge of the reflectance peak (where the IM follows a periodic linear pattern). To mitigate a more complicated IM pattern which occurs
3. Tunable PhC Laser Theory and Simulations

Figure 3.14: Simulation results for (a) time varying reflector tuning function (blue) with fixed $g_0$ at 5.3 and resulting output intensity (red) with IM = -15.64 dB. (b) Same reflector tuning function applied simultaneously with varying $g_0$ (black) mirroring intensity pattern from (a) giving a reduced IM = -26.91 dB.

Later in Chapter 4, it is shown that the average current value for laser threshold is $\sim 20$ mA and the simulations show an average value for $g_0$ at threshold to be $\sim 3$. This can allow an estimation of the required current range to be applied in order to achieve the reduced IM. The simulation shows the maximum and minimum values of $g_0$ to be 5.3217 and 5.2493, respectively, which equates to currents of 35.4782 mA and 34.9955 mA. Therefore, the current range which would be required is 0.4827 mA.

Further development of the algorithm to compute an exact bias current pattern to further reduce the IM can be explored and this shows the potential to realise a pure FM laser by applying this technique experimentally. Implementation of a feedback loop control algorithm could accomplish this task by initially keeping the bias current fixed, applying modulation to the reflector component and recording the IM. Then repeat for a range of bias current values to find the lowest IM for a given bias current. At the optimal
bias current value, the intensity pattern is recorded and the mirrored pattern is applied to the bias current control. The IM is again recorded and the mirrored pattern bias current can be adjusted to continuously reduce the value for IM until the lowest value is found. With competent acquisition speed equipment and computation software, this process could be completed in a matter of a few milliseconds.

3.5 Summary

This chapter gave a theoretical basis for the single mode laser experimental chapters to follow by describing the laser system and components thereof with the vertically coupled PhC cavity as the novel narrowband reflector device. The properties of the DA PhC cavity were explored demonstrating the possibility for multiple resonance modes on coupling from the waveguide. Vertical coupling with two waveguides namely, SU-8 and SiN have been simulated showing various reflection properties for the resonance modes. The coupling efficiency from the waveguide to the cavity determined the reflectivity of the particular resonance mode and the intrinsic Q-factor of the mode determined the bandwidth of the reflector. These reflection parameters are pertinent for use in the EC architecture described in the following experimental work.

It was shown theoretically that tuning of the narrowband reflector in a single mode laser cavity results in tuning of the longitudinal mode. The mode tracking was predicted by the linear relationship and its validity was tested by simulations. The delay differential equations model used to model swept source lasers was adapted for the single mode regime and applied by stepping the reflector central frequency. This allowed for exploration of the mode and intensity behaviour as a function of tuning the reflector. The effect of the various system parameters were investigated to find optimal operating conditions.

The concluding experimental work in this thesis (Chapter 6) explores extending the length of the laser cavity from a single mode configuration to
3. Tunable PhC Laser Theory and Simulations

A multimode configuration by placing a fiber delay line between the SOA and PhC reflector and operating in the FDML regime. The model described above has been utilised for detailed analysis of FDML lasers in [155, 157, 158]. However, the model has not been applied to the FDML PhC laser studied here as there are several other complex dynamics due to the nature of the PhC cavity (e.g. two-photon absorption) which also have been neglected in the above simulations for the single mode geometry. Nonetheless, the single mode regime tends to exhibit less complex dynamics than the multimode regime. Further development of the model can be undertaken to incorporate the underlying physics of the PhC cavity however, it is beyond the scope of this thesis. Therefore, an approximated set of parameters and operating conditions for the simulations above were used to assist the single mode tuning experimental work in Chapter 5.
Chapter 4

Single Mode PhC Laser Characteristics

The use of III-V materials with silicon has become a viable solution to realise compact on-chip hybrid lasers. The combination of a commercially available RSOA chip with a novel silicon reflector chip to form an EC laser which exhibits high SMSR, low threshold current, and mW output power is an attractive solution for a compact, cost effective light source. Such a laser can be realised as an on-chip solution which can find applications in data communications or sensing.

As outlined in Chapter 2, much research attention has been paid to the integration of III-V materials with silicon and one of the first demonstrations of an electrically driven III-V/silicon hybrid laser employed a silicon DBR grating as the reflector component [134]. However, the use of DBR gratings results in a relatively long laser cavity with a reduced longitudinal mode spacing hence, suffering from mode-hopping with variation of bias current and ambient temperature. A mode-hop free laser over the full current tuning range has the attraction of single mode wavelength stability helpful for multiplexed schemes. A III-V/silicon hybrid PhC laser presented by Bakoz et al. [160] demonstrated wavelength stability with changes of ambient temperature by means of power tuning made possible by non-linear absorptive heating in the PhC cavity. Previous reports have studied the strong non-
4. Single Mode PhC Laser Characteristics

Linear effect of silicon PhC cavities [161, 162] owing to their high Q/V ratio which has been exploited to realise bistable optical switches [163, 164]. In this work, the non-linear properties of the III-V material are enhanced by the silicon PhC cavity non-linearities producing a bistable hybrid laser in several operating regimes.

This chapter presents experimental results and observations for a hybrid III-V/silicon PhC laser using several RSOA lengths and PhC devices. Firstly, an overview of the laser cavity and experimental setup is provided, followed by amplified spontaneous emission (ASE) characterisation of the different RSOAs, and separate characterisation of the PhC cavity reflector. Subsequently, the experimental results of the hybrid laser are presented and examination of the unique characteristics which are attributed to the underlying physics of the silicon PhC cavity resonator coupled with the III-V gain material. By engineering a reduced cavity length to ensure the longitudinal mode spacing is wider than the reflector bandwidth, an extended mode-hop free range is realised.

4.1 Laser configuration and experimental set-up

The RSOA acted as the gain medium with one facet high-reflective (HR) coated and the other anti-reflective (AR) coated. The reflector chip consisted of an SU-8 waveguide vertically coupled to a 2D PhC cavity realised by periodic holes etched into the silicon substrate with shifted holes adjacent to a line defect to form the cavity (see Chapter 3). Coupling was achieved by the butt-coupling of the gain medium waveguide to the SU-8 waveguide and thus, the PhC cavity (Fig. 4.1).

The experimental setup (Fig. 4.2(a)) involved mounting of both the gain chip and silicon chip on translation stages. The gain chip was wire-bonded to a gold-ceramic submount then wax-fused to an aluminium submount. The aluminium submount was flipped RSOA down and mounted to a pitch and
4. Single Mode PhC Laser Characteristics

Figure 4.1: (a) Laser cavity consisting of RSOA chip with a ridge waveguide geometry with one facet HR coated and output facet AR coated butt-coupled to an SU-8 waveguide vertically coupled to a silicon PhC cavity on a silicon-on-insulator (SOI) chip. (b) Schematic of overhead view of laser cavity.

yaw stage on top of an XYZ stage which gave 5 degrees of freedom for alignment to the silicon chip waveguide. The silicon chip was placed on a horizontal linear translation stage and the transmitted light from the waveguide on the output facet was collected via a lensed fiber in a fiber holder which was also mounted to a 5-axis translation stage to collect the output light efficiently. The output from the lensed fiber was split to a power meter (PM) and optical spectrum analyser (OSA) as shown in Fig. 4.2(b). Both
chips were placed on Peltier temperature controllers to maintain the laser system temperature which remained stable to ±0.03°C.

Active alignment of the 3 components (RSOA, silicon chip and lensed fiber) was carried out using an InGaAs infrared camera with a 20X objective lens positioned vertically above the silicon chip. When the light exiting the RSOA waveguide was coupled to the waveguide on the silicon chip, vertical
scattering of the light from the PhC cavity was observed on the infrared camera (Fig. 4.3). This gave a first estimate of the alignment position and allowed for alignment of the lensed fiber at the output facet when there was sufficient transmitted power. Single mode lasing was then achieved by real time observation of the continuously scanned optical spectrum while nano-positioning the stages. Coupling was further optimised by setting the RSOA bias current below threshold and maximising the output power by adjusting the RSOA position. Variation in the coupling position led to a change in scattered light from the PhC cavity. This change in scattering pattern meant that a different resonance mode of the PhC crystal could couple more efficiently and win favour for lasing for the same fixed bias current depending on the losses for the other PhC modes (see Chapter 3).

The estimated losses for each stage of the laser cavity include: <1.5 dB from the RSOA waveguide to SU-8 waveguide and the losses incurred from coupling to the SU-8 waveguide to the PhC cavity. These losses vary depending the coupling quality factor for each mode and typically range from 1-3 dB. The output mirror (PhC cavity reflector) loss varies depending on the reflectivity of the resonance mode with typical reflectivities ranging from 10-50%. Finally, the power collected from the output waveguide facet to lensed fiber had an estimated loss of 3 dB.
4. Single Mode PhC Laser Characteristics

4.2 RSOA characterisation

As the gain had a significant contribution to the laser characteristics, it was first necessary to characterise the RSOA. 200 µm, 250 µm and 400 µm long ridge waveguide commercially available RSOAs (from CST Global) were used for the experiments described here. The waveguide had dimensions of $W \times T$: $3 \times 2$ µm. The RSOA comprised multiple quantum wells of AlGaInAs/InP quaternary alloys and contained $Al^{3+}$ ions, which minimised carrier leakage at high temperatures facilitating continuous operation of the device [165].

To form the laser cavity, the back facet of the RSOA waveguide was HR coated ($R > 90\%$) to provide low optical loss. The front facet was AR coated ($R < 1\%$) to avoid unwanted lasing caused by the RSOA and silicon chip waveguide facet reflections.

The three main parameters of the amplifiers which are examined in this section are: gain profile with variation of length, bias current, and temperature. By placing a lensed fiber directly at the waveguide output of the RSOA to collect the ASE spectrum, data of the RSOA gain profile was obtained and is presented below.

The ASE spectrum of each RSOA length was obtained from the OSA for an operating temperature of 20°C and a fixed current of 50 mA (Fig. 4.4(a)). It is clear from the spectra that the wavelength range of the gain curve is reduced with increasing length but produces more output power for the same bias current. Also present on the spectra is the “gain ripple” as a result of non-ideal AR coating on the output facet. The magnitude of the ripple peaks is dependent on the quality of the AR coating and increases with increasing bias current. The ripple is lowest in magnitude for the shortest device as the gain per pass is lower for the same injection current. The period of the ripples relates to the length of the gain chip and was measured as 1.74 nm, 1.39 nm and 0.88 nm for the respective lengths (Fig. 4.4(a): inset). Later discussed for the laser characterisation (Section 4.4) is the significance of this ripple and its contribution to the favoured wavelength position the lasing peak.
4. Single Mode PhC Laser Characteristics

Figure 4.4: (a) ASE spectra at 50 mA for 200 µm, 250 µm and 400 µm RSOA. Inset: zoomed section showing gain ripple fringes. (b) ASE spectra at current density of 4 kA cm\(^{-2}\) for each RSOA length.

In order to examine the bias current dependence, the current was increased for each device in steps of 2 mA from 0 mA up to 80 mA for the 200 µm device and up to 100 mA for the 250 µm and 400 µm devices (maximum current chosen for safe operation to avoid device burnout). The saturation current due to thermal rollover (which is a result of temperature increasing in the device) was determined from the LI curves (Fig. 4.5(a)) which was approximately 50 mA, 60 mA, and 80 mA for the 200 µm, 250 µm, and 400
4. Single Mode PhC Laser Characteristics

µm device, respectively. The IV curves in Fig. 4.5(b) show a decrease in resistance in the linear region with increasing length with resistances of 15 Ω, 11 Ω and 8 Ω. The IV curve is used to calculate the wall plug efficiency (WPE); a figure of merit with regard to integration of hybrid devices as EC lasers [129].

![Graphs](image)

**Figure 4.5:** (a) LI and (b) IV curves for each RSOA.

Fig. 4.6(a), (b) and (c) show the ripple peaks centre wavelengths for each current step for the devices. The refractive index change behaved as expected for a semiconductor optical gain material in that, as the carrier concentration was increased, the refractive index changed and initially exhibited a blue-shift in wavelength (more noticeably for the 400 µm device). Then as the carrier concentration was further increased, heat was generated and the thermo-optic effect first cancelled the electro-optic effect until eventually the thermo-optic effect dominated and a net red-shift in wavelength was observed. This initiated at significantly lower currents for the short device as more heat was generated for the same current due to a higher resistance. The thermo-optic effect began to dominate at approximately 20 mA, 40 mA and 80 mA for the 200 µm, 250 µm and 400 µm devices, respectively.

Tracking the wavelength shift of one of the RSOA fringes to determine the net wavelength shift with increasing bias current allowed for the refractive
4. Single Mode PhC Laser Characteristics

Figure 4.6: Gain ripple peak wavelengths for (a) 200 µm, (b) 250 µm and (c) 400 µm RSOA. (d) Refractive index change, ∆n as a function of current density for each device.

Index change ∆n to be calculated using equation:

\[ \Delta n = \left( \frac{\lambda_0 - \lambda_1}{\lambda_1} \right) n_g \]  \hspace{1cm} (4.1)

where the group index of the material, \( n_g = 3.6 \) (value calculated later in Section 4.4.2), and \( \lambda_0 \) and \( \lambda_1 \) are the centre wavelengths of the ripple peaks for each step. The refractive index change was plotted as a function of the current density for each device length for comparison in Fig. 4.6(d). The shortest device shows greatest change in refractive index for the same current density as the thermal effect has the largest contribution again, due to the higher resistance of this device.

