Hybrid Frequency Modulated Silicon Photonic Crystal Laser

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Andrei Bakoz

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Hybrid Frequency Modulated Silicon Photonic Crystal Laser

by

Andrei Pimanovitch Bakoz

A thesis submitted for the degree of

Doctor of Philosophy

Research Supervisor: Dr. Stephen P. Hegarty

Thesis prepared in association with

Submitted to Cork Institute of Technology, 2019
Declaration

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

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

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Supervisor’s signature:
Stephen P. Hegarty
Acknowledgements

I would like to express my gratitude towards a number of people who was helping and supporting me during my PhD and thesis preparation process.

First of all, I would like to express my utmost gratitude towards my supervisor, Dr. Stephen P. Hegarty, who offered me a position at CAPPA and guided through my PhD, always being available for frequent meeting and discussions. Also, I would like to thank my co-supervisor, Dr. William Whelan-Curtin (Liam O’Faolain) for scientific guidance and useful insights. Special thanks go to Alexandros Liles (St Andrews) for providing me with the samples and the time spent in the lab.

Moreover, I would like to thank my colleagues and friends from CAPPA for creating pleasant working atmosphere especially Simone Iadanza, Sharon Butler, Praveen Singarevelu and Dzianis Saladukha.

I am very grateful to Professor Mark Sorel for his time and effort in reading and improving this thesis.

Last, but not the least, I would like to thank my family for all the support that it provided me with.
List of Publications


Abstract

Silicon photonics takes advantage of the mature complementary metal-oxide semiconductor (CMOS) infrastructure and processes, and is actively pursued for the implementation of complex optical components and photonic integrated circuits (PICs) at low cost and high volumes. Despite a constant refinement of silicon photonics technology to meet the evolving requirements for applications, the poor light emission ability of silicon remains a constraint. As a result, the most essential building block of an optical system, an efficient light emitter, remains absent in PICs based on silicon.

This thesis is focused on study of the potential of an external cavity (EC) hybrid III-V - Si laser design, comprising an InP reflective semiconductor optical amplifier (RSOA) and a silicon reflector chip. The Si resonant structure was acting as a wavelength selective element determining the lasing wavelength. Two types of EC lasers were studied. The first, utilized a Si$_3$N$_4$ 1D photonic crystal (Bragg grating) and the second, exploits a 2D Si photonic crystal (PhC) vertically coupled to a low refractive index waveguide. Both types of lasers demonstrated a single mode mW-level continuous-wave (CW) power output at room temperature with SMSR > 40 dB. The Si$_3$N$_4$ reflector laser demonstrated a thermal wavelength stability of ±0.55 nm in the range of 20 - 80°C, and the Si PhC reflector laser showed a ±0.38 nm deviation for the same range.

Finally, using the thermal modulation of the refractive index of the PhC cavity, the frequency (wavelength) modulation of the short cavity EC laser was demonstrated. The studied architecture eliminates the necessity for wavelength matching between a source and modulator, as both roles were accomplished by the tunable resonant
PhC cavity, which together with a low power consumption is a good candidate for practical applications in silicon photonics.
Contents

Statement of Originality i
Acknowledgements ii
List of Publications iii
Abstract iv

1 Introduction 1
1.1 Directly Modulated Lasers for Short-reach Communications . . . . . 3
1.2 Photonic Crystal Lasers ........................................... 5
1.3 Aims of the Thesis ................................................. 6
1.4 Thesis Structure ................................................... 9

2 Si$_3$N$_4$ Grating Resonant Reflector Laser 10
  2.1 Introduction ......................................................... 10
  2.2 Theory of Photonic Crystals ........................................ 14
    2.2.1 1D Photonic Crystal ........................................ 15
  2.3 Passive Standalone Characterisation of the Reflector .............. 18
  2.4 Active Characterisation of the External Cavity Laser ............ 29
    2.4.1 Materials and methods ..................................... 30
  2.5 Fabry-Perot cavity assisted mode hop free lasing ................. 36
  2.6 Conclusion ....................................................... 40

3 Si Photonic crystal-based resonant reflector laser 42
  3.1 Introduction ....................................................... 42
  3.2 Theory of 2D Photonic Crystals .................................. 43
3.3 Photonic Crystal Cavities as Narrow-band Reflectors ................. 45
3.4 Real Si 2D Photonic Crystal Cavity Reflector .......................... 51
  3.4.1 Materials and Methods ........................................... 51
  3.4.2 Results and Discussions .......................................... 53
3.5 Conclusion ........................................................................ 63

4 Thermally induced frequency modulation ................................. 65
  4.1 Introduction ..................................................................... 65
  4.2 Frequency Modulated PhC Laser Concept ............................. 66
  4.3 Experimental Set-up and Design Considerations .................... 69
    4.3.1 Sample 1: Thermal PhC - Si$_3$N$_4$ Reflection Phase Tuning via
         Carrier Injection ...................................................... 70
    4.3.2 Sample 2: Thermal PhC - SU-8 Reflection Phase Tuning via
         Carrier Injection ...................................................... 76
    4.3.3 Sample 3: Thermal PhC - SU-8 Reflection Phase Tuning via
         Microheater ............................................................. 78
  4.4 Conclusion ....................................................................... 83

5 Modal dynamics of PhC laser .................................................. 84
  5.1 Introduction ..................................................................... 84
  5.2 Photonic Crystal Laser with Phase Tuning Section: Brief Description
      and Static Characterization ............................................. 85
  5.3 Single mode “Quiet” Lasing ................................................ 87
  5.4 Two-color Lasing .............................................................. 88
  5.5 Multi-mode “Quiet” Lasing on a Single Resonance .................. 91
  5.6 Multi-mode “Modulated” Lasing on a Single Resonance .......... 92
  5.7 Bursting Phenomenon: Switching Between “Quiet” and “Deep
      Modulation” modes ...................................................... 94
  5.8 Conclusion ....................................................................... 95

6 Conclusion and Future Work ................................................. 97
  6.1 Si$_3$N$_4$ Grating ............................................................. 97
  6.2 Silicon Photonic Crystal reflectors ....................................... 98
      6.2.1 Improvements in Direct Frequency Modulation .......... 99
6.3 Fast and Slow dynamics in External Cavity PhC laser . . . . . . . . . . 100

Bibliography 102
List of Figures 120
List of Tables 133
Chapter 1

Introduction

With the demand for information accessibility anytime and anywhere, and as fast as possible, optical telecommunication technology has emerged as the backbone of the modern information transfer infrastructure. In terms of bandwidth and distance, a copper-based interconnect is unable to satisfy constantly increasing requirements for the domain of telecommunications. Additionally, further miniaturization of integrated electronic circuits leads to overheating with significant disturbance by unwanted quantum effects. To tackle this issue, a turn towards optics has been made here also. The advantages of optical links are not only being more lightweight and less cumbersome than their copper-based counterparts, but also insensitive to electro-magnetic noise and, in principle, they have higher bandwidth. Long haul fiber-optics solutions for telecommunications have been developed since early 80’s. However, with the growing use of cloud-based services with data centers as their core, the need for more efficient short distance optical interconnects for chip to chip and even intra-chip communications became obvious.

Although, the substitution of electrical interconnects with optical equivalents promises indisputable advantages in bandwidth, there are several barriers that generally involve high cost and practical obstacles. The main factors that should be addressed are fabrication and packaging cost, power consumption and ease of integration with existing infrastructure [1, 2]. Silicon Photonics introduces the necessary means to meet these requirements by accommodating both electrical and optical components. Taking into account that silicon is the basic material of the
electronics industry, the use of silicon for optical interconnects allows integration with existing electronic circuits. Furthermore, silicon photonics can take advantage of the mature CMOS process technology to provide low-cost, high-performance optical components and Photonic Integrated Circuits (PIC) at high volumes.

From the time of initialization of silicon photonics in the mid-80’s by Soref, Bennett and Lorenzo [3, 4] all the major interconnect blocks necessary for employment in practical applications have been demonstrated on silicon: low-loss waveguides [5, 6], (de)multiplexors [7], high-bandwidth photodetectors [8] and fast modulators [9]. According to the International Technology Roadmap for Semiconductors the goal for the energy consumption of individual devices by 2022 is set as $\sim 20$ fJ/bit for intra-chip communication and $\sim 10$ fJ/bit for on-chip interconnects [10]. As the main power consuming optical interconnect blocks are a light source and modulator, significant effort have been made toward the development of effective Si optical devices. The development of effective micro-photonic resonator based components, such as ring resonators and photonic crystal cavities, made possible the chip scale integration of modulators with sub-pJ/bit switching energies [11–14]. Even though the problem of wavelength matching between the light source and modulator is solved by the use of additional control loops, that increases the overall footprint of the device, these solutions still remain promising for applications such as WDM systems due to their wavelength selectivity and energy efficient nature [15].

Although silicon photonics technology constantly improves in order to meet the challenges brought by application requirements, there is still a constraining factor hindering the overall process of full-scale migration from electrical interconnects to their optical equivalent. The major issue originates from Si being a Group IV semiconductor with an indirect band gap rendering efficient light emission impossible (Fig. 1.1). Consequently, silicon photonics is lacking the most important element for optical communication systems. Therefore, III-V group elements based energy efficient semiconductor laser of various designs are currently employed.
1.1 Directly Modulated Lasers for Short-reach Communications

For the data encoding applications two approaches exist - one is to use laser operating in continuous wave (CW) regime in conjunction with external modulator and the second method employs directly modulated lasers (DMLs). DMLs are cost effective for constructing transmitters compared with lasers integrated with an external modulator. But the limiting factor for their total dominance is their maximum transmission distance restriction by dynamic chirp, which is caused by a refractive index change in the laser cavity due to the current injection. Thus, DMLs are bounded by applications where the reach is less than 100 km. Typical cavity lengths of InGaAlAs 1.3µm DFB lasers that widely used for 10- and 100-Gbit/s Ethernet networks are less than 200µm. Reduced cavity length reduces the product of the resistance and capacitance (RC) time constant, which is leading to reduced power consumption.

Multi-mode vertical-cavity surface-emitting lasers (VCSELs) are widely employed inside datacenters and supercomputers due to their ability to provide optical links with low power consumption and low cost in conjunction with multi-mode fiber. The combination of DBR mirrors and a small active volume in VCSELs allows to achieve low threshold currents and low operating energies [17–19]. This is
due to the threshold current and the relaxation oscillation frequency (ROF) [20] being proportional to the active volume and the square root of the carrier density, respectively. In comparison with DFB lasers, VCSELs demonstrate lower maximum power output due it’s small value of the gain region. However, they provide sufficient power to run networks inside datacenters.

Short-wavelength (850 - 1060 nm) multimode VCSELs are widely used for datacenter’s and supercomputer’s optical links in the rack-to-rack scale [21, 22]. In Table 1.1 listed characteristics of recently developed short-wavelegth VCSELs. As we can see, the VCSELs can transmit data as fast as 40 - 50 Gbit/s with relatively low power consumption of 100 fJ/bit [23] at a high temperature in semi-cooled or uncooled environment [24].