The thermal effect on the gain curve was further examined by adjusting the RSOA temperature. This was implemented with a Peltier element placed under the aluminium submount with a temperature sensor positioned...
as close to the RSOA as possible (within 5 mm) on the aluminium holder and using a closed loop controller to adjust the system temperature. Fig. 4.7(a) shows the gain profile for the 250 µm device at 50 mA for temperatures of 20°C, 30°C and 40°C exhibiting a red-shift in the overall gain curve. There was also a reduction in the gain with increasing temperature due to increased threshold carrier density. Injected carriers cover a larger energy range at higher temperatures which reduces gain [135]. Fig. 4.7(b) shows from 20-45°C in steps of 5°C, selecting one of the gain ripple peaks at ~1550 nm (Fig. 4.7(a): inset) and tracking the peak wavelength shift for each temperature step. Again, this shows a red-shift in wavelength indicating a clear linear progression. The slope gives the change in wavelength with respect to temperature resulting in $\Delta \lambda / \Delta T = 98.7$ pm/°C. This enables calculation of the thermo-optic coefficient (TOC) of the material by applying Eq. 4.1 to $\text{TOC} = \Delta n / \Delta T = 2.29 \times 10^{-4}$ K$^{-1}$, which is in close agreement to the average stated value for III-V materials of $2 \times 10^{-4}$ K$^{-1}$ at room temperature [166, 167].

Figure 4.7: 250 µm RSOA at 50 mA bias current (a) smoothed gain spectrum for 20°C, 30°C and 40°C. Inset: zoomed section of original data (not smoothed). (b) Tracked peak wavelength shift for ~1550 nm ripple for 20-45°C in steps of 5°C.
4. Single Mode PhC Laser Characteristics

4.3 PhC cavity fabrication and characterisation

Fabrication and design of the PhC devices was performed by Alexandros A. Liles in the University of St. Andrews [168] and details of the fabrication process were provided and are outlined below.

The fabrication process for the two dimensional Si PhC cavity begins with standard 220 nm silicon-on-insulator (on top of 2 µm buried silicon dioxide commonly known as BOx) wafer available from SOITEC. Electron-beam lithography, followed by CHF$_3$ and SF$_6$ chemistry based dry etching process are used to define the PhC cavity structures on the 220 nm Si layer. In the following step, the fabricated PhC cavity is treated with Piranha solution (i.e. H$_2$SO$_4$:H$_2$O$_2$ in 3:1 ratio) to clean and improve the adhesion of the surface for the next step. The Spin-On-Glass (SOG) polymer available from Honeywell (Accuglass-T) is used as an intermediate layer and fills the PhC cavity holes. The SOG refractive index of 1.46 is a close match to that of the SiO$_2$. The intermediate layer improves the symmetry of the cavity mode and adds mechanical stability to the device. The thickness of this layer is critical to obtain efficient coupling between the polymer waveguide mode and PhC cavity mode to help attain a high quality (Q) factor of the PhC cavity modes. A total Q factor of >20,000 was achieved experimentally for a thickness of 200 nm. Once the target thickness is achieved, the device needs to be annealed at 425°C under N$_2$ atmosphere for one hour.

Microchem SU8-2 is used to form the polymer waveguide on top of the PhC structure. The SU8-2 polymer is spun at 2400 rpm for 50 seconds and exposed to the e-beam dose of 5 μC/cm$^2$ to obtain the targeted waveguide dimensions of 3 µm × 2 µm (chosen for TE single mode operation of the polymer waveguide at 1550 nm).

The experimental setup to characterise the PhC cavity involved using an “end-fire” setup (Fig. 4.8(a)) which consisted of a broadband ASE source of wavelength range 1520-1620 nm (Fig. 4.8(b)). This was injected into
the waveguide via an optical fiber to an objective lens which was coupled in free-space to an objective lens on the input facet with a polarising beam splitter (PBS) between the input coupled lenses to ensure TE polarisation. The output light of the waveguide was collected in the same manner and the optical fiber was sent to an OSA to observe the transmission spectrum. Alternatively, lensed fibers can be used in place of the objective lenses to couple light to and from the waveguide facets.

![Diagram](image)

**Figure 4.8:** (a) End-fire setup for simultaneous measurement of transmission and reflection spectra. Light from the ASE source is sent to a circulator, objective lens (blue), a polarising beam splitter (PBS), and again to an objective lens to focus the light to the input waveguide on the silicon chip (Si). The transmission spectrum is collected at the output waveguide from a pair of objective lenses and sent to the OSA. The reflected spectra is collected from port 3 on the circulator and sent to the OSA. (b) Optical spectrum of ASE source used for the measurements.

As previously discussed, the PhC cavity consists of multiple resonance
modes owing to the Fabry-Perot nature of the cavity which are typically separated by 6-8 nm. The hole period, ‘a’ in nm is defined by the distance between adjacent hole centres. Fig. 4.9 shows the transmission spectrum of two different PhC cavity structures with a hole period of $a = 390$ nm and 394 nm (hole radius of 90 nm). The 4 nm difference in PhC period for these devices shifts the transmission spectrum by $\sim 1$ FSR (in this case when comparing the shift of the fourth resonance). Note that a change in the PhC period will not affect the value of the FSR as this is inversely proportional to the length of the PhC cavity. Enhanced control of the position of the resonances can be achieved by slightly changing the position of the innermost holes adjacent to the line defect during fabrication [141].

![Figure 4.9](image)

**Figure 4.9:** Transmission spectrum of PhC cavity with a period of $a = 390$ nm (blue) and 394 nm (red).

To observe the reflection and transmission spectrum simultaneously, the input light was sent through a broadband fiber circulator to port 1 then passed to the objective lens via port 2. Port 3 of the circulator was then fiber coupled with the transmitted waveguide output and sent to the OSA (Fig. 4.8(a)) and the reflection and transmission spectrum is shown in Figs. 4.10(a) and 4.10(b) for passive waveguide lengths (from silicon chip input facet to PhC cavity) of 0.47 mm and 4.72 mm, respectively. The spectrum shows transmission dips where there are reflection peaks. The fringes present
4. Single Mode PhC Laser Characteristics

on the reflection spectrum are as a result of internal reflections from the PhC cavity to chip facet and the fringe spacing is inversely proportional to the length of the waveguide. The reflection bandwidth for each of the PhC resonance modes varies depending on the mode coupling efficiency and Q-factor of the cavity as discussed in Chapter 3. The reflectivity was highest for the third mode and in the laser configuration, this mode was generally favoured for lasing as it required the lowest threshold current provided it was close to the gain spectrum maximum.

![Transmission and Reflection Spectra](image)

(a) Normalized Transmission (T) and Reflection (R) spectrum for waveguide lengths of 0.47 mm (a) and 4.72 mm (b). (c) Schematic of silicon chip layout with varying waveguide lengths from chip facet to PhC device.

**Figure 4.10:** Transmission (red) and reflection (green) spectrum of PhC cavities with passive waveguide lengths (from silicon chip input facet to PhC cavity) of (a) 0.47 mm and (b) 4.72 mm. (c) Schematic of silicon chip layout with varying waveguide lengths (black) from chip facet to PhC device (blue rectangle).
4. Single Mode PhC Laser Characteristics

The small variations between devices in terms of resonance wavelengths, reflectivity and reflection bandwidths for the same resonance modes can be attributed to fabrication variations. Changes in the mode coupling efficiency and Q-factor of the cavity were found to have small variations between different devices for the same resonance modes. Comparing to the simulated spectra in Fig. 3.6(a), the resonance modes are at slightly different wavelengths, again which can be attributed to fabrication variations. The thickness of the intermediate SOG layer is a crucial factor in determining the resonance wavelengths and any variation in the fabricated and simulated thickness affects these.

Table 4.1 summarises the parameters of the first three resonance modes of the device shown in Fig. 4.10(b) (see Chapter 3 for calculation methods). The sampling resolution of the OSA was 2 pm using a monochromator with a bandwidth of 20 pm which was sufficient to distinguish the narrow spectral features observed.

<table>
<thead>
<tr>
<th>PhC cavity mode</th>
<th>Centre λ (nm)</th>
<th>FWHM (pm)</th>
<th>Q_{Total} of PhC cavity</th>
<th>Extracted reflect. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>1552.50</td>
<td>79</td>
<td>19,600</td>
<td>3.7</td>
</tr>
<tr>
<td>2nd</td>
<td>1546.95</td>
<td>160</td>
<td>9,612</td>
<td>32</td>
</tr>
<tr>
<td>3rd</td>
<td>1540.81</td>
<td>399</td>
<td>3,855</td>
<td>49</td>
</tr>
</tbody>
</table>

14 identical PhC structures were fabricated on a single silicon chip with varied SU-8 waveguide lengths with equal step size of 0.25 mm with a 1 mm gap between 2 mm and 3 mm lengths as shown in Fig. 4.10(c). The reflection fringe spacing was measured for each of these devices and the values for each waveguide length were used to calculate the group index of the SU-8 waveguide, \( n_{gSU8} \) from the equation:

\[
\text{Reflection fringe spacing} = \frac{c}{2n_{gSU8}L_{SU8}} \quad (4.2)
\]
where \( c \) is the speed of light and \( L \) corresponds to the length of the waveguide. By fitting the value of \( n_{gSU} \) to the measured data (Fig. 4.11), it was found to be 1.6275 which is in close agreement to the simulated value of 1.5891 (from FIMMWAVE simulation for the target SU-8 waveguide dimensions of \( 3 \times 2 \) \( \mu m \) used in these experiments). The slight difference of the values can be attributed to fabrication variations. This exact calculation of the SU-8 group index enables calculation of the group index of the RSOA waveguide which will be demonstrated in Section 4.4.2. The SU-8 group index value calculation also allows for the optimisation of AR coatings to reduce internal reflections from the chip facets.

![Figure 4.11: Reflection fringe spacing as a function of waveguide length (red triangles) and calculation of group index of the SU-8 waveguide, \( n_{gSU} \) by fitting to experimental data.](image)

4.4 Laser characterisation

Single mode lasing is realised when the PhC cavity reflection peak partially overlaps with the one of the maxima of the gain ripple at a longitudinal mode solution. The ideal case is illustrated in Fig. 4.12(a) where the maximum of the reflection peak perfectly aligns with maximum of the gain ripple and longitudinal mode solution. In the actual laser, these peaks can be offset by a certain amount provided that there is sufficient gain and reflectivity
4. Single Mode PhC Laser Characteristics

to overcome losses. The experimental laser is shown in Fig. 4.13 overlaid with the ASE spectrum of the RSOA and normalised reflectivity of the PhC resonance mode confirming that the position of the lasing mode exists at an overlap of the RSOA gain ripple and one of the PhC reflection peaks.

![PhC reflection peak](image1)

**Figure 4.12:** Reflection peak (black), lasing mode(s) (red) and gain ripple (blue) for longitudinal mode solutions (green) with spacings that are (a) larger and (b) smaller than reflection bandwidth.

The longitudinal mode solutions are determined by the total length of the laser cavity incorporating both optical path lengths (group index multiplied by physical waveguide length) of the RSOA and SU-8 waveguide:

$$L_{MS} = \frac{c}{2(n_g \mu RSOA L_{RSOA} + n_g \mu SU8 L_{SU8})} \quad (4.3)$$

where $L_{MS}$ is the longitudinal mode spacing, $c$ is the speed of light, $n_g$ is the group index and $L$ is the length of the waveguide of the RSOA and SU-8.

The LMS can be either larger (Fig. 4.12(a)) or smaller (Fig. 4.12(b)) than the PhC reflection bandwidth (FWHM$_{reflec}$) depending on the total length of the laser cavity. By keeping the gain section length constant, it is possible to control the length of the laser cavity by varying the length of the passive waveguide (as described in Section 4.3).
4. Single Mode PhC Laser Characteristics

4.4.1 Operation with varied RSOA bias current

Laser characterisation for the shortest and longest passive waveguide lengths of 0.47 mm and 4.72 mm of the PhC devices described above was performed. The 400 \( \mu \text{m} \) RSOA was selected for the gain section since its ASE spectrum showed peak power at \( \sim 1540 \text{ nm} \) to coincide with one PhC resonance and minimise possibility for lasing on the other resonances to avoid PhC resonance mode-hopping (discussed later in Section 4.5) while also providing high output power. The 400 \( \mu \text{m} \) length RSOA gave total cavity lengths of 0.87 mm and 5.12 mm. The lasing spectra at 50 mA bias current for both the short and long devices are presented in Figs. 4.13(a) and 4.13(b) overlaid with the gain ASE and normalised PhC cavity reflectivity. The shorter cavity shows an SMSR of \( \sim 40 \text{ dB} \) as the large FSR of the cavity ensures a single longitudinal mode lies within the bandwidth of the reflector. The longer cavity shows adjacent modes lasing as the LMS is reduced and several modes lie within the bandwidth of the reflector, reducing the SMSR to 4 dB at this bias current. The difference in lasing wavelength between the two devices is due to inter-die variations of the PhC cavities on fabrication.

![Figure 4.13](image)

**Figure 4.13:** Lasing spectrum of the PhC laser (blue) at fixed gain current of 50 mA for (a) 0.87 mm and (b) 5.12 mm cavity lengths with superimposed ASE gain spectrum (black) at 50 mA and normalised PhC cavity reflection spectrum (red).

To examine the effect which the gain driving current had on the laser characteristics for both the short and long cavity, the current was increased
4. Single Mode PhC Laser Characteristics

from 0-100 mA in steps of 1 mA and the OSA spectrum was acquired for each step. Figs. 4.14(a) and 4.14(b) show the colourmap of each device with the lasing peak displayed in yellow. Less intense peaks are also visible which represent the adjacent longitudinal modes. The threshold current was $\sim 20$ mA with a maximum output power of 400 $\mu$W for the shorter device.

The shorter cavity showed continuous single mode lasing (Fig. 4.14(a)) exhibiting mode stability over the current range. Longitudinal mode-hopping was observed for the longer cavity as the longitudinal mode spacing was less than the bandwidth of the reflector (Fig. 4.14(b)). This shows stable single mode operation can be realised by optimisation of the laser cavity length to ensure the condition that the LMS is greater than the reflection bandwidth as will be verified in the next section.