<table>
<thead>
<tr>
<th>Group</th>
<th>Wavelength (nm)</th>
<th>Modulation Speed (Gbit/s)</th>
<th>Bias Current (mA)</th>
<th>Energy Cost (fJ/bit)</th>
<th>Temperature °C</th>
<th>Year</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>TU Berlin</td>
<td>850</td>
<td>25</td>
<td>1.1</td>
<td>77</td>
<td>25</td>
<td>2012</td>
<td>[25]</td>
</tr>
<tr>
<td>TU Berlin</td>
<td>980</td>
<td>38</td>
<td>3.6</td>
<td>177</td>
<td>85</td>
<td>2014</td>
<td>[26]</td>
</tr>
<tr>
<td>IBM-Furukawa</td>
<td>1060</td>
<td>28</td>
<td>2.21</td>
<td>120</td>
<td>70</td>
<td>2015</td>
<td>[27]</td>
</tr>
<tr>
<td>Chalmers</td>
<td>850</td>
<td>40</td>
<td>1.7</td>
<td>99.9</td>
<td>85</td>
<td>2015</td>
<td>[24]</td>
</tr>
<tr>
<td>Chalmers</td>
<td>850</td>
<td>50</td>
<td>2.5</td>
<td>128</td>
<td>85</td>
<td>2016</td>
<td>[28]</td>
</tr>
<tr>
<td>Chalmers-HPE</td>
<td>1060</td>
<td>50</td>
<td>2.5</td>
<td>100</td>
<td>25</td>
<td>2017</td>
<td>[23]</td>
</tr>
</tbody>
</table>

**Table 1.1:** Parameters of short-wavelegth directly modulated VCSELs.

Long-wavelength VCSELs (1.3 or 1.5μ) are desirable in order to extend transmission distance and employ WDM technologies. Also, the difference in absorption coefficient in Si for 860-1060 nm range and 1300 - 1550 nm is 10 orders of magnitude dimming GaAs-based VCSELs useless for silicon photonics (Fig. 1.2). In order to create long-wavelength VCSEL an InP-based compound semiconductor should be used. The best up-to-date device demonstrates a 50 Gbit/s modulation speed with bias current os 6.8 mA, which corresponds to 130 fJ/bit energy cost [29]. On the other hand, the high-temperature device performance degrades due to reduction of the conduction band offcet in the InP-based multiple quantum well (MQW) layer compared with the GaAs-based one. The lasing wavelength control of VCSEL is determined by wavelength-scale cavity length, which is difficult to
control. One of the way to solve this issue is employment of a high-contrast grating (HCG), whose geometric position can be controlled [30].

1.2 Photonic Crystal Lasers

Due to increase in data traffic the importance of chip-to-chip and on-chip optical interconnects is increasing. However, one of the main issues in the process of substitution of metallic interconnects by their optical analogs is the operating energy of the transmitter. According to Miller [32], in order to compete with conventional Si processors, the allowed energy for single bit transmission for an optical transmitter was estimated to be 37 and 7 fJ/bit for chip-to-chip and on-chip, respectively. Such energies per device is unachievable for VCSELs. Thus, new approaches are required in order to further reduce volume of the active region.

Microtoroids, microdiscs, microrings, microposts and photonic crystals (PhCs) are possible candidates for employment of ultra-compact laser cavities with high Q $\sim 10^8$ [33]. However, the current injection realisation is challenging. Contrary to the microtoroids, the fabrication of the current injection structure in microring and microdisc lasers is more straightforward [34–36]. However, in these cases light
confinement realised by means of the large refractive index contrast in the III-V/air border, which results in poor heat extraction. Additionally, reduction in their diameter increases electrical resistance and optical losses, leading to the decreased Q-factor. Contrary to the previous approaches, a wavelength-scale PhC cavities formed in a 2D slab are insure good thermal management and demonstrate a high Q-factor of $\sim 10^6$ [37]. For these reasons, PhC lasers attracting much attention [38–40]. Furthermore, 2D PhC is suitable for current injection pumping and could be relatively easy integrated with other functional devices fabricated on SOI platform.

There are a number of works where electrically pumped PhC lasers were demonstrated: pulsed operation with $\sim 260\mu A$ threshold current [41], CW operation for GaAs quantum-dot PhC laser with 181 nA threshold at 50 K [42], CW room temperature lasing with $390\mu A$ threshold and output power of 1.82 $\mu W$ at 2 mA [43]. However, the best result for electrically driven $\lambda$-scale embedded active-region (LEAP) PhC laser was reported in [44], where 4.8 $\mu m$ treshold current and output power of 2.17 were achieved. For the device, which had an active volume as small as 0.12 $\mu m^3$ ($2.6\mu m \times 0.3\mu m \times 0.15\mu m$), the power consumption for 10 Gbit/s non-return-to-zero (NRZ) modulation was 4.4 fJ/bit (bias current 25$\mu A$ and voltage of 1.74 V). This results shows that wavelength scale directly modulated lasers can be used as a light source within CPUs optical links.

1.3 Aims of the Thesis

Considering that a state of the art short-wavelength VCSELs cover the demand for the relatively power efficient light sources in the short-reach datacomms and directly modulated LEAP PhC lasers (which is still in it’s infancy) with low power output could cover on-chip optical communications, the hybrid directly frequency modulated PhC laser can potentially find it’s application somewhere in-between. Indeed, taking into account still inferior InP VCSELs operation in the 1300/1550 nm range due to thermally induced deterioration in data-center environment and insufficient power output of the LEAP lasers due to the very
small gain region, the hybrid solution can provide additional flexibility. Therefore, the main focus of this thesis is the employment of butt-coupled RSOA - Si based resonant reflectors in order to achieve continuous wave (CW) and subsequently frequency modulated (FM) single mode (SM) operation at 1.5 µm lasing wavelength. Two types of Si resonant structures were tested:

- Si₃N₄ Bragg grating on top of SOI wafer (Fig. 1.3a);
- Si photonic crystal cavity (PhC) vertically coupled with either polymer photoresist SU-8 or Si₃N₄ waveguide (Fig. 1.3b).

In the first case a second order reflection resonance of a single dimensional photonic crystal (1D) (Bragg grating) is utilized as the optical feedback. The key motivation
is to attain mode hop free single mode lasing for a broad range of injection currents and stable lasing wavelength maintenance in the 20 - 80°C temperature range (so called athermal operation). The desire for athermal operation suggests the photonic crystal material should have low thermo-optical coefficient (TOC) defined as dn/dT, i.e. change of refractive index per degree Celsius/Kelvin. Additionally, the refractive index should be higher than SiO$_2$ in order to satisfy the high contrast condition for waveguiding. A material that can satisfy these criteria, as well as being widely processed is Si$_3$N$_4$.

Owing to the small size of the PhC cavity (typical length between 10 and 20µm) and high Q-factor/Volume ratio [45], PhC cavities show low capacitance (∼10 aF) thus low charge/discharge energies [46]. Direct frequency modulation of the considered lasers could be obtained either by carrier depletion (blue-shift for PhC pn junction reflectors) or heat induced tuning (red-shift). In this work, only the thermal mechanism is studied for both the pn diode (due to high resistance on reverse bias originating from non-optimized doping recipe) and microheater configurations. The proposed scheme tackles the wavelength matching issue between the laser and narrow-band modulator. Finally, vertically coupled PhC cavities are not limited by the edge/butt coupling configuration and could be adopted by other III-V - Si integration approaches. The main application considered for the studied lasers is WDM interconnects with low power consumption for data centers. However, this solution could be interesting for employment in such areas as gas detection, biomedical instrumentation or light detection and ranging (LIDAR) as part of a machine vision system.

A possible development of the RSOA-PhC configuration can lead to the integration of an RSOA bar with several PhCs, reflecting at different resonant frequencies (wavelengths) (Fig. 1.4). As the laser “color” selection for each channel is defined by a PhC reflector and corresponding fast amplitude modulator (AM), a utilization of the standard RSOA bars can potentially reduce the footprint per channel.
1.4 Thesis Structure

The thesis consists of 6 Chapters. Chapter 2 focuses on a theoretical description of the 1D photonic crystal (Bragg grating) with subsequent experimental set-up and acquired data discussion. The samples were designed by Danilo Panettieri with part of simulations performed by myself. The samples with Bragg gratings were fabricated in LETI, France. Passive and active characterization were performed by Simone Iadanza and I. Chapter 3 is similar to Chapter 2, but with a focus on a 2D photonic crystal cavity as a resonant reflector. Sample design and the fabrication of 2D PhC cavities samples were carried out by A. A. Liles from the nanophotonic group from the University of St. Andrews, UK. All measurements were made by myself. Here we will discuss continuous wave (CW) operation under varying conditions. Chapter 4 discusses the frequency modulated operation of the InP - PhC laser with the employment of a pn junction and microheater as a means for modulation. Samples were produced by Alexandros Liles, all measurements conducted by myself. Chapter 5 focuses on fast dynamics experimental results, observed through the microheater laser cavity total phase modulation. Finally, Chapter 6 gives an overview of the thesis with suggestions for the future work and summarizes the key findings.
Chapter 2

Si$_3$N$_4$ Grating Resonant Reflector Laser

2.1 Introduction

The use of PICs as part of an information transfer system in the harsh environment of datacenters imposes stability requirements for the light source. The most straightforward way to ensure stable operation of conventional semiconductor lasers is an active tuning of the lasing wavelength via a phase tuning section and temperature control of the entire III-V/Si platform. However, such an approach results in increased power consumption by the data processing infrastructure. The ideal solution would demonstrate stable single mode lasing within a wide range of the ambient temperature without active tuning or cooling.

Since silicon has a high thermo-optic coefficient (TOC), it requires active cooling to maintain a stable output wavelength [47], which is inefficient in terms of energy and cost, or else it requires the use of wide channel spacing, making WDM inefficient [48]. To deal with thermal drifts, integration of micro-ring feedback controls [49], loop mirrors and Mach-Zehnder Interferometers as frequency discriminators [50, 51] have been demonstrated. Yet, these solutions fail to address the thermal stability issue, as thermal tuning is energy inefficient and silicon rings do not provide an athermal reference. However Si$_3$N$_4$ is completely CMOS-compatible and has a five times lower TOC and lower free carrier absorption compared to Si, offering
excellent thermal stability for laser operation.

The first semiconductor laser butt coupled to an external resonant optical reflector (ROR) was demonstrated by Olsson et al [52], where a Si$_3$N$_4$ quarter wave shifted distributed feedback (DFB) resonator was implemented as a high-Q reflecting structure. This device demonstrated linewidth of 135 kHz, which was comparable to the previously reported narrow-linewidth semiconductor external cavity laser reported by Mooradian et al. [53]. However, Olsson (et al.) made the first step towards miniaturization (from 15 cm long cavity length in [53] towards just a few mm) of the laser without compromising linewidth reduction, which is crucial for telecom applications. A key element that enabled reduction of the physical laser cavity length was an employment of the ROR as a frequency dependent output mirror.

Similar approach was used by Tanaka et al. [54] in order to achieve better control over temperature dependent wavelength stability (in order to eliminate mode hoping and improve bit error rate during transmission) and lower dynamic chirp in direct modulation. However, this time grating was simultaneously acting like a second output mirror for reflective semiconductor optical amplifier (RSOA) and narrow-band filter. An RSOA was flip-chip bonded to a Si terrace in order to butt-couple gain chip with silica waveguide. Maximum power output was around 1.1 mW at 1543 nm and 25°C. Mode-hop free single mode lasing was achieved in the $\Delta T = 20^\circ$C temperature range with thermal wavelength stability $d\lambda/dT = 1.4 \times 10^{-2}$ nm/$^\circ$C (an improvement by one order of magnitude in comparison with conventional laser diode). It was achieved by incorporation of Si grooves region inside laser cavity which had a negative thermooptic (TO) coefficient [55], which balanced positive TO of the gain and silica waveguide. A direct modulation at 2.5 Gb/s with pseudo-random binary sequence (PBRS) was also demonstrated.

Large progress has been made in the past on the emission spectrum control. For instance, distributed feedback (DFB) and distributed Bragg reflector (DBR) lasers with SM emission have been reported in [56]. In those heterogeneously integrated lasers, the Bragg gratings were etched on silicon waveguides by keeping the IIIV
waveguide as simple as possible. Threshold current varied from 65 up to 130 mA in $\Delta T = 60^\circ$C temperature range (from 20°C to 80°C) for DBR laser and 18 - 50 mA for DFB laser in the same temperature range. It is interesting to note, that if DFB laser showed SM lasing for the whole range of currents and temperatures, it wasn’t the case for the DBR laser, which had a kinks in the LI curve resulted by longitudinal mode hops. InP based gain section was 440 μm long and maximum output power was exceeding 10 mW at 15°C in both cases.

Further development of the 1D Si PhC integration as a key element of a hybrid laser were made in [57–60]. Tanaka et al. [57] integrated butt-coupled RSOA with Si platform by flip-chip bonding. The laser cavity comprised 600μm long InP RSOA, ring resonator (RR) and DBR as a second mirror. In conjunction with short cavity length RR acted as an intracavity narrow-band filter insuring SM operation. The fabricated laser had a low threshold current (for this class of lasers) of 9.4 mA and high power output of 15 mW (at 200 mA) at 20°C. Power output of >10 mW was maintained up to 60°C. Single mode mode-hop free lasing was demonstrated for the whole range of temperature sweep as temperature coefficient of the laser (0.0787 nm/°C) was very close to that in the peak wavelength of RR filter (0.076 nm/°C) and that allowed to select the same longitudinal mode.

Zilkie et. al [58] demonstrated butt-coupled III-V/Si DBR laser with 600μm long InP RSOA and 0.7 mm long grating. It had a higher wall-plug efficiency (WPE) in comparison with [57] (9.6% at 52 mA vs 7.5% at 70 mA) due to a more simple structure and therefore lesser number of elements which induce additional loses. However, a continuous SM operation was disrupted by the mode hopping as temperature coefficient of the laser longitudinal modes was significantly higher than one for the Si reflector peak wavelength. Similar results were obtained by Duan et. al [60] for heterogeniously integrated III-V/Si DBR laser with threshold < 20 mA and power output > 14 mW (160 mA at 20°C). For the same reason as was mentioned above, continuous SM operation was interfered by mode hopping. Nevertheless, second architecture where 2 RR with micro heaters incorporated into laser cavity as a buffer between gain section and 2 (rear and front) Bragg reflectors allowed to obtain wavelength tunability in a 50 nm span. Self-homodyne linewidth
measurement revealed that it varied in the range between 1 and 10 MHz depending on injected current and applied heating power on RRs.

Another example of the same idea was reported by Creazzo et al. [59] with integrated tunable C band laser, where AlGaInAs multiple quantum wells were used as a gain material and wavelength tuning was realized by two Bragg gratings (1d PhC) connected through multimode interference device (MMI). Each grating had integrated heater which provided independent tuning by thermo-optic effect. Two combined gratings were necessary in order to utilize Vernier effect. RSOA was metal-bonded within etched pit receptor sites inside the SOI wafer. The laser demonstrated maximum power output of 7 mW at 20 °C and an ability to sustain single mode operation (> 40 dB in all regimes) in 20 - 80°C with increase in threshold current from 41 mA up 125 mA respectively. Authors didn’t highlight this part, but there were kinks in the LI curves obtained at different temperatures, which is a clear evidence of mode hopping (i.e. SM lasing on different laser longitudinal modes).

In this chapter, a hybrid, low threshold Si₃N₄ Bragg grating laser system is presented. It does not require active tuning of any kind, with the system exhibiting mode-hop free lasing over a wide range of injected currents, and wavelength thermal stability up to 80°C. The Si₃N₄ based hybrid laser reported here offers a very promising solution for dense WDM applications in datacenters and is ready for fabrication at wafer scale.

The Bragg grating could be represented as a 1D photonic crystal, where perturbation of the refractive index exists only along the optical axis of the system. Such an approach helps to achieve uniformity in description of the resonant reflective elements regardless of the dimension count used for the implementation of periodic permittivity modulation.
2.2 Theory of Photonic Crystals

Photonic crystals (PhCs) are a class of optical media represented by natural or artificial dielectric structures with periodic modulation of the refractive index. Such optical media have some specific properties which grant an opportunity for several applications to be implemented on their basis. There are 3 major categories of PhCs: one-dimensional (1D), two-dimensional (2D) and three-dimensional (3D) structures. This work is focused on 1D (Si$_3$N$_4$ Bragg grating) and 2D structures.

Periodic modulation of the permittivity in 1D Photonic Crystals is realised in one direction only, while the other two directions are kept uniform. As a common example of such structures the Bragg grating of vertical cavity surface emitting lasers could be considered. Such PhCs are widely used as an anti-reflective coating to reduce significantly the reflectance from the surfaces of optical components such as lenses, prisms, beam splitters etc.

2D PhC have a relatively large number of geometries due to the variation of the permittivity along two directions, while the third direction remains uniform. A silicon substrate with periodically etched holes in it is a good example of such structures. This type of 2D PhC can also be found in nature. Colourful iridescence on the butterfly’s wings occurs due to their microstructured pattern.
2.2.1 1D Photonic Crystal

To illustrate the concept of a photonic band gap a 1D photonic crystal could be considered. The structure has a unidirectional periodic permittivity ($\varepsilon$) modulation, which is schematically represented on Fig. 2.2a. The xy plane represents all possible directions for uniformity of $\varepsilon$ and periodical dielectric function in z-direction is described as $\varepsilon(z) = \varepsilon(z + \chi \alpha)$, where $\alpha$ - period and $\chi = ..., -1, 0, 1, 2, ...$ an integer. Furthermore, an electromagnetic wave that propagates along the z-axis should be considered. The only non-zero wave vector component is $k_z$ or $k$ for simplicity.

The traditional way, introduced by Lord Rayleigh (1917), to analyse this system is to imagine that a plane wave propagates through the material and to consider the sum of the multiple reflections and refractions that occur at each interface. A different approach will be used here, which is to evaluate in the form of Bloch waves as described in detail in [61]. Subsequently, following the Bloch theorem, the modes of the wave propagating in the periodic structure could be described as follows:

$$E_k(z) = e^{ikz}u_k(z), \quad (2.1)$$

where $u_k(z)$ is a periodic function with a period $\alpha$ and could be written in a Fourier series as

$$u_k(z) = \sum_{n=-\infty}^{+\infty} E_n e^{inGz}. \quad (2.2)$$

Following the fact, that $\varepsilon(z) = \varepsilon(z + \chi \alpha)$ we can write, that $u(z) = u(z + \chi \alpha)$ with integer $\chi$, with a reciprocal lattice vector $G = 2\pi/\lambda$. Then, if we substitute $k$ with $k + 2\pi \alpha$ in Eq. 2.1, we will get

$$E_{k+2\pi\alpha}(z) = e^{ik'z}(e^{i2\pi \alpha}u_{k+2\pi\alpha}(z)), \quad (2.3)$$

The $e^{i2\pi \alpha}u_{k+2\pi\alpha}(z)$ term is a periodic function with a period $2\pi/\lambda$ and $k' = k + 2m\pi/\alpha (m = ..., -1, 0, 1, ...)$. If we assume that for the periodic structure, shown on Fig. 2.2a, $\varepsilon_1 = \varepsilon_2$, then it will lead to a homogeneous dielectric bulk medium and in this case the dispersion
Figure 2.2: (a) Medium with one-dimensional periodicity in the z-direction. The high permittivity regions ($\varepsilon_1$) are shown in red and the low ones ($\varepsilon_2$) are shown in green. The distribution of the two possible modes at $k = \pm \pi / \alpha$ is depicted by the black and blue curves. The low-frequency mode $\omega_{\text{low}}$ tends to concentrate its energy in the high-$\varepsilon$ regions, while the higher frequency $\omega_{\text{high}}$ concentrates the majority of its energy in the low permittivity regions. (b) Dispersion relation ($\omega - k$) for propagation in the z-direction of a homogenous medium (solid lines). The assumed arbitrary periodicity leads to the periodic repetition of the dispersion curves at $k' = k + 2m\pi / \alpha$ (dashed lines). (c) Band diagram (dispersion relation) for propagation in the z-direction of a z-periodic medium. A photonic band gap (frequency region marked in yellow) arises due to the appearance of two modes with different frequencies ($\omega_{\text{high}}$ and $\omega_{\text{low}}$) at the same $k = m\pi / \alpha$. The red rectangle indicates the irreducible Brillouin zone.
relation could be written as $\omega(k) = ck/\sqrt{\varepsilon}$ (Fig. 2.2b). The periodicity in this case results in repetition of the dispersion relation at $k' = k + 2m\pi/\alpha$, which is indicated by dashed lines. Although we can rewrite $k' = k + 2m\pi/\alpha$ only as $k$ because of the actual homogeneity of the medium, it is convenient to introduce quasi periodicity, as a region of $-\pi\alpha < k < +\pi\alpha$ (cross points of the dashed lines) represent a Brillouin zone or $0 < k < +\pi\alpha$ irreducible Brillouin zone due to the symmetry considerations. Subsequently, we can conclude, that there are two modes with frequency $\omega = c\pi/\alpha$ which exist in the periodic medium and can be expressed as $f(z) = \cos(\pi z/\alpha)$ and $f(z) = \sin(\pi z/\alpha)$ (Fig. 2.2a). Due to the actual uniformity of the permittivity in the $z$ direction, the two modes have the exact same frequency.

In a multilayer stack with periodicity $\alpha$ and $\varepsilon_1 > \varepsilon_2$, the two modes are no longer “equivalent”. To be more precise, the simultaneous existence of two modes with the same $k$-vector and different frequencies is allowed or, simply speaking, there is a low-frequency mode $\omega_{\text{low}}$ and a high-frequency mode $\omega_{\text{hig}}$ ($\omega_{\text{hig}} > \omega_{\text{low}}$). The difference in frequency originates from the spatial distribution of the energy for each mode. The high-$\varepsilon$ regions accommodate the energy of the low-frequency modes and the low-frequency modes tend to localise a large fraction of their energy in the low-$\varepsilon$ regions (Fig. 2.2a). As a result, a range of frequencies appears for which there is no allowed energy distribution that is able to translate itself through the periodic medium (Fig. 2.2c). The 1D periodic stack acts as a mirror for the frequencies inside the band gap (typical Bragg reflector). The size of the photonic band gap $\Delta\omega$ depends on the permittivity contrast of the two materials forming the periodic medium, $\Delta\omega$ increasing with higher $\Delta\varepsilon$.