The shift of the lasing peak and mode-hopping to the longer wavelength with increasing bias current is attributed to the thermo-optic effect on the gain chip as observed in RSOA characterisation in Section 4.2. It must also be noted that there is a red-shift of the PhC resonance due to heat dissipation on account of absorption in the PhC cavity [160]. This confirms that both the gain ripple peak and reflection peak are red-shifting simultaneously (albeit disproportionately) ensuring that over this current range, the same gain ripple peak will remain within the reflection bandwidth for continuous single mode lasing in the shortest cavity case.

4.4.2 Optimisation of cavity length for extended mode-hop free operating regime

Further analysis of the longitudinal mode spacing variation and mode-hopping effect was performed by utilising the devices of varied length of the SU-8 waveguide. Now taken into account are the conditions which determine mode stability: (i) LMS $<$ FWHM$_{reflec}$ and (ii) LMS $>$ FWHM$_{reflec}$.

These experiments were performed using the same 400 $\mu$m length RSOA and utilising the 14 identical PhC devices with stepped passive waveguide lengths described in Section 4.3. All devices had the same PhC period (a
4. Single Mode PhC Laser Characteristics

Figure 4.14: Colourmap of OSA spectra for increasing RSOA current for (a) 0.87 mm and (b) 5.12 mm cavity lengths. Insets: corresponding LI curves.

= 390 nm) and lased on the same resonance mode i.e. the same reflector bandwidth, FWHM_reflec = 48 GHz, therefore the single variable was the LMS given by the total length of the laser cavity set by the length of the passive waveguide.

The SU-8 waveguide group index which was calculated from the reflection fringe spacing measurements in Section 4.3 enabled calculation of the group index of the RSOA using Eq. 4.3. The LMS for each of the 14 lengths was obtained from the OSA spectra for a fixed bias current above threshold and the value for $n_{gRSOA}$ was fitted to the measured data and found to be 3.6 (Fig. 4.15). The importance of the calculation of the group index values for the waveguides is the facilitation for exact cavity length design and fabrication to ensure an extended mode-hop free operating regime.

Again, the RSOA bias current was stepped from 0-100 mA in steps of 1 mA and the OSA spectrum was acquired for each current step then extraction of the peak wavelengths gave an overview of the longitudinal mode-hopping cases. Fig. 4.16(a) shows 5 devices with LMS of 18, 20, 39, 44 and 57 GHz. A single device satisfied $\text{LMS} > \text{FWHM}_{\text{reflec}}$ and showed continuous single mode lasing for the current range and longitudinal mode-hopping was observed for the remaining devices with the condition $\text{LMS} < \text{FWHM}_{\text{reflec}}$. The total red-shift in wavelength for the current range for the shortest device
was 0.03 nm and the total shift increased approximately linearly up to \( \sim 1 \) nm for the longest device. The accompanying LI curves are presented in Fig. 4.16(b) showing power drops at the points of mode-hopping.

The length of the laser cavity also had an impact on the SMSR value throughout the current range. The value of SMSR reduced at certain currents for devices with smaller LMS due to the overlap of longitudinal modes within the reflector bandwidth. Fig. 4.16(c) shows SMSR as a function of the bias current with the continuous single mode device showing stable SMSR for the current range. The longer device shows mode-hopping with dips in SMSR values as this is the transition to the adjacent mode and several modes lase simultaneously thereby reducing the SMSR drastically.

**Figure 4.15:** Longitudinal mode spacing as a function of cavity length (green triangles) and calculation of group index of the RSOA waveguide, \( n_{gRSOA} \) by fitting to experimental data.
4. Single Mode PhC Laser Characteristics

![Figure 4.16](image)

**Figure 4.16:** (a) Peak wavelength shift as a function of increasing bias current for devices with LMS of 18, 20, 39, 44 and 57 GHz, and (b) corresponding LI curves. (c) SMSR as a function of increasing bias current for devices with LMS of 18 GHz and 57 GHz.
4.5 Bistable operating regimes

Further from Section 4.4.1, increased heat dissipation in the PhC cavity due to absorption drives a red-shift of the resonance wavelength. In order to quantify the effect with regard to power in the PhC cavity, light from a TLS source was injected into a PhC device and the transmission spectrum was captured from the waveguide on the output facet. It can be seen that only a fraction of the input power was transmitted as a large amount was coupled to the PhC cavity and also various losses were incurred. The losses arise from: 1) coupling from the source to waveguide, 2) coupling from the waveguide to the PhC cavity, 3) waveguide transmission, and 4) material absorption.

![Figure 4.17: Transmission spectra as a function of scanned TLS wavelength showing resonance shift with increasing input power. Power in waveguide was estimated as 3 dB loss from TLS input power to lensed fiber to waveguide. Part of this power is coupled to the PhC cavity, depending on the coupling quality factor for the resonance mode.](image)

The TLS wavelength was stepped by 1 pm and scanned across one resonance for increasing input powers. This resulted in a red-shift of the resonance up to $\sim 150$ pm for an applied input power in the waveguide of 10.6 dBm (Fig. 4.17). Increased power in the cavity also showed some broadening of the resonance bandwidth. Each transmission dip was fitted to a Lorentzian curve to calculate the FWHM and showed a broadening of the resonance bandwidth by $\sim 30$ pm for the maximum input power. In the laser cavity, increased current to the RSOA leading to heat generation (Section
4. Single Mode PhC Laser Characteristics

4.2) is expected to have a similar impact on the PhC resonance as this will increase heat dissipation in the cavity.

The effect on the resonance was also examined for the reflectivity of the PhC cavity by again varying the input power of the TLS and here the wavelength was stepped by 20 pm. The reflected power was measured using a circulator and a power meter and Fig. 4.18 shows the reflected power for each wavelength step. Again, a fraction of the power in the waveguide is reflected after coupling to the PhC cavity. The fringes were from the reflections from the chip facet as described in Section 4.3 and these showed to blue-shift with increasing power due to the negative thermo-optic coefficient of the SU-8 waveguide. The overall resonance envelope red-shifts with increasing temperature in the silicon cavity as shown above. The sharp drop in power at \(\sim 1539.4\) nm is indicative of optical bistability where the absorption is at maximum and subsequently the resonance returns to the “cold” state.

![Figure 4.18: Reflection spectra as a function of scanned TLS wavelength showing bistability arising with increasing input power in waveguide.](image)

The thermal bistability of the cavity occurs due to the coupled power into the cavity and is dependent on the detuning of the wavelength with respect to the resonance peak [169, 170]. As the wavelength is stepped from short to long, more power is coupled into the cavity inducing a red-shift of the resonance. The peak shifts asymmetrically as more power is absorbed at the centre of the peak compared to the tails. This effect is dependent on the direction of the wavelength sweep with respect to the resonance peak.
4. Single Mode PhC Laser Characteristics

center. Sweeping from short to long wavelength, the resonance also shifts towards the longer wavelength due to increasing coupled power in the cavity consequently increasing the temperature in the cavity. The pump laser and resonance wavelength peak eventually overlap where maximum absorption is reached and the cavity cannot compensate further for the temperature increase. The resonance then quickly returns back to the cold state and detunes further from the pump laser. The bistability region is at that point of maximum absorption caused by the abrupt change in the cavity temperature. If the pump laser is swept in the opposite direction from long to short wavelength, again the resonance will shift with increased coupled power but in this situation the shift is opposite to the pump laser wavelength. In this case, the absorption does not reach maximum thereby inducing hysteresis from the pump laser wavelength sweep direction. Ref. [171] gives a clear visualisation of this phenomenon showing the hysteresis behaviour which arises from sweeping the pump laser from short to long wavelengths and vice versa.

With regard to Fabry-Perot semiconductor laser resonators, their non-linear properties have been well studied and understood [172–174]. Bistability arises from various effects within the active gain material such as non-linear absorption due to two-photon absorption and free-carrier absorption. The non-linear refractive index change gives rise to dispersive bistability [174], due to the intensity dependent refractive index. If initially the lasing frequency is detuned from the Fabry-Perot resonance, then with increasing light intensity in the cavity, a change in the refractive index occurs, blue-shifting the resonance towards the lasing frequency. This will cause an asymmetry in the resonance as the increased intensity causes a larger phase change at the peak centre, consequently reducing the material optical gain more than for intensities further from the peak. The asymmetric resonance will then have bistable solutions at increased intensities in the resonator.

This is a similar effect on the resonance as described above for silicon however, the thermal effect is dominant in the silicon resonator due to the strong light-matter interaction and high stored energy density in the microcavity.

In the hybrid laser cavity, the non-linearities of both the silicon PhC
4. Single Mode PhC Laser Characteristics

cavity and the RSOA combined gave rise to bistable laser operating regimes. Taking into account the thermal bistability of silicon and the detuning of lasing mode with respect to the reflectance peak, the various regimes described below were observed.

The different lengths of RSOA which were characterised in Section 4.2 were utilised to study different lasing regimes of the PhC laser and application of increasing and decreasing bias current resulted in 3 bistable regimes: (i) single longitudinal mode, (ii) longitudinal mode-hopping, and (iii) PhC resonance hopping which are examined in the following sections.

4.5.1 Single longitudinal mode

Utilising the RSOA length of 400 µm and the PhC device which exhibited continuous stable single mode lasing in Section 4.4, with the application of increasing and decreasing bias current, hysteresis was observed in the LI curve (Fig. 4.19(a)). Hysteresis was present for the current range of 30-80 mA where an anti-clockwise loop was evident. For currents >80 mA the curve indicates equal power in both directions as the temperature variation close to the final current was mostly unchanged. The current step rate was ∼1 mA/s therefore, the thermal time constant of the system including the larger aluminium blocks had a significant role in the hysteresis observed meaning these were bistable states within a limited timeframe.

The refractive index change of the RSOA changes the cavity length hence the roundtrip phase leading to tuning of the longitudinal mode. Simultaneously, the reflectance band shifts due to heating in the PhC cavity giving additional mode tuning in the same direction. For decreasing bias current, thermal relaxation occurs at different rates for the RSOA and the PhC cavity resulting in the hysteresis loop.

This regime was established by the relative position of the longitudinal mode and reflectance peak given by the current density and the non-linear absorption of silicon. The absorption in the PhC cavity can be considered as a self-tuning of the resonance wavelength, shifting the reflectance peak due
to the stored energy in the cavity. The RSOA refractive index change and resonance shift occur simultaneously but disproportionally to each other.

The wavelength hysteresis for this regime was not detected on the OSA (Fig. 4.19(b)) hence, the inferred mode and reflector position is illustrated in
4. Single Mode PhC Laser Characteristics

Fig. 4.19(c) showing the new mode position relative to the reflectance peak for the increasing current direction which is less reflective giving more output power, while operating close to the reflectance peak centre (see Chapter 3). For the same current change on decrease, the resonance shifts by less, which sustains more output power as evident on the LI curve.

4.5.2 Longitudinal mode-hopping

Hysteresis was observed in the longitudinal mode-hopping regime with the longest waveguide PhC device (smallest LMS) and the 400 µm RSOA. This exhibited typical mode-hopping behaviour following a “staircase” pattern and hysteresis (Figs. 4.20(a) and 4.20(b)). Contrarily to the continuous single mode device, the hysteresis in the output power follows a clockwise loop and for increasing current, a mode-hop is indicated where there is a drop in power. This can be considered as described above with the longitudinal mode shifting with the refractive index change and the resonance shifting due to PhC cavity heating. The drop in power occurs as the mode hops to the adjacent longitudinal mode solution and a different position relative to the reflectance peak. The output power is dependent on the amount light reflected into the cavity and consequently transmitted where the output power can indicate the likely relative mode/reflecter alignment. Compared to the other bistable regimes examined here, this regime had the largest power change for the least amount of applied current in each direction between high and low states.

Fig. 4.20(b) shows the wavelength hysteresis in an anti-clockwise motion as the longitudinal mode hops to a longer wavelength for increasing current and shorter wavelength for decreasing current. The hysteresis loop current range for the longitudinal mode-hops was \(~5\) mA.

Similarly for the single mode, this bistable regime occurred on account of the relative position of the longitudinal mode and reflectance peak. Given that the absorption in the PhC cavity self-tuned the resonance, this changed the position of the longitudinal mode relative to the reflectance peak. As
shown in the simulations in Chapter 3, the direction by which the reflectance peak shifts can induce hysteresis in the lasing wavelength at the points of mode-hopping. It was shown that this was dependent on the carrier density and gain given by the mode-reflector relative position and reflected power into the cavity.

The change of direction of the hysteresis loop between this case and the previous single mode case can be explained as follows: for the previous case, it was considered that the change in output power was on account of the mode detuning by a small amount from the reflectance peak as illustrated in Fig. 4.19(c). The power change is interpreted as the change of the relative position of the mode and reflectance peak on increase and decrease of the bias current. In this case of longitudinal mode-hopping, the mode moves further away from the reflectance peak and likely closer to the edge of the reflectance peak to the point where it is no longer a stable solution. A drop in power was observed at the point of mode-hopping due to the gain switching to the adjacent mode and requiring a further build up in power again in that mode. Hence, the observed hysteresis loop changed direction for this regime.
4. Single Mode PhC Laser Characteristics

4.5.3 PhC resonance hopping

In this regime, mode-hopping occurs between PhC resonances as opposed to mode-hopping to the adjacent longitudinal mode as described in the previous section. This regime presented when using the shortest passive waveguide length and a 200 \( \mu \text{m} \) length RSOA which had the flattest gain profile. The flat gain profile enabled switching between two adjacent PhC resonance modes and the laser exhibited hysteresis behaviour. This RSOA length also had the most current density over the current range with accompanying large refractive index change (Section 4.2) therefore, causing significant tuning of the lasing mode leading to greater possibility to shift further from the resonance and compete with another resonance. As this device had an even larger LMS due to the reduced length of the RSOA, mode-hopping occurred between PhC resonances rather than adjacent longitudinal modes as with the previous case.