The dispersion relation $(\omega - k)$ of the photonic crystals is usually referred to as a band diagram or band structure. It is a most important tool for their analysis which describes them in $k$-space (which is the spatial Fourier transform of the real space crystalline lattice). As was mentioned previously, a zone contained within the region of $0 < k < \pi/\alpha$ is called the irreducible Brillouin zone (Fig. 2.2c) and, due to the symmetry of the first Brillouin zone $-\pi/\alpha < k < \pi/\alpha$ about $k=0$, is sufficient for the complete study of the reciprocal periodic medium.
2.3 Passive Standalone Characterisation of the Reflector

It was mentioned before that the Bragg grating is a typical example of a 1D photonic crystal (PhC) and is widely used as an end mirror for a variety of laser configurations. The advantage of this approach is that there is a means to control the reflectance and the spectral range $\Delta \omega$ of the reflected light, which were discussed in the previous section. In addition to this fact, the EC laser configuration allows one to optimise separately one of the end-mirrors (a grating in our case) and the gain medium. The second mirror is considered as a high reflection (HR) coating, applied on one of the facets of the reflective semiconductor optical amplifier (RSOA) (Fig. 2.3a). The grating appears as a stack of trapezoids (Fig. 2.3b) with a refractive index $n_{Si3N4} = 1.99$ at 1550 nm. The main geometrical parameters for such a grating are waveguide width $c$, corrugation depth $b$, period $\alpha$ and grating length $l_{grating}$. Periodic modulation of the effective refractive index $n_{eff}$ is realised by the modulation of the waveguide width. In other words, $n_{eff}$ of the grating as a whole lies in-between the values of the group index for the waveguides with width $a$ ($n_a$) and $a-2b$ ($n_{a-2b}$). Therefore, the extreme values of $n_{eff}(z)$ are equal to $n_a$ and $n_{a-2b}$.

Anti-Reflection Coating: model and experimental results

In order to mitigate an influence of a parasitic Fabry-Perot fringes which originated from the cavity (Fig. 2.4) formed by the input facet of the Si$_3$N$_4$ waveguide and the resonant reflector ($l_{\text{passive}}$) an anti-reflection (AR) coating was required. An AR coating is a type of optical coating that can be applied to the surface of optical elements to reduce back-reflections which are occurring on the border of two dielectrics. For a simple case of two dielectrics with refractive indexes $n_1$ and $n_2$ ($n_1 < n_2$) and normal beam incidence, the reflectance at the interface between them is given by “Fresnel’s formula”

$$ R = \left(\frac{n_2 - n_1}{n_2 + n_1}\right)^2. \quad (2.4) $$

18
Figure 2.3: (a) EC schematics of the hybrid EC laser based on the butt-coupled RSOA and Si$_3$N$_4$ mirror. The reflector comprises a Si$_3$N$_4$ waveguide with a Bragg grating etched on to it, on a silicon dioxide substrate and cladded in a low-index flowable oxide. (b) Schematic view of the Si$_3$N$_4$ Bragg grating. Where $l_{\text{grating}}$ - grating length, $l_{\text{grating}} = 1504 \, \mu\text{m}$; $c$ - waveguide width, $0.9 \, \mu\text{m} \leq c \leq 1.1 \, \mu\text{m}$; $b$ - corrugation depth of the grating, $b = 0.09 \, \mu\text{m}$. Red dashed line indicates a basic trapezoid element which constitute the complete grating.
The principle of the function of AR coating is based on the destructive interference of the beams which reflected off the different interfaces within considered optical structure. For simplicity, let’s consider the case of a single layer AR coating under normal incidence (Fig. 2.4). The AR coating reduces the back-reflection of the incident beam by addition of a \( \pi \) phase shift between beam A and beam B, which results in destructive interference between A and B. Consequently, the demand for destructive interference implies equal reflectance for the interfaces where beam A and B were reflected, i.e. applying Eq. 2.4 we can write that (following the notation of Fig. 2.4)

\[
\left( \frac{n_2 - n_1}{n_2 + n_1} \right)^2 = \left( \frac{n_{\text{Si}3\text{N}4} - n_2}{n_2 + n_{\text{Si}3\text{N}4}} \right)^2, \tag{2.5}
\]

where \( n_{\text{Si}3\text{N}4} \) is a group index of the \( \text{Si}_3\text{N}_4 \) waveguide, i.e. depends on its geometry.

The refractive index of a single layer AR coating can be found from Eq. 2.5 to be \( n_2 = \sqrt{n_1 n_{\text{Si}3\text{N}4}} \). Considering that the phase change of a light wave with vacuum wavelength \( \lambda_0 \) that propagates in a material with refractive index \( n \) for a distance \( d \) is \( \delta = \frac{4\pi}{\lambda_0} nd \cos \Theta \), and applying the condition of a \( \pi \) phase change during the round-trip propagation in the AR layer, the thickness of the AR film must be \( d_{AR} = \frac{\lambda_0}{4n_2} \) (for \( \Theta = 0^\circ \)).

Considering that the refractive index of the \( \text{Si}_3\text{N}_4 \) waveguide \( n_{\text{Si}3\text{N}4} = 1.94 \), the

![Figure 2.4: Schematic view of the Si₃N₄ waveguide with single layer AR coating.](image)
Figure 2.5: Reflectance as a function of wavelength from air (n=1)/Si$_3$N$_4$ (n=1.94) interface. a) Simulated reflectance without coating (black line), with single layer of theoretically ideal AR coating (n = 1.41) of 274 nm (red line), with MgF$_2$ (n = 1.37) of 282 nm (cyan line) and with MgO (n = 1.71) of 226 nm. b) Close-up comparison of the coatings described in “a”). c) Part of Si$_3$N$_4$ blank waveguide normalized transmission spectrum, where blue line - transmission spectrum before deposition of AR coating, red line - spectrum after single layer deposition of 227 nm of MgO.

Theoretical ideal refractive index for the coating $n_2 = 1.41$. A material with the index value closest to the theoretical one and with a good physical properties for a coating is MgF$_2$ (n = 1.37 @ 1550 nm). However, at the moment when experiment has been conducted it was unavailable and MgO (n = 1.72 [62]) was applied instead. The thickness of the coating was determined from the $\frac{\lambda_0}{4n_{MgO}}$ rule ($\lambda_0 = 1550$ nm and normal incidence assumed) and resulted in $d_{MgO} = 227$ nm. Fig. 2.5a and Fig. 2.5b show the reflectance from the air-Si$_3$N$_4$ interface and the suppression that can be achieved by an ideal AR coating, by MgF$_2$ and by MgO with parameters mentioned above. The results were calculated using the transfer matrix approach. Respectively, Fig. 2.5c demonstrates the experimentally obtained transmission spectra from blank Si$_3$N$_4$ waveguide. After deposition of a 227 nm
thick MgO layer on the waveguide facets, an improvement in the transmission spectrum was achieved, i.e. the reduction of the modulation depth by 50%.

**Si$_3$N$_4$ Bragg Grating Design Considerations**

In order to determine optimal parameters of the Si$_3$N$_4$ grating a numerical modeling in the Lumerical MODE Solutions was performed. First of all, a maximal cross sectional dimensions of the waveguide were determined which support only single mode propagation. Considering Si$_3$N$_4$ refractive index $n_{Si_3N_4} = 1.94$ @ 1550 nm, the optimal dimensions were found to be 1.1$\mu$m and 0.6$\mu$m (width and height respectively). The effective index $n_{Si_3N_4 eff}$ with these parameters is 1.68. Applying expression for the Bragg wavelength

$$\lambda_{Bragg 1} = 2\Lambda n_{eff},$$

(2.6)

the period of the grating is $\Lambda = 460$ nm for $n_{eff} = n_{Si_3N_4} = 1.68$. However, in order to achieve narrower resonance a 2nd order Bragg grating was required of a period $\lambda_{Bragg 2} = 2\lambda_{Bragg 1}$ (Fig. 2.6). Thus the period for the required grating was estimated to be 920 nm.

On the next step there was a necessity to determine a shape of the grating, i.e. rectangular, trapezoidal and triangular. According to [63], the shape of the grating strongly influences the coupling coefficient of the grating, which can be interpreted as the amount of reflection per unit length. For the rectangular grating, where $n_{eff 2}$ is the refractive index of the wider part and $n_{eff 1}$ is the refractive index of the thinner part, the coupling coefficient [63] is defined as

$$\kappa_{rect} = 2\frac{n_{eff 2} - n_{eff 1}}{2n_{eff} \Lambda} = 2\frac{\Delta n}{2n_{eff} \Lambda} = \frac{2\Delta n}{\lambda_{Bragg}}.$$

(2.7)

For a sinusoidal effective index variation $n(z) = n_{eff} + \Delta n/2 * \cos(2\beta_0 z)$, the coupling coefficient is reduced by a factor of $\pi/4$:

$$\kappa_{sin} = \frac{\pi \Delta n}{2\lambda_{Bragg}}.$$

(2.8)
Figure 2.6: Simulated reflection and transmission spectra for the 1st and 2nd order triangular Bragg grating ($\Lambda_1 = 460$ nm and $\Lambda_2 = 920$ nm respectively). Number of periods $N = 1600$

For the other effective index variations, we can take the Fourier expansions $n(z) = n_{eff} + \sum_i \Delta n_i / 2 \cdot \cos(i \cdot 2\beta_0 z)$, and the coupling coefficient can be derived from the first-order Fourier component: $\kappa = \pi \Delta n_1 / (2\lambda_{Bragg})$. Therefore, we can obtain for a triangular grating

$$\kappa_{\text{triang}} = \frac{4\Delta n}{\pi \lambda_{\text{Bragg}}},$$

which is reduced by a factor of $2/\pi$ compared to the square case 2.7. And for trapezoidal case

$$\kappa_{\text{trapez}} = \kappa_{\text{rec}} \frac{2\sqrt{2}}{\pi}.$$  

The bandwidth between the first nulls around the main reflection peak can be determined by [63]:

$$\Delta \lambda = \frac{\lambda_{\text{Bragg}}^2}{\pi n_g} \sqrt{\kappa^2 + (\pi/L)^2},$$

where $L = N \Lambda$ grating length proportional to a number of periods $N$ and $n_g = n_{eff} - \lambda \frac{dn_{eff}}{d\lambda}$ is a group refractive index [63].
Therefore, according to 2.11 for the fixed $L$, in order to achieve narrower bandwidth a grating with smallest $\kappa$ should be selected. In our case a triangular grating was selected.

![Graph](image1)

**Figure 2.7:** Simulation results for the Bragg grating with triangular effective index modulation. a) Simulated dependence of the grating reflectance and corresponding central peak FWHM bandwidth vs corrugation width. b) Simulated dependence of the grating reflectance and corresponding central peak FWHM bandwidth vs grating length.

When the value for the grating period was determined as $\Lambda = 940$ nm, a numerical modeling was performed in order to select corrugation width. According to the Fig. 2.7a, the optimum value for the corrugation $b = 90$ nm due to relatively small bandwidth of 0.45 nm and peak reflectance of 0.43. The number of the grating periods $N$ was selected to be 1600 as further increase in length didn’t provide significant bandwidth decrease (Fig. 2.7b).

In order to simulate the mode profiles of the RSOA and the 1.1 x 0.6 nm Si3N4 waveguides a FIMMwave was used (Fig. 2.8a, 2.8b). A maximum coupling $K$ was calculated as high as 0.48. Also misalignment dependent coupling curves in vertical, horizontal and light propagation directions (Fig. 2.8c, 2.8d) were calculated. According to these results $K>0.38 (>80\%$ from the maximum coupling) was maintained within $\pm 0.5\mu m$ range in horizontal axis and $\pm 0.25\mu m$ range in vertical axis.
Passive Characterisation

The Si$_3$N$_4$ device was fabricated on the 300 mm R&D silicon photonic platform of STMicroelectronics Crolles, France [64, 65]. Fabrication started with a 1.4 µm thick buried silicon dioxide layer growth on a silicon bulk wafer. A 600 nm Si$_3$N$_4$ layer was then deposited via low temperature PECVD. Si$_3$N$_4$ patterning was performed with DUV lithography followed by dry etching. An encapsulation layer of 1.5 µm thick silicon dioxide was used to complete the process.