Fig. 4.21(a) shows the lasing peak wavelengths for increasing and decreasing bias current and reveals switching between resonances. Figs. 4.21(b)-(d) show the OSA spectra for one bias current value for both directions with an illustration of the inferred position of the PhC reflectance peaks which would facilitate lasing. Lasing occurs at resonance mode 3 (RM 3: higher reflectivity, narrower bandwidth) and resonance mode 4 (RM 4: lower reflectivity, wider bandwidth). With increasing current, RM 3 begins lasing first then switches to RM 4 which although has lower reflectivity, RM 3 now has no longitudinal mode solutions within the bandwidth due to the resonance shift. This gives favour to RM 4 which then overcomes threshold. A longitudinal mode-hop occurs at 54 mA to a shorter wavelength due to the wider bandwidth of RM 4 allowing the gain ripple to provide sufficient threshold on the shorter wavelength side of the reflectance peak.

Again, for the change in current direction, the heating and cooling for both the RSOA and PhC occur at different rates leading to a change in the lasing mode wavelength and relative position to the reflectance peak. Point 1 at 18 mA shows for decreasing current there is a lower current value
4. Single Mode PhC Laser Characteristics

Figure 4.21: (a) Multiple PhC resonance mode-hopping with OSA spectrum for increase (red) and decrease (blue) at (b) 18 mA, (c) 40 mA and (d) 65 mA with gain at the same current (black) and illustrated inferred reflectance peak positions (RM 3 and RM 4).

for threshold indicating the relative mode/reflective position was at a higher reflectivity than that for increasing current. Point 2 at 40 mA shows the two different resonances lasing for the same bias current where hysteresis presents mostly due the non-linear heating effect in the PhC. Energy stored in PhC allows the lower reflectivity mode to lase on decrease and switches from higher reflectivity. Lastly, Point 3 at 65 mA, the resonance is in approximately the same position for increasing and decreasing current therefore, the lasing mode is at the same wavelength.
4. Single Mode PhC Laser Characteristics

This regime also occurs due to the non-linear properties of the gain and silicon and also on account of the multiple resonance modes of the PhC cavity where one or more overcome threshold for lasing. As summarised in Table 4.1, each of the resonance modes has a different bandwidth and reflectivity and when a longitudinal mode solution at a resonance met the threshold condition, lasing occurred. This was either simultaneous with another PhC mode or operation by switching between the modes. The lasing on the resonance mode was highly dependent on the gain profile to provide sufficient threshold for one or more PhC modes.

4.6 Summary

Presented in this chapter was a hybrid III-V/silicon PhC laser in a single mode configuration and examination of the lasing characteristics which have been determined to depend entirely on the specific geometry and materials of the system. Examination of the gain characteristics gave greater insight to their contribution to the laser operation. The PhC cavity characterisation revealed the specific reflection properties and profiles for use as the external reflector of the laser cavity. Both contributions of the individual components combined produced the laser characteristics which were analysed.

By utilising a range of SU-8 waveguide lengths, it was possible to calculate the group index of the waveguide and subsequently, allowing for calculation of the RSOA waveguide group index. This then facilitated determination of the total length of the laser cavity and in relation to the reflector bandwidth, revealed either continuous single mode or mode-hopping regimes for the applied RSOA bias current range. Optimisation of the passive waveguide length to achieve stable, mode-hop free single mode lasing over the current range was achieved. These design parameters are essential to ensure a compact on-chip laser with an increased wavelength stability range without the need for additional mode stabilisation. Due to the efficiency of the vertical coupling technique to the PhC cavity, the need for additional coupling elements are eliminated e.g. spot size converters, ultimately achieving an ultra-short
4. Single Mode PhC Laser Characteristics

Fabry-Perot length hence, a hybrid laser with wider LMS than the reflector bandwidth.

Finally, the properties of both the gain and PhC reflector combined resulted in a bistable hybrid laser. Multiple bistable operating regimes of the PhC laser were revealed with subsequent analysis undertaken. This type of bistable hybrid laser can offer a solution for memory elements or optical switching devices. Optical switching devices thus far tend to rely on the non-linear properties of these separate materials, i.e. III-V devices or silicon optical switches alone which tend to have short memory time. This bistable laser can be used directly as a control signal in an electro-optic network and utilisation of the silicon photonics platform allows for integration in electro-optic circuits.
Chapter 5

Single Mode PhC Laser
Wavelength Tuning and
Frequency Modulation

In this chapter, I describe the modulation of the hybrid III-V/silicon lasers consisting of an RSOA and a PhC cavity resonant reflector, as per the configuration described in Chapter 4. For the experiments described here, a modulator situated at the PhC cavity was employed. Two types of modulators were examined namely, a microheater with an SU-8 waveguide, and a doped p-n junction with a SiN waveguide (Fig. 5.1). The use of a SiN waveguide gives considerable freedom in the choice of the mode size allowing a good match to be achieved with the RSOA waveguide. Additionally, the addition of the SiN layer gives the potential for integration of other devices, such as multiplexer/demultiplexers.

As described in Chapter 4, the resonant reflectance band of the PhC cavity overlaps with a longitudinal mode of the laser cavity that then lases. Chapter 3 predicted that FM of the reflectance peak would induce modulation of the lasing mode frequency (Fig. 5.2) and the experiments described here aim to characterise this tuning mechanism.

Previous research has demonstrated electro-optical modulation of the
5. Single Mode PhC Laser Wavelength Tuning and FM

PhC cavity reflectance using a p-n junction as a means of wavelength tuning the reflectance band [175] by carrier induced refractive index change. This work uses this approach and focuses on the thermo-optic effect in silicon as a means of wavelength tuning and FM. Modulation of the voltage across either the microheater or doped p-n junction on the silicon reflector of the EC laser will change the refractive index which will tune the reflectance band and hence, modulate the lasing frequency.

![Figure 5.1: Single mode FM laser configuration: III-V InP RSOA and silicon PhC cavity resonant reflector. Separate voltage to RSOA and modulating voltage to p-n junction at PhC cavity.](image)

Thermal switching has been demonstrated by Beggs et al. [176] using a microheater on a PhC cavity/waveguide, while Akiyama et al. [177] and Lin et al. [119] have also used the approach of an integrated microheater to tune the resonance wavelength of a ring resonator in a configuration that exhibits strong mode-hopping. PhC cavities have smaller modal area (see Chapter 3) than a typical ring resonator and have a larger FSR that results in less severe mode competition effects. The thermo-optic effect can achieve maximum speeds in the low MHz range which is sufficient for sensing applications.

The work in this chapter focuses on single mode laser FM with moderate tuning speed and small tuning range which also exhibits a low IM.
5. Single Mode PhC Laser Wavelength Tuning and FM

This type of laser can be useful for applications where precise wavelength registration/high resolution is essential such as trace-gas detection. For gas detection techniques, a low IM over a frequency scan can be advantageous for identifying absorption features by eliminating the need for error correction of the signal or further calibration caused by IM.

![Reflectance band overlaps with one longitudinal mode. Modulation of lasing mode (laser FM) achieved by modulation of the reflectance band.](image)

**Figure 5.2:** Reflectance band overlaps with one longitudinal mode. Modulation of lasing mode (laser FM) achieved by modulation of the reflectance band.

This is the first time that this effect has been observed in a hybrid III-V/silicon laser. Furthermore, by virtue of the small size of the PhC cavity, tuning can be more efficient than the frequency tuning which is employed in DFB lasers as the heating power is applied only to the PhC cavity rather than the entire laser cavity as with traditional tuning approaches.

### 5.1 PhC cavity resonant modulators

These devices were designed by Alexandros A. Liles; the SU-8/microheater devices were fabricated in the University of St. Andrews and the SiN/p-n devices were fabricated in Tyndall National Institute. Details of the design, fabrication, and material processing were provided and are outlined below. Each of the PhC cavity devices had the same geometry as described in Chapter 4, i.e. period = 390 nm and hole radius = 90 nm.
5. Single Mode PhC Laser Wavelength Tuning and FM

5.1.1 SiN waveguide with p-n junction

A low refractive index SiN waveguide is located vertically above a silicon PhC cavity. The two parts are separated by a thin oxide layer, which acts as a physical buffer and allows the evanescent exchange of light between the waveguide mode and the cavity mode [125]. A DA PhC cavity design is used [142] as it offers high disorder tolerance and good mode overlap with the utilised low index waveguide (see Chapter 3). The DA PhC cavity (Fig. 5.3(a)) is implemented on a 220 nm SOI platform by electron-beam lithography and Reactive Ion Etching (RIE). The height and width of the waveguide are 500 nm and 1 µm respectively, allowing low coupling losses to both the RSOA waveguide and the lensed fiber used to collect the output of the laser. Coupling losses from the RSOA and SiN waveguide were found to be 50% from FIMMWAVE simulation, and the losses are also shown for the same device interfaces in [178]. A ∼170 nm thick layer of spin-on-glass (Accuglass by Honeywell) is used as a buffer layer between the Si and SiN. Both facets of the reflector chip are coated with an anti-reflection layer (single layer MgF₂) to reduce back-reflections.

![Figure 5.3](image-url)

(a) (b)

**Figure 5.3:** (a) SEM image of PhC before p-n contact pads addition. (b) Microscope image of PhC and p-n contact pads post fabrication.

To create the p-n junction, four different levels of doping are used. The low doped p-n junction is designed to overlap with the DA cavity to achieve maximum electro-optic efficiency. The p-n junction is created by implan-
5. Single Mode PhC Laser Wavelength Tuning and FM

tation of boron and phosphorous ions to realise the targeted doping concentration of $10^{16}$ cm$^{-3}$. Although the overlapped doping region increases the free-carrier losses, the measured total Q-factor of the cavity was 15,000 (for the fundamental mode, corresponding to a reflector bandwidth of $\sim 15$ GHz). The p-n junction is designed 2 $\mu$m away from the centre of the cavity. Rapid Thermal Annealing (RTA) is performed on the wafer for 60 seconds at 1000°C under N$_2$ environment to provide maximum carrier activation.

\[\text{Figure 5.4:} \] (a) IV curve for p-n junction. (b) Microscope image of needle probes applied to contact pads on sample. (c) ASE characterisation of PhC cavity with resonance wavelength shift as a function of applied power to p-n junction for 2-4.5 V, insets: (bottom right) full applied voltage range of 0-7 V, (top left) transmission spectrum of PhC cavity at 0 V.
5. Single Mode PhC Laser Wavelength Tuning and FM

To inject the free carriers into the p-n junction, the metal contacts (Fig. 5.3(b)) are formed by dry etching the vias through the oxide layer and then depositing aluminium contact pads. The heavy doped p-n junction helps to form an ohmic contact between the Si layer and Al pads, giving the low contact resistance \( p = 240 \), \( n = 270 \) Ω/sq. sheet resistance.

The heat is dissipated in the highly thermally conductive silicon layer, which is thermally isolated from the SiN waveguide. Coupled with the low thermo-optic coefficient of SiN, any effects of the p-n junction on the optical length of the SiN is negligible. Thermo-optic tuning of the PhC cavity resonance is caused by a local change in temperature and thus, the material refractive index, achieved by ohmic heating.

The IV curve in Fig. 5.4(a) was generated by applying voltage to the p-n contact pads using a voltage source and needle probes as shown in Fig. 5.4(b) and measuring the current. The slope resistance in the linear region (4-7 V) was measured as 130.5 Ω. The temperature rise generated from injection of carriers shifted the PhC resonance. Fig. 5.4(c) shows the resonance shift as a function of applied power to p-n junction, (by PhC cavity transmission spectrum measurement as described in previous chapter). The resonance shifts by \( \sim 3.75 \) nm for an applied power of 80 mW (up to 4.5 V - the range of interest as will be demonstrated in Section 5.2.1 for laser wavelength tuning).

5.1.2 SU-8 waveguide with microheater

The same DA PhC cavity design is used as described in the previous section but instead is vertically coupled to an SU-8 polymer waveguide (similar to the devices described in Chapter 4). The height and width of the waveguide is \( \sim 3.1 \) and 2.1 µm, respectively, again allowing low coupling losses (<3 dB/facet) to both the RSOA waveguide and the lensed fiber used to collect the output of the laser. A \( \sim 130 \) nm thick layer of FOx (Accuglass by Honeywell) is used as a buffer layer. Again, both facets of the reflector chip are AR-coated (single layer MgF\(_2\)) to minimise back-reflections.
Figure 5.5: (a) SEM image of PhC cavity and isolation trenches before fabrication step of microheater addition. (b) Design schematic of PhC cavity (grey), microheater (brown) and trenches on silicon (green). (c) Microscope image of fabricated silicon chip with PhC, microheater contact pads, trenches and SU-8 waveguide.

Trenches are defined on the silicon layer around the PhC cavity (as shown in Fig. 5.5(a)) for improved thermal isolation (that would consequently increase the efficiency of the thermo-optic effect). The metal contacts (Fig. 5.5(b)) are formed on the oxide layer (Fig. 5.5(c)) by a 220 nm thick layer of Ni on top of a 20 nm layer of Cr (used for better adhesion). The contact pads are designed to minimise the losses that the overlap with metal would induce in the propagating optical field (see [179] for design considerations). The width of the contact electrode is reduced in the vicinity of the PhC cavity to ensure increased resistance (and therefore a larger localized temperature change for a given voltage).

The IV curve for the resistor (Fig. 5.6(a)) was generated by applying voltage via needle probes on the metal contact pads (Fig. 5.6(b)) and measuring the current. The slope resistance was measured as 33.5 Ω (in the linear
As described in Chapter 4, the transmission spectrum of the PhC cavity was characterised using a broadband ASE source and is shown in Fig. 5.6(c):

region, 0-1.5 V). As the voltage was increased >1.5 V, there was a non-linear response in the resistance. This can be attributed to the temperature coefficient of resistance for the Ni-Cr metal, which is the change in resistance with changing temperature [180].

Figure 5.6: (a) IV curve for microheater showing 33.5 Ω slope resistance in linear region. (b) Microscope image of needle probes applied to microheater metal contact pads on silicon chip. (c) Transmission spectrum of PhC cavity characterised with broadband ASE source showing shift in PhC cavity resonances by thermally induced refractive index change by application of current to microheater. Inset: Full transmission spectrum showing all PhC cavity resonance modes (at 0 V).
5. Single Mode PhC Laser Wavelength Tuning and FM

inset. The separation of the resonances is \(\sim 8\) nm related to the FSR of the PhC cavity (see Chapter 3). When current was applied to the microheater pads, the heat generated in the resistive material adjusted the temperature in the PhC cavity which in turn red-shifted the PhC resonance by 0.26 nm for an applied power of 75 mW (1.5 V) to the microheater (Fig. 5.6(c)).

5.2 Laser wavelength DC tuning

Both of the modulator devices were employed in the single mode laser configuration to establish wavelength tuning and the experimental results are presented in the following sections. The EC laser was realised as per the description in Chapter 4, as were the spectral and output power measurements which were undertaken.

5.2.1 SiN/p-n junction

The length of the RSOA was 400 \(\mu\)m with a group index of 3.6 (see Chapter 4) and the SiN waveguide length was 2,240 \(\mu\)m with an estimated group index of 1.94 (Fig. 5.7). Thus, the estimated total cavity optical length was 5,786 \(\mu\)m with an FSR of 25 GHz. As the SiN waveguides had straight facets, an RSOA with a straight waveguide facet was used.

![Figure 5.7: Overhead schematic of laser cavity layout with RSOA and silicon chip (including PhC cavity, p-n junction and SiN waveguide) indicating waveguide lengths.](image)

The RSOA gain was biased at 50 mA and single mode operation was achieved at a lasing wavelength of \(\sim 1540.5\) nm with an SMSR of \(\sim 30\) dB.
5. Single Mode PhC Laser Wavelength Tuning and FM

(Fig. 5.8(a)). With the gain bias fixed, a DC voltage was applied to the p-n junction as described in Section 5.1.1 and thus, tuning of the single mode lasing peak was realised.

![Graph](image)

**Figure 5.8:** (a) OSA spectrum of single mode operation at $\sim 1540.5$ nm, SMSR $\sim 30$ dB at a pumping current of 50 mA with 0 V applied to p-n junction. (b) Colourmap of optical power spectrum showing red-shift of the lasing mode for 3-4 V (25 mW applied power) to p-n junction and (c) peak shift of lasing mode from starting wavelength for each applied power step showing $\sim 65$ pm shift for this range.

For a stepped DC voltage of 3-4 V applied to the p-n junction (equal to average applied power of 25 mW), a red-shift of the lasing mode was observed. The colourmap in Fig. 5.8(b) indicates the optical power at the associated wavelength and the lasing peak showing as the most intense points in yellow. Less intense peaks are also present with $\sim 1$ nm separation, which
are related to the RSOA gain ripple and the smaller fringes are associated with the longitudinal mode spacing as discussed in Chapter 4. Continuous single mode tuning of \( \sim 65 \) pm was achieved for the applied power range (Fig. 5.8(c)).

At this resonance wavelength (5th order mode), the bandwidth of the reflector was 62.4 GHz (0.5 nm) which was wider than the FSR of 25 GHz. Nonetheless, single mode lasing was sustained as the side modes did not have sufficient reflectivity to overcome threshold. The lasing mode tracks the reflectance peak shift but the significantly large reflector bandwidth to FSR ratio resulted in weak tracking.

**Figure 5.9:** Comparison of (a) lasing spectrum with peak shift for applied voltage of 2-4 V in steps of 0.1 V to p-n junction, (b) ASE spectrum of RSOA (directly from RSOA waveguide output), and transmission shift (by ASE characterisation) of PhC cavity for the same applied voltage range in steps of 0.5 V to p-n junction.

Discrete wavelength tuning was also observed for a larger applied voltage range of 2-4 V in steps of 0.1 V and is shown in Fig. 5.9(a). The ASE gain spectrum was measured at the output facet of the RSOA coupled directly to a lensed fiber as described in Chapter 4. The transmission spectrum for the PhC cavity is shown for the same applied voltage range in steps of 0.5 V.
5. Single Mode PhC Laser Wavelength Tuning and FM

and shows a red-shift as expected (Fig. 5.9(b)). The mode-hop is dominated by the position of the gain ripple and reflector position in this case showing the longitudinal mode-hop to the next favourable gain ripple peak aligned with the reflection peak rather than the adjacent longitudinal mode. A wider wavelength tuning range is achieved although, as discrete steps rather than continuous. On account of the straight waveguide facet of the RSOA, there was a strong gain ripple present and coupled with the large bandwidth of the reflection peak, discrete wavelength tuning occurred. Therefore in this case, the continuous tuning range is not only limited by the cavity FSR since the role of the gain ripple has a large effect on the position of the lasing mode when more than one ripple falls within the reflection band. Losses are reduced close to the gain ripple maximum and where the transmission dip/reflection peak coincide, the longitudinal mode solution at that point becomes more favourable.

5.2.2 SU-8/microheater

As above, single mode laser operation was realised with the RSOA waveguide (length = 400 µm) butt-coupled to the SU-8 waveguide (length = 3,110 µm with a group index of 1.58) as shown in Fig. 5.10. The total cavity optical length was \( \sim 6,354 \) µm with an FSR of 23 GHz. With the RSOA bias current fixed at 50 mA, current was applied to the microheater pads as described in Section 5.1.2 and again, tuning of the longitudinal mode was achieved.

![Figure 5.10: Overhead schematic of laser cavity layout with RSOA and silicon chip (including PhC cavity, microheater and SU-8 waveguide) indicating waveguide lengths.](image-url)
5. Single Mode PhC Laser Wavelength Tuning and FM

Figure 5.11: OSA spectrum of (a) lasing peak showing longitudinal mode shift for stepped current applied to microheater from -50 to +50 mA, (negative values indicate decreasing steps and 50 mA equates to an applied power of 75 mW, 0 mA indicates no applied power). (b) Extracted plot of 3 current steps of 11.6, 19.2 and 26.5 mA (marked on (a)), at the points where the lasing peak blue-shifts then transitions to multimode lasing then red-shifts to the next available single longitudinal mode solution.

Fig. 5.11(a) displays the lasing spectrum for each current step applied to microheater pads. As before, the colourmap indicates the optical power at the associated wavelength and the lasing peak shows as the most intense points in yellow and less intense peaks are also visible. It was observed that the laser longitudinal mode blue-shifted with increased applied current to the point where it mode-hopped to the next longitudinal mode. The transition from one longitudinal mode to the adjacent mode first exhibited multimode lasing then subsequently single mode at the longer wavelength (Fig. 5.11(b)).

The result of a blue-shifted longitudinal mode was on account of the SU-8 waveguide undergoing heating due to the negative thermo-optic effect of this material. However, when the longitudinal mode-hop occurred, it was a red-shift in wavelength due to the red-shifting of the PhC resonance. These two effects were counteracting in this configuration as the longitudinal mode solution on the longer wavelength side in the reflectance band became more favourable.

Fig. 5.12 illustrates the mode shifting and hopping mechanism with the
blue and red shift counteracting effects. The longitudinal mode solutions with mode index, \( m \) are given by:

\[
\lambda_m = \frac{2}{m} (n_{ga}L_a + n_{gp}L_p)
\]  

(5.1)

where \( n_{ga} \) and \( L_a \) are the group index and length of the active section (i.e. RSOA), respectively and assumed to be fixed in this case. \( n_{gp} \) and \( L_p \) are the group index and the length of the passive section (i.e. SU-8 waveguide from input facet to PhC cavity), respectively. With heating, a change in the group refractive index of the waveguide, \( \Delta n_{gp} \) occurs, modifying the effective length of the cavity thus, leading to tuning of the longitudinal mode solutions given by:

\[
\frac{\Delta \lambda_m}{\lambda_m} = \frac{n_{ga}L_a + \Delta n_{gp}L_p}{n_{ga}L_a + n_{gp}L_p}
\]  

(5.2)
5. Single Mode PhC Laser Wavelength Tuning and FM

where $\Delta \lambda_m$ is the amount by which the mode shifts. Intentionally neglected is the reflection phase contribution of the PhC cavity expressed in Eq. 3.15 in order to emphasise the dominant cavity phase change given by the changing length of the cavity on account of the waveguide. While the negative thermooptic coefficient of the SU-8 waveguide causes a blue-shift of the mode, the heating of the PhC cavity causes a red-shift in the resonance due to the optical properties of silicon (indicated by the Lorentzian curve in Fig. 5.12). When the resonance peak is in close alignment with a gain ripple peak maximum, lasing occurs at the position of the most favourable longitudinal mode solution.

Variation in the emitted laser power was also observed during mode tuning. This can be attributed to the detuning of the lasing mode from the reflectance peak as discussed in Chapter 3. However, for the experimental conditions, the role of the gain ripple must also be taken into consideration. For this reason, analysis of the emitted power alone cannot accurately determine the position of the lasing mode relative to reflectance peak and gain ripple peak but certain assumptions can be made.

Figure 5.13: (a) Peak wavelengths extracted from OSA spectra in Fig. 5.11(a) for peaks greater than -45 dBm for each applied current step to the microheater. (b) Corresponding laser output power for the applied current steps.

Fig. 5.13 shows the variation in output power as the laser wavelength
was tuned. The peak points were extracted from the OSA lasing spectra in Fig. 5.11(a) for the peaks greater than -45 dBm. Observed for the single mode regions from 0-10 mA and 23-35 mA, an applied current increase gives an increase in the output power. It could be inferred that the increase in output power is detuning of the longitudinal mode from the reflectance peak or the mode tunes closer to the gain peak maximum. A decrease in power shows for 15-21 mA where in this region, there is the transition to multimode lasing indicating the effect the modal dynamics has on the output power. In the region of multimode lasing, the power is reduced effectively increasing carriers hence, increasing the material gain allowing multiple modes to reach threshold. There is a sharp drop in power for 37-42 mA as the mode hops briefly to the next gain ripple at a position of assumed significantly lower reflectivity at the edge of the reflectance peak hence, the drop in power. The transition from that point, there are two modes lasing on two gain ripple peaks at 42 mA giving an increase in power and finally returning to single mode with a small variation in power to the end of the applied current range.

5.3 Laser frequency modulation

Measurements of the laser frequency modulation were taken using the experimental setup shown in Fig. 5.14. The output of the laser was collected via a lensed fiber and passed through an isolator (ISO) then to a 1×2 splitter with one path to a channel of the oscilloscope (OSC) to capture the output intensity and the other path was passed through a 3×3 splitter and mixed with a tunable laser source (TLS). A beating signal was generated by setting the TLS output close to the lasing wavelength and mixing these two signals using a polarisation controller (Pol) to maximise the beating signal. The beating frequency was observed via a 33 GHz bandwidth photodetector to the oscilloscope to capture the frequency dynamics of the laser and thus, observing the laser frequency modulation generated by the modulation of the PhC cavity temperature. A power meter (PM) and optical spectrum analyser (OSA) measured the output power and recorded the optical spectrum.
The modulation signal was applied to the p-n junction via the needle probes using a function generator, power source, and bias-tee to give a 3-4 V (linear region of IV curve) sine wave modulation. The beating signal as a function of time which was generated on the scope was captured and post-processed. The processing of the intensity time trace involved implementing a sliding window Fast Fourier Transform (FFT) algorithm to determine the frequency components for a series of short time segments. A rectangular window function of 100 ns width was applied to the intensity time trace and advanced in steps of 50 ns. The FFT of each time window was computed to determine the frequency components and the fundamental frequency was determined as the beating frequency between the lasing mode and TLS. The computed spectrogram is shown in Fig. 5.15 with the beating frequency as a function of time for an applied modulation frequency of 50 kHz. The colourmap represents the magnitude of the frequency component in the Fourier spectrum. The TLS was fixed at the longer wavelength side of the laser wavelength therefore, as the laser wavelength decreases, the difference from the TLS wavelength increases leading to an increase in beating frequency and vice versa.

An appropriate time window value needs chosen to include enough sample points and at least one oscillation on the time trace in order to obtain the beating frequency in the Fourier transform of the time segment. The resolu-
5. Single Mode PhC Laser Wavelength Tuning and FM

**Figure 5.15:** Time varying beating frequency of laser mode and TLS wavelength for 50 kHz sine wave modulation to p-n junction.

...tion limit is set by the minimum detectable frequency change between each time window and is determined by the sampling frequency (i.e. frequency resolution) which is inversely proportional to the sampling time. The frequency resolution may be increased by adding extra data points by interpolation and also by zero padding but this will also increase the computational time required.

For comparison between both the p-n junction and microheater devices, analysis of the modulation depth with increasing modulation frequency was made by means of large signal modulation as opposed to small signal modulation as the small signal change in frequency was not detectable due to resolution limitations of the scope. Nevertheless, the largest possible modulation depth (i.e. continuous, without mode-hopping) for a given modulation frequency, input sine wave and fixed driving voltage amplitude was recorded and is presented in Fig. 5.16. It can be seen that the modulation depth, $\Delta \nu$ is highly dependent on the modulation frequency determined by the frequency response of the modulator. Greater modulation depth was achieved with the p-n junction as compared to the microheater for the same modulation frequencies owing to less frequency roll-off for the p-n junction.

Considering that these devices undergo modulation by the thermo-optic
effect, the large roll-off of the frequency response is likely attributed to the thermal time constant of the device. The microheater metal contacts are formed on the FOx layer which has low thermal conductivity thereby, the heat transfer rate is reduced. The microheater devices response is lower in depth as they rely on the heat transfer from the resistive element to the PhC cavity. For the p-n devices, heat is generated directly at the PhC cavity but heat extraction with non-efficient heat sinking remains to be a factor hence, the roll-off of the frequency response. Also, it is likely that there was misalignment of the p-n junction and PhC cavity which can further reduce the FM efficiency. Improvement in fabrication of these devices would result in an increase of the bandwidth and FM efficiency.