Good reproducibility of the Si$_3$N$_4$ reflectors and a high fabrication yield are crucial for high volume manufacturing. In order to verify repeatability and high yield, the inter-die variations of the 300 mm wide Si$_3$N$_4$ on SOI wafer have been studied. 20 chips in total, 5 per quadrant, were cleaved to be characterized optically on a
Figure 2.9: Schematic view of the set-up used for passive characterisation of the reflector sample. SR - silicon reflector chip; SMF - single mode fiber; IRC - infra-red camera; PBM - polarising beam splitter; OSA - optical spectrum analyser; TLS - tunable laser source; L1-L5 - aspheric lenses; ASE - amplified spontaneous emission broadband source. Collection of the transmission and reflection spectrum was carried out separately.

set-up shown on Fig. 2.9. Figure 2.10b illustrates one of the collected reflection spectrum. On those chips, 4 different devices with the same grating period of 510 nm, and different waveguide widths of 0.9 µm, 1.1 µm, 1.3 µm and 1.5 µm respectively, were selected for the acquisition of optical spectra and the Bragg reflection peak central wavelengths have been plotted for every device (Fig. 2.10c). The standard deviation of the resonance wavelengths is within the range of 2 - 3 nm, and the average shift is ±7 nm over all four waveguide widths (Fig. 2.10d). The chip-to-chip deviations of the central wavelength were highly likely caused by slight variations in the exposure dose and other more random factors such as Si3N4 thickness variation. Therefore, with a little bit of adjustments, these reflectors are potentially suitable for mass-production on a wafer scale, utilizing the advantages of maturity of the lithographic process.

A temperature change of the material would lead to a change of its refractive index by the amount determined by its thermo-optic coefficient, hence shifting in wavelength the reflection peak of the gratings and also changing the effective optical length of the laser cavity, affecting the lasing wavelength and the laser thermal behavior.
Figure 2.10: (a) Tilted SEM view of the 600 nm thick patterned silicon nitride before encapsulation. (b) The reflection spectrum of the 1505 µm long Si₃N₄ grating acquired at 20°C. Blue curve - real reflection spectrum; red curve - lorentzian approximation excluding Fabry-Perot influence. (c) Plot of the measured reflection peaks central wavelengths of the 4 devices on all 20 chips. Waveguide widths are 0.9 µm (blue curve), 1.1 µm (red curve), 1.3 µm (yellow curve) and 1.5 µm (purple curve). (d) Blue axis shows the most frequent resonant wavelengths over all 20 chips at each waveguide width and the red axis shows the resonant wavelength standard deviation over all chips at each waveguide width.

To verify the thermal stability of the passive chip, a characterisation of the thermo-optic coefficient of the Si₃N₄ was performed. This was carried out by experimentally measuring the wavelength shift of a grating’s reflection peak with temperature. A change in the device temperature led to a change in both the group and effective refractive indices of the material, thus changing the Bragg condition of the grating and shifting the reflector peak wavelength.

For this thermal study, the reflection and transmission spectra of the gratings on the
Si$_3$N$_4$ passive chip were acquired at room temperature that exhibited Fabry-Perot fringes superimposed on the Bragg reflection peak. This fringe spacing $\Delta \lambda_{\text{fringes}}$ can be related to the material properties of the device and its length by:

$$\Delta \lambda_{\text{fringes}} = \frac{\lambda^2}{2n_g L_{\text{chip}}} \quad (2.12)$$

A $\Delta \lambda_{\text{fringes}}$ of 0.097 nm was measured at 20°C. This value corresponds to a group index, $n_g$, of the cladded Si$_3$N$_4$ waveguide of 2.03, with the passive chip length being 6.1 mm, and the grating 1.505 mm long. This value is in good agreement with the simulated group index, $n_g^{\text{sim}}=2.01$ of the structure, with over 92% of the fundamental TE mode confined in the Si$_3$N$_4$ waveguide.

\[\text{Figure 2.11: Plot of the central wavelength of the Bragg grating reflection peak as a function of operating temperature. The device displays a constant shift of 12.4 pm/°C}\]

In the next step, thermal characterization of the Si$_3$N$_4$ material was carried out. Optical spectra of the Si$_3$N$_4$ Bragg grating were measured at temperatures starting from 20°C, up to 80°C with a 5°C step. In Fig. 2.11, the central wavelength of the reflection spectrum is plotted against temperature. The Bragg reflector central wavelength shifted by 0.744 nm, from $\lambda_0=1556.048$ nm at 20°C to $\lambda_1=1556.792$ nm at 80°C, resulting in the measured thermal sensitivity of the Si$_3$N$_4$ Bragg reflector of 12.4 pm/°C.
From this measured thermal sensitivity, the corresponding thermo-optic coefficient (TOC) can be determined through the following relation [66, 67]:

\[
TOC = \frac{1}{\Delta T} \left( \frac{\lambda_1 - \lambda_0}{\lambda_g} \right) n_{g}^{\text{room}} = 1.62 \times 10^{-5} \frac{RIU}{^\circ\text{C}} \tag{2.13}
\]

The above thermal behaviour of the device is mainly caused by the TOC of Si$_3$N$_4$, since the high confinement of the mode in the Si$_3$N$_4$ region and the very low TOC of the substrate and cladding being $9.5 \times 10^{-6}$ RIU/$^\circ$C [66]. The acquired experimental value of the Si$_3$N$_4$ TOC is in good agreement with [68]. This measured value is lower than the TOC of $2.5 \times 10^{-5}$ RIU/$^\circ$C for N-rich Si$_3$N$_4$ reported in [69]. The mismatch is probably due to the difference in stoichiometry of the Si$_3$N$_4$ layers of both materials.

### 2.4 Active Characterisation of the External Cavity Laser

To characterise the external cavity (EC) laser the set-up shown in Fig. 2.12 was used. Quaternary quantum wells in AlGaInAs/InP were selected as the material for the reflective semiconductor optical amplifier (RSOA). The Al$^{3+}$ ions contained in the AlGaInAs quaternary quantum wells deepen the potential well and obstruct carrier (electrons) leakage at elevated temperatures, thus facilitating higher temperature operation [70]. To mitigate mode mismatch between the gain and passive section the optimal waveguide height and width has been selected. Due to the high gain coefficient material, the length of the gain chip used was as short as 250 $\mu$m, many times shorter than some competing solutions [60, 71], hence leading to very cost effective employment of III-V materials. The Bragg gratings were part of the actual 1.1 $\mu$m wide Si$_3$N$_4$ waveguides, greatly reducing the reflector footprint, thus unlocking high integration density and allowing a high channel count. The gratings were designed for a UV photolithography compatible approach that leads to volume manufacture and decrease in device costs.
2.4.1 Materials and methods

The gain section, comprising an AlGaInAs/InP die mounted onto an aluminum nitride ceramic tile with its front end protruding beyond the sub-mount edge, was positioned by a five-axis alignment stage. The Si reflector sample was rested on a single-axis horizontal translation stage. Alignment optimization between the RSOA and the silicon reflector chip was carried out below the laser threshold, with an infrared InGaAs camera equipped with a 100x objective lens used for observation from above. Both the RSOA and the reflector chips could be independently temperature controlled by Peltier elements, within the temperature range of 20 - 80°C. It should be noted that the Peltier elements were used for the sole purpose of studying the lasing characteristics of the device with varying temperature (the device ran effectively without active cooling). The laser output was collected at the other end of the Si$_3$N$_4$ wave-guide with a lensed single mode optical fiber mounted on a three-axis stage. A fiber coupled isolator with isolation >50 dB was placed after the lensed fiber to minimize undesired external optical feedback from the measuring set-up components. A 2 x 2 fiber coupler was used for the simultaneous observation of the lasing spectra and output power.
During operation, injected carriers recombined in the quantum wells of the RSOA, emitting light, which then coupled into the Si$_3$N$_4$ waveguide and propagated towards the mirror. The light component that was off-resonance with the grating was transmitted to the output facet of the waveguide while the on-resonance component was partially reflected back to the RSOA. A wavelength-selective feedback was thus generated, with a span on the order of 0.1 nm, forming a laser cavity between the grating and the HR facet of the RSOA (as shown in Fig. 2.13). The emitted laser wavelength corresponded to the longitudinal cavity mode that lied in the resonant response of the grating.

![Power vs. Wavelength plot](image)

**Figure 2.13:** Power vs. Wavelength plot, showing the spectral overlap of the gain ripple (blue curve), the Si$_3$N$_4$ Bragg mirror (red curve) and the total cavity laser spectrum (black curve).

The longitudinal mode spacing of a composite cavity, $\Delta\nu$, is defined as the speed of light divided by the total round-trip optical path. The corresponding wavelength spacing, $\Delta\lambda$, is:
where $l_{\text{gain}}$ and $n_{\text{gain}}$ are the length of the gain chip and its group refractive index respectively, $l_{\text{passive}}$ and $l_{\text{eff}}$ are the lengths of the waveguide and the effective length of the gratings respectively, with $n_{\text{passive}}$ being the group refractive index of the passive chip and $n_{\text{grating}}$ the refractive index of the grating.

To demonstrate the athermal operation of our proposed hybrid laser, several Si$_3$N$_4$ gratings that were butt-coupled to the quaternary RSOA to form the EC lasers were used. The laser operation data was recorded with increasing driving currents at room temperature ($20^\circ$ C), without active cooling for drive currents up to 100 mA, with 1 mA current steps. Lasing spectra were acquired at each current step.

In Fig. 2.14a, the time-averaged optical spectrum of one of such EC laser was plotted in a false color map as a function of the drive current. Notice the single mode lasing regime free of mode-hopping achieved from 15 mA to 62 mA drive current. This single longitudinal mode lasing was attained by matching the longitudinal mode of the total laser cavity with the Bragg reflection peak (as seen in Fig. 2.13). Moreover, it can be noticed from Fig. 2.14a that our EC laser has a threshold current as low as 10 mA and has an output power up to 3 mW as shown in Fig. 2.14c. The emitted output power was measured by collimating the outcoming beam with a lens onto a power meter sensor head.

All of the EC lasers that have been characterized have low threshold currents in the range of 10 mA and 20 mA, with the lowest values of 10 mA corresponding to the gratings with the highest reflectivity ($R \sim 78\%$) determined as $R \approx P_{\text{ref}}/(P_{\text{in}}K)$, where $P_{\text{ref}}$ - measured reflected power, $P_{\text{in}}$ - injected power into the waveguide and $K$ - coupling losses ($\sim 0.5$) between Si$_3$N$_4$ waveguide and input lens or lensed fiber. The output power was measured to be in the range of several mW for all of the characterized devices.

Over the full mode-hop free lasing regime shown in Fig. 2.14a, a side-mode
Figure 2.14: Laser characterization. (a) False colour plot of the optical spectrum of the laser, averaged in time, with increasing driving current. (b) Normalized reflection spectrum of the Bragg gratings, with the wavelength axis matched to that on the left. (c) L-I curve of the EC laser. (d) Optical spectrum of the EC laser at room temperature and 85 mA of driving current. The laser line shows 49 dB of SMSR. (e) Linewidth of the hybrid EC laser (blue) equal to 1.7 MHz and fit (dashed red). (f) Multi-mode regime spectrum at 67 mA.
suppression ratio (SMSR) higher than 40 dB was measured, with a maximum of 49 dB as shown in Fig. 2.14d. The linewidth of the single mode laser was measured with a tunable laser source through a heterodyne measurement, and was found to be lower than 3 MHz over the complete operating regime.