Figure 5.16: Laser frequency modulation depth as a function of modulation frequency (log scale) for p-n junction (green) and microheater (blue).

The following measurements were performed with the p-n junction device as this showed greater modulation depth. To observe the FM and IM simultaneously, a triangular wave signal of 2.7-4 V at 10 kHz was applied to the p-n junction (Fig. 5.17(a)). The laser output IM generally followed the shape of the FM and using the calculation for IM in Eq. 3.27 from Chapter 3, it was found to have a value of -3.8 dB (Fig. 5.17(b)) for the conditions during this measurement. This value could be further reduced by optimising the pumping current as described in the simulations in Chapter 3. However,
5. Single Mode PhC Laser Wavelength Tuning and FM

variation of the bias current led to mode-hopping due to the small FSR of this laser cavity therefore, optimisation was challenging so the bias was fixed at 50 mA. Furthermore, this IM value is not as low as the simulation results due to idealised simulation parameters used which do not account for non-ideal experimental conditions. The frequency shift $\Delta \nu$ was $\sim 4$ GHz (Fig. 5.17(c)) for this drive signal range.

![Figure 5.17](image)

**Figure 5.17:** (a) Driving signal input to p-n junction of 10 kHz triangular waveform, (b) laser output intensity with IM of -3.8 dB and (c) beating frequency showing FM of the laser giving a frequency shift $\Delta \nu$ of $\sim 4$ GHz.

The shape of the FM was somewhat distorted to the triangular waveform input which was to be expected as the reflector shift and frequency shift do not have the perfect linear relationship as shown in the simulations in Chapter 3. Also, the asymmetry in the FM shape could be explained by the hysteresis effects which were presented in Chapter 4 owing to absorption in the PhC cavity [160].

The hysteresis was further examined by extracting the y-axis data from Fig. 5.17 and plotting the laser frequency shift and output intensity as a function of the driving signal input to the p-n junction and is shown in Fig. 5.18(a). The linear region of the IV curve for the p-n was used with
5. Single Mode PhC Laser Wavelength Tuning and FM

the expectation of a linear reflector shift. The mode-reflector detuning is
generally indeterminable but inferences can be drawn from the direction of
the laser frequency and accompanying output intensity. This analysis can
offer some insight into the hysteresis type behaviour as the laser undergoes
FM. The solid red and blue lines indicate increasing reflector drive voltage
while the dotted red and blue lines indicate decreasing reflector drive voltage.

**Figure 5.18:** (a) Frequency shift and output intensity extracted from Fig. 5.17
and plotted as a function of driving voltage with range of 2.7-4 V to the reflector
for 10 kHz modulation. Laser frequency shift with increasing driving voltage is
indicated by the solid blue line and decreasing by dotted blue line. The output
intensity with increasing driving voltage is indicated by solid red line and decreas-
ing by dotted red line. (b) Different longitudinal mode for a driving voltage range
of 4.1-4.5 V at 10 kHz modulation. (c) Different longitudinal mode for a driving
voltage range of 4.18-4.44 V at 1 kHz modulation. (Note: varying x-axis scales;
left y-axis scales equal; right y-axis scales equal.)

Fig. 5.18(a) shows that as the driving voltage to the p-n increases,
the laser frequency decreases accompanied by the same effect to the output
power. As the driving voltage decreases, the laser frequency increases
but has deviated from the position in the opposite tuning direction, separated
by a maximum of $\sim 1.5$ GHz.

Further measurements were taken for different longitudinal modes and
modulation frequencies and were plotted using the same technique. A change
of the reflector drive range or small variation of the RSOA coupling position
allowed for a different longitudinal mode to lase. Fig. 5.18(b) shows the
opposite effect on frequency shift occurring for a different reflector drive range
of 4.1-4.5 V operating on a different longitudinal mode. This would also have
a different mode-reflector relative position which may explain mode tuning
direction if operating close to reflectance peak where the mode tuning tends
to curve around the peak (as shown in simulations in Chapter 3). Fig. 5.18(c)
is a slightly different drive range of 4.18-4.44 V with 1 kHz modulation and
lasing on another longitudinal mode was achieved by a change in the RSOA
coupling position. This slower modulation frequency causes the hysteresis
loop to essentially close (and the variation in this case can be attributed to
experimental noise). The more linear response again suggests the significance
of the thermal time constant of the device. Also, it is possible the more linear
response is modulation occurring at the edge of the reflectance peak where
the change in power is greater but with the advantage of a more linear mode
frequency tuning.

5.4 Summary

Presented in this chapter was a wavelength tunable and FM PhC laser by
means of the thermo-optic effect in silicon. It can be seen in this work that the
resonance wavelength shift in the laser cavity can be achieved by local heating
of the PhC cavity. Improvements in heating efficiency can be achieved by
trenching and undercutting around PhC cavity for thermal isolation and
simulations show an improvement of three times less the amount of required
heating power for the same shift using the undercutting approach in [91].

Experimentally it was shown that the lasing mode shift does indeed track
the reflector shift however, weakly in these results. The weak tracking is due
to the wide reflector bandwidth for the resonance modes implemented in these
experiments. The cavity design resulted in resonance modes on the longer
wavelength side of the gain spectrum therefore, lasing operation was achieved
on a resonance mode with a relatively wide reflector bandwidth. Implement-
ing devices with a narrow reflector bandwidth and larger FSR would lead to
better tracking of the lasing mode which is an important consideration for
design to achieve significant tuning for less applied power.
5. Single Mode PhC Laser Wavelength Tuning and FM

While undergoing FM, theoretically the IM value is lower than what was achieved experimentally as not all the simulation parameters account for experimental conditions such as imperfect anti-reflective coatings on the RSOA and PhC chip facets. Nevertheless, both the theoretical and experimental results show a small IM which has the potential to realise a pure FM laser that can find applications in wavelength scanning absorption techniques such as FM spectroscopy and trace-gas detection where a narrow tuning range is sufficient and a high sensitivity FM is required.

Heating from the microheater device had a significant effect on the SU-8 waveguide and the negative thermo-optic coefficient of the material led to counteracting effects of phase tuning and resonance shift. This is a design consideration which should be taken into account when selecting a waveguide if this effect is not desired. The positive lower thermo-optic coefficient of SiN results in a negligible phase change contribution and is less than that of the resonance shift giving the expected tuning of the lasing mode following the reflector tuning.

The p-n junction was operated in forward bias at low modulation speeds to study the thermo-optic effect. Similar p-n PhC devices have shown up to 0.5 GHz modulation speed [175]. The p-n junction can also be operated in reverse bias for carrier depletion which has the potential to achieve 10s of GHz speed although, this is a weaker effect on the resonance shift. However, considerably higher modulation speeds are possible which can also find applications in the optical communications field.
Chapter 6

Long Cavity Multimode PhC Laser in FDML Operation

The work in this chapter aims to extend the continuous tuning range beyond the single mode regime described in the previous chapter. In the single mode regime, the fundamental maximum continuous tuning range was limited by the cavity FSR. In order to extend the continuous tuning range, a highly multimode FDML configuration was studied in this work. This configuration utilised the same PhC cavity modulator devices as described in the previous chapter and by extending the length of the laser cavity, many longitudinal modes lay within the reflectance bandwidth. FDML operation is realised by sweeping the filter at a period synchronous to the roundtrip time of the cavity as $f_{\text{mod}} = m/T$, where $f_{\text{mod}}$ is the filter modulation frequency, $T$ is the roundtrip time and $m$ is an integer. A full sweep is optically stored in the cavity which overcomes the restriction of cavity build-up time as lasing does not need to build up from spontaneous emission with each sweep [13].

Applying the principle of FDML operation in this work, the modulation frequency matched the cavity roundtrip frequency and the full spectrum was stored in the laser delay line. The corresponding sweep frequency was applied to examine the wavelength sweep range, instantaneous frequency and temporal dynamics of this laser in FDML operation. Two cavity lengths were examined using a 2 km and 45 m delay line. Unless otherwise stated, the SiN
p-n modulator device was used for the majority of experiments described in this chapter.

Reports of FDML lasers typically involve a ring cavity design with uni-directional lasing and sweeping of an optical bandpass filter [13, 75, 76]. Such lasers enforce uni-directional lasing via optical isolators, a major barrier to compact and integrated devices. For this work, a linear Fabry-Perot cavity with bi-directional lasing was implemented with forward biasing and a sine wave modulation applied to the reflector. This is the first time, to the author’s knowledge, that a tunable PhC cavity reflector has been used to demonstrate an FDML laser.

6.1 Laser configuration and experimental set-up

The laser cavity consisted of a broadband fiber reflector facet (R = 98%), a non-isolated fiber pig-tailed SOA (Kamelian OPA-20-N-C-FA, optical gain centred at 1550 nm), a polarisation controller, a fiber delay line and a lensed fiber coupled to the PhC reflector which acted as the other facet (Fig. 6.1). Similar to the experimental setup in Chapter 4, the lensed fiber was actuated by a 5-axis manual translation stage.

As described in Chapter 3, this design of DA PhC cavity is expected to contain multiple reflection peaks separated by the resonator FSR, each with a different bandwidth and reflectivity. Below threshold, the ASE spectrum showed these multiple reflection bands of varying widths and intensities (Fig. 6.1: inset). An increase of the gain could result in multiple resonances lasing and selection of one was possible using the polarisation controller within the laser cavity.

A 50/50 1×2 splitter was included in the cavity and acted as the cavity output coupler. The light was passed through an isolator to minimise back reflections, then divided between an optical spectrum analyser and to a high-
6. Long Cavity Multimode PhC Laser in FDML Operation

Figure 6.1: Laser configuration consisting of a fiber reflector, SOA, polarisation controller (Pol), fiber delay line to a lensed fiber coupled to waveguide and PhC cavity. Measurements taken from intra-cavity splitter to isolator (ISO) divided to oscilloscope (OSC) and optical spectrum analyser (OSA). Inset: ASE spectrum below threshold at 30 mA showing multiple reflection peaks of the PhC cavity resonance modes.

speed InGaAs photodetector connected to an oscilloscope to examine the laser intensity dynamics and optical spectrum.

6.2 Laser characteristics and tuning of PhC reflector

The lasing characteristics were found to be similar for both cavity lengths of 2 km and 45 m and the following results are presented for the 2 km length cavity. The laser showed a threshold value of 35 mA with a slope efficiency of 0.14 mW/mA and 11 mW power at maximum bias current of 120 mA (Fig. 6.2(a)). At pump biases just above threshold, the lasing spectrum showed a single peak. There were expected to be multiple longitudinal modes lasing within this single peak due to the small FSR (∼1.2 fm) of the 2 km cavity but these were not visible due to the resolution of the OSA which was 20 pm. As the pump power was increased, the adjacent peaks began lasing and the full bandwidth of the reflector was evident from the envelope containing
6. Long Cavity Multimode PhC Laser in FDML Operation

the narrower peaks (Fig. 6.2(b)). The narrower peaks stem from the multiple parasitic reflections from the PhC cavity to the chip facet superimposed on the PhC reflectance peak as discussed in Chapter 4. Broadening of the lasing spectrum as the pump power was increased was due to more groups of longitudinal modes overcoming loss and starting to lase. There were approximately $10^6$ longitudinal modes within the reflection bandwidth of $\sim 1$ nm for the 2 km cavity.

![Figure 6.2: Lasing characteristics of the long cavity laser. (a) Increasing SOA pump current with colourmap of OSA spectrum. Inset: LI curve. (b) OSA spectra for 47 mA and 120 mA showing broadening of lasing spectrum.](image)

As demonstrated in Chapter 5 for single mode operation, a forward DC bias voltage applied to the reflector causes tuning of the PhC cavity resonance wavelength via the thermo-optic effect in silicon. DC voltage was applied to the contact pads on the p-n junction using needle probes and a DC voltage source. The SOA was biased at a fixed current of 70 mA and voltage to the p-n junction was stepped from 0-6 V in steps of 0.2 V. As a result of heating in the PhC cavity, the reflection spectrum red-shifted and the lasing spectrum consequently shifted (Fig. 6.3). The characteristic shape of the p-n IV curve was also apparent in the lasing spectrum shift. The p-n junction showed a “switch-on” after 1.8 V in forward bias (Fig. 6.3: inset) and with increasing voltage, the power dissipated non-linearly to give the quadratic
6. Long Cavity Multimode PhC Laser in FDML Operation

curve. This gave a total wavelength red-shift of ∼10 nm for this applied voltage range.

![Figure 6.3: Lasing spectrum shift with application of DC voltage steps to p-n junction contact pads with SOA pumping current at 70 mA. Inset: IV curve of p-n junction.](image)

The instability of the multimode operation can be seen from the time averaged spectrum where multiple mode groups were active and lasing asynchronously. Fig 6.4(a) shows three captures from the OSA taken at ∼10 second intervals illustrating the unstable lasing mode groups. The smoothing effect was a result of a lower resolution set on the OSA to obtain a faster acquisition. The unstable lasing was also visible on the output intensity time trace showing large intensity fluctuations (Fig. 6.4(b)). Intensity oscillations in the GHz region were observed within the bandwidth of the 33 GHz photodetector. The instabilities observed over the seconds time range can be attributed to environmental fluctuations.

With fixed biases, the laser output intensity was unstable as a result of groups of multiple longitudinal modes lasing asynchronously without a fixed phase relationship. This behaviour is typical of multimode lasers due to mode competition for gain, mode switching and energy dispersion in the cavity [181]. For ring lasers with a static filter, regimes typically vary from continuous wave to chaotic depending on the spectral transmission at the filter.
6. Long Cavity Multimode PhC Laser in FDML Operation

position [157]. Multimode regimes for a short cavity swept laser have been
analysed in detail in [156] showing mode-locked pulsations, mode-hopping
and chaotic regimes depending on the sweep direction. Their report showed
at the turning points of the sweep (where the filter moves slowest), multiple
mode-hopping dynamics occurred comparable to a static filter. Detailed dy-
namics of an FDML laser have been analysed in [155], showing multimode
instabilities present in the long cavity laser.

![Graphs a and b](image)

Figure 6.4: (a) 3 captures of OSA of lasing spectrum at ∼10 second intervals.
(b) Laser intensity time trace ns scale showing large power fluctuations. Inset: ms
scale intensity (black) and smoothed average intensity (red).

6.3 Modulation of PhC reflector

On application of a sine wave modulation of the appropriate frequency to
the reflector, sweeping of the laser wavelength with a relatively stable and
more predictable intensity can be obtained. Using a bias-tee, a DC voltage
source and a function generator were combined to give a 3.9 V DC offset and
2.8-5 V sine wave modulation of the p-n junction in order to modulate the
reflectance peak.
6. Long Cavity Multimode PhC Laser in FDML Operation

6.3.1 2 km cavity for kHz modulation

The roundtrip time of the Fabry-Perot laser cavity, \( T = 2nL/c \) was estimated to be 20 \( \mu s \) with \( n_{\text{glass}} = 1.5 \) and \( L = 2 \) km. Hence, the modulation frequency, \( f_{\text{mod}} = 1/T \) was calculated as 50 kHz. This value was apparently close to the roundtrip frequency as the resulting wavelength sweep on the OSA began to stabilise and remain active in parts, mostly at the extremities of the sweep with a range of \( \sim 3.5 \) nm. However, the spectrum still showed some instabilities (similar to the static reflector shown Section 6.2) and not active at all in other parts of the sweep (Fig. 6.5(a)).

The modulation frequency was increased in steps of 0.01 kHz and the average power was recorded (Fig. 6.5: bottom right). The power increased to a maximum and then began to decrease and the modulation frequency with the maximum power was determined to be 50.35 kHz. At this frequency, the wavelength spectrum remained stable and showed the highest power at the extremities of the sweep, indicating the turning points where the reflector moves slowest (Fig. 6.5(b)). Deep modulation fringes of \( \sim 18 \) dB with a period of 0.18 nm were also present across the spectrum. The fringe period is closely related to the parasitic reflection peaks observed on the reflection spectrum, imposed by the reflections from the PhC cavity to the chip facet and act as an internal Fabry-Perot cavity within the larger laser cavity. By using chips with lower reflectivities, the power in these fringes (comb lines) can be reduced.

The swept laser intensity had a cyclic amplitude envelope repeating with each sweep period (Fig. 6.5(c)) with a stable average output power. Although, on a shorter time scale (ns), the intensity showed instabilities and deep modulations likely due to low coherence caused by the parasitic reflections within the cavity however, the overall intensity envelope was stable and periodic. In comparison to the static reflector case above where the intensity and average output power had large and unpredictable fluctuations, the long term stable state of the laser in FDML operation was evident. Fig. 6.5(c) also includes the intensity time traces for the corresponding spectra of
6. Long Cavity Multimode PhC Laser in FDML Operation

Figure 6.5: OSA spectra of swept laser for modulation frequencies of (a) 50, 50.7 and 51 kHz and (b) stable at 50.35 kHz with \(~3.5\) nm sweep range. (c) Laser intensity time traces for the corresponding modulation frequencies. Bottom right: Average intensities as a function of modulation frequency.

stepped frequencies in Fig. 6.5(a). These show reduced intensity in parts corresponding to the sections of the spectrum which were not active. Again, the maximum average power can be seen for the matched modulation frequency of 50.35 kHz.

In order to measure the sweeping instantaneous frequency, an interferometric technique previously described by Butler et al. [182] used to reconstruct the complex electric field of a swept laser was implemented. Utilising a 3×3 fiber coupler to mix the output signal with a delayed version of itself,
the resulting 3 outputs of the coupler produce a beating signal with a $2\pi/3$ radians phase difference. This inherent phase relationship of the coupler is then exploited to calculate the phase of the laser, see Appendix A for more details on the $3\times3$ measurement.

![Figure 6.6:](image)

(a) Averaged intensity plots of each output of the $3\times3$ coupler showing $2\pi/3$ phase shift of beating amplitudes. (b) Calculated phase from the $3\times3$ outputs. (c) Laser intensity (grey) with calculated instantaneous frequency (red).

For this measurement, an appropriate delay time to mix the signal with itself needs to be chosen. For a laser with good coherence properties, typically ns delay time will suffice. However, this laser was found to have low coherence, therefore a very short delay ($\sim30$ ps) was required to generate a long beating frequency and then a smoothed function applied to the in-
tensities produced the distinctive $3 \times 3$ beating (Fig. 6.6(a)) and allowed for calculation of the average laser phase (Fig. 6.6(b)). The actual phase had random fluctuations overall due to low coherence but the calculated phase from the smoothed function followed the sweeping modulation pattern thus, the laser instantaneous frequency was sweeping in the same manner.

The instantaneous frequency is plotted as the deviation around the central frequency which is set to zero (Fig. 6.6(c)). The scaling factor for the instantaneous frequency is determined from the full wavelength sweep range on the OSA using the maximum and minimum wavelength values to determine the frequency range. This shows a periodic frequency sweep with a range of $\sim 450$ GHz at the synchronised modulation frequency of 50.35 kHz. The intensity envelope shows some asymmetry with the sweep direction but repeats with the same cyclic amplitude variation with the period of the sweeping instantaneous frequency.

The SU-8 microheater device was also examined for comparison. As determined in the previous chapter, the microheater modulator frequency response was less efficient than the SiN p-n junction devices. A 0-2.2 V sine wave at the synchronised modulation frequency of 50.35 kHz was applied. The heterodyne beating technique as described in the previous chapter was employed to measure the sweeping frequency as the maximum sweep range was found to be within the bandwidth of the high speed photodetector of 33 GHz. The TLS was set on the short wavelength side of the swept wavelength, mixed at the output and the resulting spectrogram was computed which is shown with the applied signal in Fig. 6.7(a).

Again, this shows a wider tuning range achievable than single mode operation, beyond the main limiting factors of the FSR and the gain ripple described in Chapter 5. The driving voltage, modulator frequency response, and maximum modulation depth achievable were found to be the only limitations in tuning range using this method of FDML operation.

The SU-8 microheater chips had angled AR coated facets as opposed to straight non-AR coated facets of the SiN p-n devices. This gave a reduction in the comb lines to 7 dB as shown in Fig. 6.7(b). Although the microheater
6. Long Cavity Multimode PhC Laser in FDML Operation

Figure 6.7: (a) Top: Spectrogram of heterodyne beating frequency of sweeping laser wavelength and fixed TLS with sweep range of ~15 GHz. Bottom: Microheater driving modulation voltage of 0-2.2 V at 50.35 kHz. (b) Corresponding time averaged optical spectrum of swept wavelength with a range of ~0.1 nm.

devices had a reduction in the sweep range, they had the advantage of reduced parasitic reflections showing the possibility of comb line reduction for chip facets of this design.

6.3.2 45 m cavity for MHz modulation

This experiment was carried out using the SiN p-n junction device and a 45 m delay line with a calculated cavity frequency of 2.2644 MHz (from an approximated roundtrip time of 0.44 µs). The wavelength sweep range reduced to <0.1 nm for this modulation frequency meaning measurement of the swept wavelength range from the OSA could only be approximated as the bandwidth of the reflector was ~0.6 nm (Fig. 6.8(a)). Therefore, the sweep range is not fully visible as in the previous section with a larger sweep range and longer cavity.

Again with the synchronised modulation frequency applied, the intensity time trace indicated stable periodic output over the sweep range. The instantaneous frequency was calculated from the 3×3 measurement as described
above. As the same self-delay time was used, the same scaling factor for the instantaneous frequency was applied therefore, a closer value to the sweep range could be determined and was found to be \( \sim 15 \) GHz (Fig. 6.8(b)).

An interesting effect on the intensity with the 45 m cavity length was observed on the ns time scale which showed periodic pulse like phenomena produced for all parts of the sweep with only a slight variation in amplitude. As traditionally observed with swept laser sources and particularly FDML lasers, each part of the sweep tends to exhibit different temporal dynamics namely, mode locked behaviour for the forward part of the sweep, chaotic behaviour for the backward part of the sweep and single mode-hopping behaviour at the turning points as described in [155]. For this FDML laser cavity length, there was a small change in the overall envelope of the intensity and on the ns time scale, periodic pulsations were observed (Fig. 6.9(b)). However, the laser is not in true pulsed mode as it does not switch off completely, but the pulsations have a defined frequency over the entire sweep as can be seen in the sliding window FFT spectrogram (Fig. 6.9(c)). The static reflector intensity is shown for comparison in Fig. 6.9(a) showing unstable output similar to the behaviour described in Section 6.2.

The spectrogram reveals a fundamental frequency of 1.9 GHz over the continuous time range with the 2\(^{nd}\) and 3\(^{rd}\) harmonics also visible. This is the frequency of the pulses as can also be seen with the averaging function.
6. Long Cavity Multimode PhC Laser in FDML Operation

**Figure 6.9:** Intensity on ns scale (black) and averaging function (red) for (a) no modulation applied (static reflector) and (b) pulsations present with synchronised modulation frequency applied. (c) Sliding window FFT spectrogram of extended time trace capture of (b) showing a fundamental frequency of 1.9 GHz.

applied to the time trace (Fig. 6.9(b) - red line). One possible reason for the presence of the pulses at this repetition rate of 0.5 ns is the interference of the multiple modes inside the PhC cavity acting as a resonator. The Fabry-Perot nature of the PhC cavity causes multiple reflections (and roundtrips) of the modes in the resonator. The effective length of the PhC cavity can be considered as the length the light travels with multiple reflections given by the intrinsic quality factor and is proportional to the photon lifetime in the
6. Long Cavity Multimode PhC Laser in FDML Operation

cavity. The effective length is calculated using the equation:

\[ L_{\text{eff}} = \frac{Q_0 \ c}{\omega_0 \ n_{si}} \quad (6.1) \]

where \( Q_0 \) is the intrinsic quality factor, \( \omega_0 \) is the resonance frequency, \( c \) is the speed of light and \( n_{si} \) is the refractive index of silicon. From the relationship of cavity length and photon lifetime, it was found that 0.5 ns time equates to an effective length of 34 mm giving a Q-factor of \( \sim 10^5 \) which is in the region of the Q-factor values calculated for these devices. This behaviour could also be explained if the PhC cavity itself is considered as a saturable absorber. The resonator losses are modulated as the reflectance is modulated and could induce Q-switched pulse like behaviour in this instance.

On the ns timescale there was no obvious change observed in the laser intensity throughout the sweep. Typically for FDML lasers, the intensity exhibits different behaviour depending on the sweep direction [155]. This was not the case here as for both forward and backward sweep directions and at the turning points, the intensity dynamics behaved in a similar fashion, only showing a periodic change in the intensity amplitude envelope. This was also evident on the spectrogram in Fig. 6.9(c) revealing no change in the frequency of the pulses throughout the sweep. This may be due the fact that the reflector was being tuned just slightly rather than over a large spectral range which is commonly applied to FDML lasers. Also, the strong dynamics within the PhC cavity may have superimposed over any other laser cavity dynamics taking place.

6.4 Summary

In this chapter, a novel configuration of an FDML laser was presented using a tuning mechanism previously unreported exploiting the tuning capability of the narrowband PhC resonant reflector. When the PhC reflector was kept static, multiple longitudinal mode groups were lasing unstably within the reflection band which resulted in unstable output. When the reflector was
modulated synchronously to the delay time of the cavity by applying $f_{\text{mod}} = 1/T$, stable lasing over a sweeping wavelength range was observed. Direct measurement of the laser phase confirmed sweeping of the laser instantaneous frequency over a range which was only limited by the maximum modulation depth achievable with the PhC cavity modulator available.

A frequency comb was generated over the swept wavelength range, atypical of traditional FDML approaches, which was attributed to the parasitic reflections from the chip facet to PhC reflector. These reflections acted as an internal Fabry-Perot cavity within the laser cavity. Although the reflections within the FDML laser presented here are considered parasitic, they can have some useful applications as demonstrated in [183–186] with the intentional placement of a Fabry-Perot cavity in an FDML laser cavity. The SiN chips used were straight non-AR coated facets and for the SU-8 AR coated chips with angled waveguides, the comb lines reduced showing that a reduction of the comb line depth is possible for chips with lower reflectivities. Further improvements of the AR coating design is expected to further reduce the chip facet reflectivities.

The temporal dynamics of this FDML laser were also atypical. For the MHz modulation demonstration, the intensity envelope remained almost constant with pulsations present likely due to Q-switching or another physical effect in the PhC cavity. This symmetric behaviour for backwards, forwards and turning points of the sweep can be beneficial for specific applications of FDML lasers where it is required to predict the temporal dynamics of the system.

This configuration has potential as a compact on-chip solution of an FDML laser employing waveguides on-chip as the delay line of the cavity. The capability of operation in bi-directional lasing eliminates the need for isolators in the cavity. Debnath et al. [175] have demonstrated a similar p-n PhC cavity modulator with up to 0.5 GHz modulation speed operating in forward bias with a 20 pm wavelength shift. Therefore in principle, the cavity delay length could be in the region of 10s of cm to match this sweep speed. This shows that an increased sweep rate and shorter cavity length
6. Long Cavity Multimode PhC Laser in FDML Operation

is possible however, accompanied by a reduction in sweep range. Further improvements in fabrication of the PhC cavity modulators are on-going and aims to increase the modulation depth for higher modulation speeds which will lead to a wider sweep range. This would ultimately achieve a more compact solution while being capable of higher sweep speeds.
Chapter 7

Conclusions

7.1 General conclusions

The aim of this thesis was to develop a novel laser with the use of commercially available III-V amplifiers combined with a silicon photonics based reflector. Further to this, to demonstrate wavelength tuning and FM by applying modulation only to the reflector component. Finally, to further exploit the reflector modulation capability and employ an alternative laser geometry to realise a wider continuous tuning range in a novel FDML laser.