When the driving current was increased beyond 65 mA, the increased inhomogeneous gain of the active chip led to lasing of side modes near the centre wavelength of the reflector. This can be seen in Fig. 2.14a, where the time averaged optical spectra shows two main lasing modes, with additional, weaker sidebands starting to appear (Fig. 2.14f).

**Thermal Stability**

After the above characterization of the devices at room temperature, the characteristics of multiple EC laser devices were measured as a function of temperature by mounting both the RSOA and Si₃N₄ gratings in butt-coupled fashion on two independent thermo-electric controlled plates, fixing the RSOA in place with conductive wax. The EC laser spectra were collected with increasing driving current at each temperature, from 20°C to 80°C in 10°C steps. Fig. 2.15 shows the single mode lasing wavelength plotted against temperature for a fixed driving current of 50 mA. As the temperature of operation was increased, no red-shift of the lasing wavelength was observed, as opposed to a 6 nm increase of the lasing wavelength that is associated with the traditional InP DFB for the same change in temperature (JDS CFQ935 [72]). The hybrid EC laser showed over 40 dB of SMSR and output power in the 1 to 3 mW range over the entire temperature interval considered.

The temperature stability experiment required realignment between the RSOA and Si chip due to coupling deterioration up to the point when lasing completely disappeared. The decay from optimal coupling to “0” occurred after temperature tuning by 10°C. Coupling degradation resulted from the thermal expansion/shrinking of the bulky Al mounts used as the interface between the
components of the laser and respective XYZ stage. Strictly speaking, each data point on Figure 2.15 corresponds to a “unique” laser, i.e. each time a new longitudinal laser mode was aligned with the reflector. Moreover, recoupling introduces a slight difference in the laser cavity length thus deeming it impossible to ensure consistent positioning of each mode with respect to the reflector. Finally, in addition for the need in realignment (which is the main factor in this particular experiment) there is a lasing mode red-shift introduced by the TOC of the gain medium.

To achieve a wide temperature interval with continuous mode hop free lasing, robust integration between the RSOA and the reflector is required (flip-chip bonding). Also, to enable more precise alignment between the laser cavity longitudinal mode and the reflector central frequency a phase tuning section on the Si$_3$N$_4$ waveguide could be introduced, e.g. via a micro-heater.

The lasing wavelength of our EC laser is determined by the resonance wavelength of our narrowband Bragg grating reflector. The use of a low TOC material, here Si$_3$N$_4$, for the grating provides a negligible thermal shift of the Bragg reflector resonant wavelength and hence the lasing wavelength. This enhanced thermal stability of
the lasing wavelength of the device over a temperature range of operation of 60°C, completely eliminates the need for active cooling of the laser normally employed in Si-based DFBs.

2.5 Fabry-Perot cavity assisted mode hop free lasing

In most lasers the presence of the Fabry-Perot (FP) modes formed by parasitic cavities is an undesired feature and their influence on the behavior of the optical system could be greatly reduced by multilayer AR coating. As was described previously, in the case of the lasers studied in this work, the total elimination of the FP modes has not been achieved and they played a major role in the process of the stable single mode (SM) mode hop free lasing for a wide range of injected current at a constant temperature. An additional approach which is commonly used towards ripple reduction is to use an RSOA with angled waveguides, but the cost of this solution is a gain section enlargement leading to the higher power consumption with the same level of power output.

<table>
<thead>
<tr>
<th></th>
<th>RSOA</th>
<th>Waveguide</th>
<th>Bragg grating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (µm)</td>
<td>250</td>
<td>1426</td>
<td>451.5</td>
</tr>
<tr>
<td>$n_{group}$</td>
<td>3.601</td>
<td>1.683</td>
<td>1.669</td>
</tr>
</tbody>
</table>

Table 2.1: Simulation parameters close to those of the real system

To qualitatively describe the contribution of the FP modulation of the reflection spectrum to SM lasing we consider a simple external cavity laser, with parameters close to the tested short cavity device. Overall, there are three components comprising such a laser: a) gain section (RSOA), b) bulk waveguide (WG) and c) Bragg grating. The numerical values for the group refractive index and geometrical length are contained in table 2.1. Knowing these parameters it is possible to calculate longitudinal laser modes via the following expression:

$$\lambda_m = \frac{2(l_{gain}n_{gain} + n_{wg}l_{passive} + l_{eff}n_{grat})}{m},$$ (2.15)
Figure 2.16: A representation of the lasing condition for the short cavity laser. Red - a calculated longitudinal cavity modes, black - Bragg grating reflection spectrum modulated by Fabry-Perot fringes, blue - gain spectrum from real III-V RSOA 250 µm long.

where $l_{gain}$ - length of the RSOA gain section, $l_{passive}$ - length of the Si$_3$N$_4$ waveguide, $l_{eff}$ - effective length of the Bragg grating for the central resonant wavelength and $n_{gain}$, $n_{wg}$, $n_{grat}$ their corresponding group refractive indexes. The value of $l_{eff}$ could be determined as

$$l_{eff} = L_{grat} \frac{\sqrt{R}}{2\text{atanh}(\sqrt{R})},$$  \hspace{1cm} (2.16)$$

where $L_{grat}$ is the total length of the reflector on the grating peak reflectivity $R$ [73].

Knowing all the values for key parameters a quick graphical evaluation could be made by looking at Fig. 2.16. The general idea of the EC laser is to keep the FSR of the cavity greater than the reflector bandwidth, defined as the span at the level of reflectivity which allows lasing. With sufficient current being injected, lasing starts at a wavelength $\lambda_m$ defined by 2.15 and the gain clamps. In the real life case, the gain spectrum is not flat but demonstrates gain ripples, occurring due to the imperfection of the AR coating of the RSOA. The periodicity of the gain ripples is
set by \( \Delta \lambda = \frac{\lambda^2}{2n_{gain}l_{gain}} \) and the depth of the gain spectral modulation is defined by the reflectivity of the RSOA facets (better AR coating results in lower ripples), and the gain.

As current increases, Joule heating causes a gain section refractive index increase and \( \frac{d\lambda}{dn_{gain}} \) becomes a major factor in the longitudinal mode solutions changing. According to 2.15 for the same \( m \) with increase in \( n_{gain} \), \( \lambda_m \) increases as well. Subsequently, a mode hop free range of the injected currents \( \Delta I = I_2 - I_1 \), where \( I_1 \) is the threshold current and \( I_2 \) is the current value when lasing hops to the \( m + 1 \) mode. In Fig. 2.16 the most probable mode to lase is the one referred to as \( m + 3 \) as it meets conditions of the maximum gain (gain ripple peak) and high reflectivity.

All of the above description is valid only when a longitudinal mode \( m \) is located perfectly on the short wavelength edge of the reflector at current \( I_1 \). However, there could be a case when it is on the center of the reflector and with the same thermooptical properties the SM mode hop free regime will last for \( \frac{\Delta I}{2} \). One of the demands towards short cavity lasers, a relatively high FSR, requires a short gain section, typically 250 - 500 \( \mu m \), which is leading towards lesser allowed pumping currents (100 - 200 mA respectively) due to saturation limitation.

In the case of strong FP modulations sitting on top of the narrow band reflector it is still possible to reach SM lasing for a wide range of injected current. In most cases to build a cost effective solution a standard RSOA from the market is being used. Therefore, there is a discrete limit on the parameter \( l_{gain} \) in design considerations. The most accessible variable is \( l_{passive} \), as it is defined by how close to the designed reflector cleaving is performed. Generally speaking, it is possible to vary the number of narrow-band reflections and their width within one BG reflection band solely by changing \( l_{passive} \). In this case the reflection spectrum of such a structure could be calculated as

\[
R_{eff} = \frac{1 - (1 - R_{grat}(\lambda))(1 - R_2)}{((1 - (R_{grat}(\lambda)R_2)^{1/2})^2 + 4(R_{grat}(\lambda)R_2)^{1/2} sin^2 \frac{2\pi(l_{passive}n_{wg} + l_{eff}n_{grat})}{\lambda}}. \quad (2.17)
\]
Figure 2.17: Plot of the single FP fringe width (red) and corresponding number of fringes accommodated within the designed Bragg grating reflection peak (blue) against $\text{Si}_3\text{N}_4$ waveguide length, measured from the input facet up to the reflector ($l_{\text{passive}}$).

where $R_{\text{grat}}(\lambda)$ is the wavelength dependant reflection of the grating, $R_2$ - facet reflection of the external reflector sample, defined as the Fresnel reflection at a perpendicular angle of incidence.

As $l_{\text{passive}}$ increases so does the number of FP peaks and simultaneously each peak width reduces (Fig. 2.17). The best value of $l_{\text{passive}}$ depends on several factors, such as $\frac{dn_{\text{gain}}}{dT}$, the spectral shape of the external reflector and its $\frac{dn_{\text{eff}}}{dT}$. The current dependence here is driven by temperature, induced by light absorption in the reflector material. This factor has an insignificant role in case of $\text{Si}_3\text{N}_4$ Bragg grating, as it has quite a low TOC and could be deemed negligible. But $\frac{dn_{\text{gain}}}{dT}$ is crucial and a thorough study has to be made to apply the above design evaluations.

If InP is selected as the gain medium with a TOC$_{\text{InP}} = 2.01 \times 10^{-4} \, ^\circ \text{C}^{-1}$ [74] and a SiN reflector with a TOC$_{\text{SiN}} = 1.62 \times 10^{-5} \, ^\circ \text{C}^{-1}$ we can evaluate the optimal SiN waveguide length for our laser. Figure 2.18 shows the drift of the longitudinal laser cavity modes with temperature increase from 20°C up to 80°C (black and green lines). In the same plot the reflector peak drift versus temperature represented by the area between the 2 red lines. By selecting different waveguide lengths from
Figure 2.18: Representation of the SiN hybrid laser longitudinal mode drift at different temperatures for 4 different SiN bare waveguide lengths. Red lines represent FP fringe width superimposed with Bragg grating reflection peak. Black dashed line represents longitudinal mode with the same number. (a) Waveguide 80µm long, SM mode hop free lasing ensured for $\Delta T = 6.54^\circ$C. (b) Waveguide 800µm long, SM mode hop free lasing ensured for $\Delta T = 8.92^\circ$C. (c) Waveguide 1000µm long, SM mode hop free lasing ensured for $\Delta T = 9.08^\circ$C. (d) Waveguide 1500µm long, SM mode hop free lasing ensured for $\Delta T = 7.4^\circ$C. It is apparent that the optimal length is 1000µm.

80µm up to 1500µm we can vary the peak width (distance between red lines) and the slope of the laser modes. Thus the optimal value is 1000µm which provides SM lasing for $\Delta T = 9^\circ$C, where $\Delta T$ is defined as shown in Fig. 2.18a. This simple model doesn’t account for gain clamping, which potentially should increase the value of $\Delta T$.

2.6 Conclusion

In conclusion, we have demonstrated a low threshold hybrid external-cavity laser based on a Si$_3$N$_4$ reflector coupled to an RSOA. The laser is single mode and
mode-hop free over a driving current range of 49 mA, from 13 mA to 62 mA, with a power output on the order of mWs over the total range.

One of the road maps towards better SM operation could be further improvement of the AR coatings of the Si₃N₄ chip which will lead to the widening of the mode-hop free operation regime up to 100 mA of driving current with the same RSOA. The use of narrower reflection peaks could lead to more stable operation and higher side mode suppression ratio. However, reducing the contrast would lead to an increase of the passive chip length, reducing the FSR of the laser cavity modes, cancelling out the benefits. For this reason, a better alternative to the gratings would be a Si₃N₄ resonant mirror such as 1D and 2D photonic crystal cavities [14], whose high Q-Factors and incredibly small footprints, even compared to gratings, would lead to finer lasing wavelength control and a wider mode-hop free regime.

The second approach is to consider the non-optimised nature of the AR coatings and to evaluate the FP fringes as a mechanism to achieve a required narrowband reflector without sophisticated techniques. The only parameter that will require optimisation is \( l_{\text{passive}} \), the length of the waveguide between the input facet of the external reflector chip and the reflector. The most appropriate tool for precise control over the cleaving process could be a crack trench written on the bottom part of the Si substrate used for external reflector chip fabrication.

The studied hybrid EC laser achieved a lasing wavelength stability of 0.16 nm in the total temperature range of operation 20°C - 80°C with mW range output power, compatible with WDM standards, with 200 GHz and 400 GHz channel spacings. This paves the way for the future employment of silicon nitride chips with a series of gratings or photonic crystal cavities resonant at different densely spaced wavelengths coupled to arrays of commercialized RSOAs, generating a dense network of compact transmitters, without the need for any active temperature control, thus greatly reducing the related power consumption and cost and making these lasers an excellent prospect for low cost dense WDM applications in data centers.
Chapter 3

Si Photonic crystal-based resonant reflector laser

3.1 Introduction

As was discussed in 2.1, there are a number of demonstrated heterogeneously integrated III-V/Si lasers, which contained one or two Si DBR as a resonant mirror. Whereas such feedback elements as RRs [50, 75–77], Sagnac loops [78–81] and Sagnac loop mirror based Michelson interferometric modulator (MIM) [82] were widely represented and studied for hybrid platforms, an employment of the 2D Si photonic crystal (PhC) cavity in the same manner (with several mW output power) to our knowledge is still absent. Nevertheless, there is a single report of the continuous-wave (CW) electrically driven lambda-scale embedded active-region photonic crystal (LEAP) lasers coupled to Si waveguides. [83]. This solution indeed is quite promising due to it’s monotonically integrated nature (Fig 3.1). The active region of this laser was $3.8 \mu m \times 0.3 \mu m \times 0.15 \mu m$. It demonstrated 42 $\mu A$ threshold curve and fiber-coupled output power was 0.72 $\mu W$ at an injected current of 0.5 mA. Lasing wavelength was 1541 nm. However, there are many issues that has to be solved prior to device employment in computercom networks: leakage current between InP and SiO$_2$; output power should be increased; poor coupling efficiency between the laser and Si waveguide.

Building on the idea of a short cavity laser with external CMOS compatible reflector
[57, 58], in this chapter, a hybrid laser that comprises a III-V gain element and a silicon Photonic Crystal (PhC) cavity-based resonant reflector is demonstrated. The unique advantages of PhC cavities are exploited to provide a new type of laser that is capable of producing output powers of several milliwatts. In this configuration, the high intra-laser cavity power (10s of milliwatts) results in unprecedented stored energy densities in the PhC resonator. The enhanced light-matter interaction in the high quality factor (Q), low mode volume (V) PhC cavity leads to non-linear absorption in silicon, rendering its resonance a strong function of the output power, an effect that was used to achieve an athermal lasing.

### 3.2 Theory of 2D Photonic Crystals

A second class of PhC widely used in planar photonics are two-dimensional or 2D photonic crystals. As the name implies, a periodic modulation of the permittivity is realised in-plane (xy plane) and homogeneity exists only in the direction perpendicular to this plane (z axis). The interaction between an incident optical field and the 2D PhC is strongly dependant on how the electromagnetic field distributes within the crystal with respect to its periodicity, i.e. the response is polarisation dependant. Commonly, there are two types of polarisation states used: TE - transverse electric, with the electric field component perpendicular to the xy plane; TM - transverse magnetic, with electric field component in the xy plane.
Figure 3.2: The photonic band diagram for the modes of a triangular array of air cylinders ($\epsilon=1$) in a dielectric membrane ($\epsilon=13$), reproduced from [61]. The blue lines represent TM bands and the red, TE Bands. An inset shows the unit cell of the photonic crystal lattice. The band diagram calculated for the wave vectors in the irreducible Brillouin zone, formed by high symmetry points $\Gamma$, $M$ and $K$. A photonic band gap exists only for TE modes.

For each polarisation state there exists different periodic structures. This results from the fact that oscillating fields with TE and TM polarisations experience perturbations of the medium dielectric constant differently. An example band diagram of a triangular lattice depicted in Fig. 3.2 shows that, for selected geometrical parameters and physical properties, a photonic band gap exists only for the TE polarisation.

As was mentioned in section 2.2.1, the lattice vector $G$ is determined by $G = 2\pi/\alpha$. While looking at the ΓKM triangle (Fig. 3.2), it is obvious that for each direction the value of $G$ is different. For instance, in the Γ - M direction $G = 2\pi/\sqrt{3}\alpha$ and in the Γ - K direction $G = 4\pi/3\alpha$. It is clear then, that a 2D lattice periodicity has different values for different directions. Thus, the vectorial aspect of the wave vector should be considered, as the response of a 2D photonic crystal is strongly...
dependant on the angle of incidence and direction of propagation of the light within the lattice. 2D photonic crystals could also be represented as multidimensional superpositions of 1D photonic crystals with a given periodicity. Considering such an approximation, it is obvious that lattice topologies with maximum possible axes of symmetry are desirable in order to achieve a homogeneous response for every $k$. For example, the triangular lattice configuration has a higher rotational symmetry with its hexagonal reciprocal unit cell in comparison with the square lattice, where the unit cell is square as well.

### 3.3 Photonic Crystal Cavities as Narrow-band Reflectors

An initial study of the influence of relatively small disorder, in an otherwise periodic medium [84–87] has led to the conclusion [88], that it will not destroy a band gap. Simultaneously, these kinds of lattice perturbations form small areas which spatially confine the light at the relative resonant frequency, i.e. a single or a set of closely spaced localised modes could be formed inside the photonic band gap. Such kinds of areas are nothing other than optical cavities with their borders acting as Bragg mirrors for the allowed frequencies while filtering out all other light due to the band gap of the photonic crystal.

For the description of photonic crystal cavities two fundamental parameters are used: quality factor $Q$ and modal volume $V$. The main definition of the quality factor, or $Q$-factor for short, is the ratio of the stored energy in the cavity to the energy extraction per optical cycle. Also, the $Q$-factor could be thought of as a dimensionless lifetime, indicating the number of optical periods that elapse before the energy decays by $e^{-2\pi}$. In addition, the decay rate $\Gamma$ could be found as $\Gamma = \omega_0/2Q$. Summing up all the definitions of the $Q$-factor, it could be considered as a quantitative indicator of the spatial mode confinement. The modal volume describes the spatial extent and the energy distribution of the mode inside the cavity. Taking into account that the considered cavities are formed in a photonic band gap (meaning there is no propagation into the surrounding lattice) and has a
volumetric size as small as order of \( \lambda^3 \), the values of \( Q \) are very high.

The last statement has stronger applicability for cavities formed in the complete photonic band gaps of 3D photonic crystal lattices, only because in this case is mode confinement entirely realised by the unique properties of the PhC. In the case of real 2D slabs, there is no infinite extension of the lattice in the \( z \) direction and vertical confinement is achieved via total internal reflection. That condition, in addition to the band diagram, further limits the range of \( k \) for which light is trapped in the defect. For the case of a simple waveguide with refractive index \( n_2 \) surrounded by air, according to Snell’s law, this limitation could be written as a dispersion relation

\[
\omega = k_{\parallel}c,
\]  

(3.1)

where \( c \) speed of light in air and \( k_{\parallel} \) is a in-plane component of the \( \vec{k} \) and \(|\vec{k}| = \sqrt{k_{\parallel}^2 + k_{\perp}^2} \), with \( k_{\perp} \) being a wave vector component normal to the \( xy \) plane of the PhC slab. Or, for the more general case with a cladding material having a refractive index of \( n_1 \)

\[
\omega = k_{\parallel} \frac{c}{n_1},
\]  

(3.2)

The equation 3.2 is a so called light line, which bounds a continuum spectrum of states for all frequencies above it. The region of the band structure with \( \omega > k_{\parallel}/c \) is called a light cone (Fig. 3.3). The modes inside this cone are solutions of Snell’s law for the angles of incidence less than the critical value (meaning there is no total internal reflection). The mode solutions that lie outside the cone have lower frequencies in respect to the values the corresponding modes would have in air. Below the light line the fields that decay exponentially has an imaginary \( k_{\perp} = \pm i\sqrt{k_{\parallel}^2 - (\omega/c)^2} \) (so called index-guided modes). In other words, for the same value of \( \omega \) the wave-vector \( k_{\text{conf}} \) of the confined mode is bigger than \( k_{\text{rad}} \) of the mode that slips out from the waveguide (here \( k_{\text{conf}} \) is a wave-vector of the mode that is confined in the \( z \)-direction by total internal reflection and \( k_{\text{rad}} \) is a wave-vector of the mode that doesn’t satisfy total internal reflection conditions).

These conclusions are also valid for the case of \( n_1 > 1 \). The only difference is
the normal component of the wave-vector becomes \( k_\perp = \pm i \sqrt{k_\parallel^2 - (\omega n_1/c)^2} \) and consequently, the slope of the light line decreases, increasing the “volume” of the light cone. The slope decrease is due to the refractive index contrast decrease, leading to a decrease in the quantity of guided modes.

The number of the modes that may be accommodated through total internal reflection is limited and as a consequence energy leaks out of the cavity due to vertical radiation. In reality, the vertical energy decay is not negligible and has to be considered for the calculation of the total quality factor \( Q \) of the cavity

\[
\frac{1}{Q} = \frac{1}{Q_\parallel} + \frac{1}{Q_\perp},
\]

where \( Q_\parallel \) and \( Q_\perp \) are the quality factors of in-plane and out-of-plane power decay respectively.

There are a number of factors contributing towards limiting \( Q \). Some of them are difficult to avoid, such as intrinsic material absorption, etch-induced surface roughness and surface-state absorption and other fabrication irregularities. Despite these deviations from the ideal model, there is still the possibility to improve vertical mode confinement conditions through design.
In order to comprehend the problem and a path towards its solution, let’s consider the simple system of a Fabry-Perot cavity of length \( L \) and refractive index \( n_{\text{medium}} \), surrounded by a medium with refractive index \( n_2 \). The cavity is formed by perfect mirrors from both sides, confining light along the \( x \) axis. For simplicity, the system is homogeneous in \( y \) direction and in the \( z \) axis total internal reflection (TIR) confines the light (Fig. 3.4b).

By decomposition of the electric field inside the cavity into a set of plane wave components with respective \( \vec{k} \) by spatial Fourier transform, it is possible to analyse the strength of the vertical confinement in the \( z \)-direction. If the value for the projection of \( \vec{k} \) on the \( x \)-axis for each plane wave is less than \( n_2 \omega/c \), i.e. it lies inside the light cone, then according to Snell’s law the wave can escape from the cavity to the surrounding medium. Otherwise the condition for strong vertical confinement will be satisfied (Fig. 3.4a). Figure 3.4d shows the spatial Fourier transform (FT) spectrum of the electric field of Fig. 3.4b with leaky region \((k_{||} < n_2 \omega/c)\) indicated by the grey rectangle. The amount of field localised in this region is a considerable portion of the total stored energy and represents radiation loss from the cavity.