Chapter 1 provided an introduction to some applications of wavelength swept and tunable lasers while giving a description of some laser geometries and tuning mechanisms which are typically employed. Then Chapter 2 gave a discussion of the current state of the art solutions of monolithic, hybrid III-V/silicon, and wavelength swept lasers and a measure of their performance.

Chapter 3 provided a theoretical basis for the single mode laser in the experimental work. A theoretical description of the PhC cavity reflective component was provided and simulation results of its reflective properties were analysed. A theoretical description of the single mode tuning mechanism was provided and a linear approximation for the mode tuning was derived. This was subsequently examined in the simulation results provided by a delay differential equation model. Exploration and optimisation of the
system parameters was undertaken via modelling.

Chapter 4 described the experimental apparatus and procedure to realise
the single mode PhC laser. Characterisation of the gain section and PhC
cavity as separate components was first performed and following that, the
lasing characteristics were presented. Optimisation of the cavity length to
realise an extended mode-hop free range over the full range of bias current
to the RSOA was achieved. Finally, bistable operating regimes of the laser
were revealed and analysed.

Chapter 5 demonstrated wavelength tuning and FM of the single mode
PhC laser by modulation applied to the reflector section. This was realised by
the thermo-optic effect in silicon by means of a p-n junction or a microheater
situated at the PhC cavity and both devices were compared.

Chapter 6 demonstrated a novel FDML laser configuration by employing
the modulator devices which were introduced in Chapter 5. Extending the
laser cavity length and synchronising the reflector modulation frequency to
the cavity roundtrip time resulted in stable FDML operation over a swept
wavelength range.

The PhC cavity as a resonant reflector in an EC laser configuration has
the unique advantage of a combination of a very small footprint and large
FSR. The vertical coupling scheme to the PhC cavity offers low insertion loss
for low index waveguides to silicon. Thereby, low coupling losses to the RSOA
waveguide in the butt-coupled configuration and collection of the output via
lensed fiber are realised. This eliminates the need for spot-size converters or
other coupling mechanisms ensuring reduced fabrication complexity of the
PIC.

Silicon optical modulators show low capacitance and low switching en-
ergy when employed as resonant modulators [187]. Ring resonators act as
an optical filter therefore, an additional reflective component is required to
form an EC laser and active tuning of the resonance is required to achieve
matching to the emitted wavelength. By using a PhC cavity as a reflective
filter, this eliminates the need for active wavelength matching as the res-
onant wavelength determines the emitted laser wavelength. Moreover, the
7. Conclusions

PhC cavity acting as the reflective component in the EC laser means no additional components are needed for wavelength tuning which further reduces device footprint. As demonstrated in Chapter 4, the small footprint also ensures a very short laser cavity length for extended mode-hop free operation without the need for active mode stabilisation techniques.

A similar modulation scheme demonstrated by Dong et al. [131] using an RSOA coupled to a PIC with microrings as intra-cavity filters and by direct modulation of the reflectance of a loop mirror showed high performance. However, the PIC design is relatively complicated in comparison to the PhC cavity configuration described here. The size of their PIC was larger resulting in a higher threshold current and requiring a longer RSOA to provide sufficient gain for lasing. Improvement of the PhC resonant modulator capability will allow for increased modulation bandwidth and efficiency and thus far has been the main limitation on device performance demonstrated in this work. As similar PhC cavity p-n devices have demonstrated GHz modulation speeds [175], this can be further explored in the single mode laser configuration using a PhC reflector with improved modulation efficiency. Depletion type modulation in reverse bias can also be explored [148]. A method of FM-to-IM conversion with an integrated optical filter at the output could realise a competitive device as an on-chip light source for use within optical interconnects. This concept has been explored by our group with initial results presented in [188]. Alternatively, our group also explored using coupled PhC cavities to achieve IM by detuning one of the resonances [189] which also has the potential for GHz modulation within an integrated architecture.

Alternative design of the p-n junction can also improve the modulation efficiency, for example, by employing an interdigitated p-n junction which allows for a larger overlap with the optical mode therefore, is less sensitive to misalignment during fabrication. Timurdogan et al. [88] have demonstrated a microdisk with a vertical p-n junction (as opposed to a lateral junction for the devices described here), to give an ultralow power and high performance silicon based resonant modulator. This vertical p-n junction approach is a consideration for improvement of the existing PhC devices in this work.
7. Conclusions

which will further increase the wavelength tuning range when employed in
the single mode configuration and especially in the FDML configuration.
Achievement of GHz modulation speeds would require a much shorter delay
line to match the roundtrip period and low-loss waveguides can be employed
as an integrated delay line of 10s of cm length to realise a fully integrated
FDML laser. Current ring cavity FDML lasers which reach MHz sweep
rates require a minimum of a few hundred meters cavity length to match the
roundtrip period and are not yet available as an integrated device.

The possibility of on-chip integration as a swept source laser capable of
GHz sweep rates is one of the main advantages of using the akinetic tunable
PhC reflector which can reach sweep rates far beyond those of mechanical filters. Utilisation of the silicon photonics platform, compatibility with CMOS processing, and reduced fabrication complexity comparable to swept sources with a similar device footprint gives a distinct advantage of the technology demonstrated in this thesis.

7.2 Future work

The next intuitive stage of this work is integration of the RSOA and silicon
PhC chip. As outlined in Chapter 2, several integration techniques have al-
ready been established to realise III-V/silicon lasers. The hybrid integration
technique which was outlined involves bonding of the finished RSOA chip
and silicon chip and is the most viable method for the components described
here. Preliminary manual attempts have been undertaken and are outlined
in Appendix B.

Achievement of an integrated device will open a wide range of further
studies of the underlying physics of the single mode PhC laser and further
applications. For instance, given the advantage of separate gain bias current
and modulation current control, a zero IM output accompanying FM can
be realised i.e. a pure FM laser, which has been demonstrated for existing
multi-section lasers as discussed in Chapter 2. The preliminary simulation
results applying this technique were demonstrated in Chapter 3 and exper-
7. Conclusions

imentally with an integrated device (which would minimise external and environmental variations), this could be implemented with a feedback loop control algorithm. Further development of a control algorithm could also be implemented to obtain linear frequency sweeps ideal for LiDAR or sensing applications.

![Intensity time trace of single mode PhC laser output (black) and smoothed average (red) with 100 kHz triangular wave function applied to RSOA.](image)

**Figure 7.1:** (a) Intensity time trace of single mode PhC laser output (black) and smoothed average (red) with 100 kHz triangular wave function applied to RSOA. Inset: optical spectrum showing two PhC resonances lasing simultaneously. (b) and (c) zoom of intensity of sections marked on (a).

Further study of the underlying physics of the integrated device can then be undertaken. Owing to the high Q/V ratio of the PhC cavity and multiple resonances, complex dynamics of the single mode laser were observed. An example is shown in Fig. 7.1 with a triangular wave function applied to the RSOA. Lasing occurs between two PhC resonance modes and energy
7. Conclusions

switching dynamics were observed on the intensity time trace. A deeper understanding of these dynamics is warranted but is beyond the scope of this thesis. Recently, collaborators have modelled the dynamics of the single mode PhC laser showing regimes such as Q-switching and suppressed relaxation oscillations [190] thus, experimental work to verify these modelling results should naturally follow.
Appendix A

3×3 Measurement

The 3×3 measurement used in Chapter 6 to measure the instantaneous frequency of the laser is described in detail in [191]. Below is a summary of the governing equations and the experimental setup used for the measurement.

Considering the electric field inputs to a 3×3 coupler, each output of the coupler has a contribution of the inputs with a $2\pi/3$ phase shift, e.g. the electric field output of port 1 is:

$$E_{out}^1 = \frac{1}{\sqrt{3}} \left( E_{in}^1 + E_{in}^2 e^{\frac{2\pi}{3}} + E_{in}^3 e^{\frac{4\pi}{3}} \right)$$  \hspace{1cm} (A.1)

Then for 2 inputs $E_{in}^1$ and $E_{in}^2$, the 3 electric field outputs are expressed as amplitude R and phase $\phi$ of the 2 inputs:

$$E_{out}^1 = \frac{1}{\sqrt{3}} \left( R_1 e^{i\phi_1} + R_2 e^{i(\phi_2 + \frac{2\pi}{3})} \right)$$  \hspace{1cm} (A.2)

$$E_{out}^2 = \frac{1}{\sqrt{3}} \left( R_1 e^{i(\phi_1 + \frac{2\pi}{3})} + R_2 e^{i\phi_2} \right)$$  \hspace{1cm} (A.3)

$$E_{out}^3 = \frac{1}{\sqrt{3}} \left( R_1 e^{i(\phi_1 + \frac{2\pi}{3})} + R_2 e^{i(\phi_2 + \frac{2\pi}{3})} \right)$$  \hspace{1cm} (A.4)

The intensity measured on the scope is the square of these 3 fields, i.e. $I_n = |E_{out}^n|^2$ and can therefore be expressed in terms of the input amplitude and
A. 3×3 Measurement

phase to give:

\[ I_1 = \frac{1}{3} \left( R_1^2 + R_2^2 + 2R_1R_2 \cos \left( \phi_1 - \phi_2 - \frac{2\pi}{3} \right) \right) \]  \hspace{1cm} (A.5)

\[ I_2 = \frac{1}{3} \left( R_1^2 + R_2^2 + 2R_1R_2 \cos \left( \phi_1 - \phi_2 + \frac{2\pi}{3} \right) \right) \]  \hspace{1cm} (A.6)

\[ I_3 = \frac{1}{3} \left( R_1^2 + R_2^2 + 2R_1R_2 \cos (\phi_1 - \phi_2) \right) \]  \hspace{1cm} (A.7)

Hence, the phase difference can be solved algebraically to give:

\[ \phi_1 - \phi_2 = \arctan \left( \frac{\sqrt{3}}{2} \frac{I_1 - I_2}{I_3 - \frac{1}{2}(I_1 + I_2)} \right) \]  \hspace{1cm} (A.8)

The phase difference between the two inputs must remain within the bandwidth of the detector therefore, the input signal is mixed with a delayed version of itself using a short delay time (typically in the order of a few ns) on the second arm input to the 3×3 coupler. A polarisation controller is used to maximise the beating signal between the two inputs (Fig. A.1). The two electric field inputs are given by \( E(t) \) and \( E(t - \tau) \), where \( \tau \) is the time delay. Then the phase difference \( \eta(t) \) is given by:

\[ \eta(t) = \phi(t) - \phi(t - \tau) \]  \hspace{1cm} (A.9)

Utilising an expansion for the time derivative of \( \phi \) and taking the first two terms (as terms \( \geq 2 \) will be small when using a short time delay therefore can be neglected) then we get:

\[ \dot{\phi}(t) = \frac{\eta(t)}{\tau} + \frac{\eta(t)}{2} = 2\pi f(t) \]  \hspace{1cm} (A.10)

which provides the measurement of the instantaneous frequency of the laser.

The fourth channel on the oscilloscope simultaneously measures the laser intensity and this can be combined with the calculation of the instantaneous
A. $3 \times 3$ Measurement

Figure A.1: $3 \times 3$ measurement setup: the output of the swept laser is passed through an isolator and split 10% to an OSA to simultaneously view the wavelength spectrum. 90% is sent to a 50:50 splitter with one arm directly to a channel on the oscilloscope to record the laser intensity. The other arm of the splitter is divided again to a 50:50 splitter sending the laser output to one input of the $3 \times 3$ coupler, the other input is the delayed signal. A polarisation controller is used to maximise the beating between the two inputs. Each of the intensity outputs of the $3 \times 3$ coupler are simultaneously recorded on the oscilloscope which are subsequently processed to obtain the phase measurement data.

frequency to reconstruct the full electric field given by:

$$E(t) = \sqrt{I(t)} \exp \left( i \left[ 2\pi \int f(t) dt \right] \right) \quad (A.11)$$

Since this measurement is based on the algebraic manipulation of the beating intensity amplitudes, it is important that each channel on the oscilloscope is synchronised in time. Any small variations in the fiber lengths will add an extra delay and cause numerical errors on calculation of the phase. Synchronisation of the channels can be achieved using the skew feature on the oscilloscope by triggering each channel on the same event and aligning them in time. The power levels of each channel must also be aligned as there can be small variations between detectors. To avoid errors in the calculation, a baseline for the power level on each channel should be recorded with no signal input. Then the measured data can be corrected to its baseline in order to align each detector power level for accurate calculation of the $3 \times 3$ measurement data.
Appendix B

Manual Integration

Following the single mode experimental work in this thesis, preliminary manual attempts for integration via chip bonding have been undertaken. Firstly, direct bonding of the chips with an optical adhesive (Dymax OP-67-LS) was pursued. This method was unsuccessful in that, the depth thickness of the chips was not enough to support their area and the bond did not sustain. Subsequently, larger aluminium blocks were designed to affix to the translation stages replacing the smaller blocks described in Chapter 4. The chips were fused on the separate aluminium blocks using cyanoacrylate glue and the optical adhesive was applied to the larger aluminium blocks. After manual alignment with the stages to achieve a single mode laser, the adhesive was cured by UV light. However, while undergoing curing, the linear shrinkage (0.08%) of the adhesive led to misalignment of the chips and single mode lasing ceased. Further attempts to cure the adhesive in shorter time intervals then realigning were pursued but lasing ceased on each final curing step.

The above attempts proved manual integration to be quite challenging. A new design of the aluminium blocks to use less adhesive but still maintain the bond can be further explored. Accurate alignment techniques to use a smaller amount of adhesive or one which has a lower expansion or shrinkage on curing in order to remain within the tolerance of alignment can also be further explored. However, the optical adhesive used had the lowest linear shrinkage specifications available. The use of other types of adhesives can be
B. Manual Integration

investigated further.

Applying techniques described for flip-chip bonding outlined in Chapter 2 would be the most viable solution. High precision equipment and alignment procedures would undoubtedly achieve a flip-chip integrated device.
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172
Bibliography


Bibliography


Bibliography