Theoretically, it is convenient to idealise a plane wave as infinite in real space, because the FT spectrum of such a “perfect” wave is a pair of Dirac delta function at \( \pm f \) spatial frequencies. If the wave is of finite nature then the spatial frequency spectrum is determined as a convolution of the separate Fourier spectra at \(-f\) and \(+f\). In the case of a laser cavity the electric field profile can be expressed as a product of an envelope function \( \chi(x) \) determined by cavity geometry and a fundamental sinusoidal wave with wavelength \( \lambda \). The corresponding frequency values of the delta function acquired by FT of the fundamental wave equal to \( k = \pm 2\pi/\lambda \), while the FT of \( \chi(x) \) modifies the shape of the spectrum. In the case of Fig. 3.4b, where \( \chi(x) = 1 \) for \( x \in [-L/2, L/2] \) and \( \chi(x) = 0 \) for all other values of \( x \), the corresponding FT spectrum is a sinc function. Despite the fact that the peak values of the FT spectrum are outside the leaky region, an abrupt change of the envelope function at the points \(-L/2\) and \( L/2 \) results in
localisation of significant components inside the leaky region or light cone (Fig. 3.4d).

Figure 3.4: a) Schematic representation of the light confinement in the $z$-axis realized by total internal reflection. b) Schematic representation of the electric field (blue) distribution in a cavity with a rectangular envelope function (red dashed line). c) Schematic representation of the electric field distribution in a cavity with a Gaussian envelope function (dashed red line), $n_1 > n_2$. d) Spatial Fourier transform of the field in b). e) Spatial Fourier transform of the field in c). The gray rectangle in d) and e) indicates a leaky region inside the light cone.

The apparent conclusion could be made from the above, it is necessary to soften the abruptness of the borders of the cavity in $x$ direction. Ideally, an envelope function $\chi(x)$ should be a Gaussian function due to the fact that the FT of the Gauss distribution is Gaussian as well. In other words, the refractive index of the laser cavity should be modulated according to Gauss distribution in order to
reduce the portion of the electric field that accommodated within leaky region. On Fig. 3.4e an obvious reduction of the fraction of the mode inside the light cone (leaky region) can be seen.

Figure 3.5: (a) Double heterostructure cavity formed by the integration of a PhC structure with lattice constant $a_2$ into one with $a_1$ and its schematic band diagram [89]. (b) Width-modulated line-defect PhC cavity. “Red” holes sustain the biggest shift while the distance for the “blue” ones is smallest (reproduced from [90]). (c) Dispersion adapted (DA) cavity with confined first order mode. Green circles indicate the holes that have been shifted (reproduced from [91]).

The first simulated results utilising this concept were shown by Srinivasan et al [92]. The calculations predicted values of total $Q \sim 10^5$ with a mode volume of 0.25 cubic half-wavelengths inside the defect cavity of a graded square lattice. The first practical realisation of “gentle confinement”, were shown by Akahane et al [93]. The Gaussian-like shape of the mode was achieved by the physical shift of the air holes at the boundaries in an L3 photonic crystal cavity and a $Q$ as high as 45000 was shown. Later on, a number of 2D PhC cavity designs have been demonstrated utilizing the same principle: width-modulated line-defect PhC cavities [37], double
heterostructure nanocavity [89] and dispersion-adapted (DA) cavity [91]. Fig. 3.5 illustrates these types of PhC cavities.

3.4 Real Si 2D Photonic Crystal Cavity Reflector

Following the above brief insights into the theoretical background of the resonant 2D PhC cavities concept, an experimental study of the named structures in conjunction with III-V gain material was carried out. The whole characterisation process could be roughly divided into three stages: (1) standalone characterisation of the PhC reflector chip in order to measure the corresponding transmission and reflection spectra; (b) construction of a short cavity laser, similar to that described in the Chapter 2; (c) a characterisation of the frequency modulated short cavity laser. In this chapter we will discuss stage (a) and (b) with discussion of the (c) in the following chapter.

3.4.1 Materials and Methods

The silicon-based reflector chip consisted of a low refractive index waveguide vertically coupled to an oxide clad Photonic Crystal (PhC) cavity. The Dispersion Adapted (DA) PhC cavity design was chosen here specifically due to its suitability for mass manufacture via Deep Ultra-Violet photolithography [94]. The Photonic Crystal cavity was fabricated (Fig. 3.6a) on a standard 220 nm SOI platform by electron-beam lithography and Reactive Ion Etching (RIE), similar to [95]. Accuglass-T by Honeywell was used for the oxide upper cladding. SU-8 polymer (n \approx 1.58\text{ at } 1550\text{ nm}) was selected for the waveguide, but the possibility of employing other low-index materials has been demonstrated [95]. The width and height of the waveguide were \approx 3.1\text{µm} and \approx 2.1\text{µm}, respectively, and its facets were normal to the SOI chip surface and AR-coated with a single MgF\text{2} layer for normal incidence. Both the SU-8 and RSOA waveguides were single-moded in all regions. Sample design and the fabrication of 2D PhC cavities samples were carried out by A. A. Liles from the nanophotonic group from the University of St. Andrews, UK. All the detailed design and fabrication considerations can be found in Ref. [96, 97].
Here we will treat the external reflector as a closed system with a certain response.

Figure 3.6: (a) An example of the fabricated PhC structure. (b) Typical reflection and transmission spectra of the DA PhC cavity reflectors at 20°C used in this work. (c) Measured PhC resonance peak position versus temperature set by a Peltier element. Measured thermal sensitivity $d\lambda/dT$ is 61 pm/°C.

For sample characterisation, a similar set-up (Fig. 2.9) to that described in section 2.3 was used. A typical transmission and reflection spectrum is shown in Fig. 3.6b, where several resonances can be seen. The distance between resonances was equal to the FSR of the PhC cavity and was typically 7 - 8 nm, which was in good agreement with simulation results. A strong modulation of the reflection spectrum by Fabry-Perot (FP) modes, from the cavity formed by the input facet of the SU-8 waveguide and the PhC reflector can be seen here, greatly disturbing the designed response. A double layered AR coating optimized for the resonance wavelength should smooth spectral response of the PhC.

By sweeping the temperature of the sample holder aluminium mount from 20°C up to 100°C in 10°C steps, a value of the thermal sensitivity $d\lambda/dT$ equal to 61 pm/°C
has been measured (Fig. 3.6c), which is quite close to the 73 pm/°C reported in [98]. In [98] Si PhC L3 cavity was formed by air holes with air filled undercut. Therefore, in comparison with our case, where PhC structure was resting on SiO$_2$ and holes were filled with flowable oxide (FOx), a Si PhC covered by air is expected to show higher temperature response due to its higher thermal insulation contrary to FOx. Apart slightly different value of $d\lambda/dT$, studied Si PhC reflector resonance demonstrated expected linear response which is in good agreement with previously reported results [98, 99]. And finally, contributing to the higher TOC of Si, thermal sensitivity of Si PhC is 5 times greater than the one measured for the Si$_3$N$_4$ Bragg grating from the previous chapter.

A conceptual representation of the considered laser architecture is shown in Fig. 3.7. The laser cavity is formed by butt-coupling the RSOA waveguide to one end of the SU-8 waveguide on the reflector chip, as shown in Fig. 3.7a. The low refractive index of the waveguide combined with its large cross section enables better matching with the mode of the RSOA, resulting in low butt-coupling losses (<1.5 dB) and improving the tolerance to misalignment between the two parts. As the fiber-coupled power of the compact PhC laser was mW level, it was decided to use the self-heterodyne measuring technique (Fig. 3.8) instead of heterodyne beating the laser under test with a narrow linewidth tunable laser source. CW laser characterization was carried out as has been done for the short cavity hybrid Si$_3$N$_4$ Bragg grating laser.

### 3.4.2 Results and Discussions

During operation, the light generated in the RSOA was coupled to the SU-8 polymer waveguide (Fig. 3.9). At the resonant wavelength (red arrows) of the PhC cavity, light coupled evanescently from the waveguide mode to the PhC cavity mode. Once power was built up inside the PhC cavity, light coupled back to the waveguide in two different directions: forwards to the output facet of the waveguide and backwards, to the RSOA. The backward propagating light component acted as a wavelength-selective feedback, with a linewidth on the order of 0.01 nm to
Figure 3.7: The hybrid PhC laser configuration comprising a RSOA and a Si PhC based resonant mirror. A schematic representation of the device is given in (a) and a microscope view is shown in (b). The employed reflector consisted of a low index dielectric waveguide located vertically over a PhC cavity on silicon-on-insulator (SOI), the two separated by a thin buffer layer of oxide allowing their evanescent coupling [95]. The laser cavity was formed by butt-coupling the RSOA to the waveguide on the silicon chip, which acted as a narrowband reflector at the resonant wavelengths of the PhC cavity, as described in [100]. Filter reflection spectrum (black curve) and laser spectrum (red curve) superimposed in (c).

0.1 nm (depending on the coupling conditions selected), resulting in the formation of a laser cavity between the reflective facet of the RSOA and the PhC cavity (Figs. 3.7a, 3.7b). The emitted wavelength was determined by the longitudinal mode of the laser cavity that was lying within the PhC cavity reflection band (Fig.3.7c).

In general, due to their large quality-factor modal volume (Q/V) ratio, PhC cavities can achieve extraordinarily high stored energy densities in small volumes. As a consequence, in the case of silicon PhC cavities, nonlinear phenomena can
Figure 3.8: Self-heterodyne linewidth measurement set-up. The output light collected by the lensed fiber, passes through a 1550 nm fiber coupled optical isolator, then split by 50/50 coupler. One arm is sent to acousto-optic modulator (AOM) driven at constant frequency of 55 MHz, the other one through a 10 km fiber delay to achieve incoherence with respect to the AOM branch. The two uncorrelated parts were combined with a 90/10 coupler with 90% directed to the electrical spectrum analyser (ESA) and 10% to the optical spectrum analyser (OSA). The polarisation matching condition was achieved by a manual polarisation controller.

be observed even at low (of the order of µW) input powers [101]. In particular, two photon absorption (TPA) scales with the square of the energy stored in a silicon cavity [102, 103]. Every pair of TPA-absorbed photons gives rise to an electron-hole pair that may result in the absorption of further photons via the free carrier absorption (FCA) mechanism.

Thus, in the examined situation, the power decay rate of the silicon PhC cavity on the reflector chip (defined as \( \Gamma = \omega_0/2Q \), with \( \omega_0 \) being the resonant frequency and \( Q \) the quality factor of the cavity), consisted of four components: decay due to radiation and scattering losses (described by \( \Gamma_{rad} \)), total energy decay rate from the PhC cavity to the waveguide (\( \Gamma_{coup} \)), decay due to two photon absorption (\( \Gamma_{TPA} \)), and decay due to free carrier absorption (\( \Gamma_{FCA} \)), which was proportional to the free carrier density in the volume of the optical mode and can be expressed as

\[
\Gamma = \Gamma_{rad} + \Gamma_{coup} + \Gamma_{TPA} + \Gamma_{FCA} \quad (3.4)
\]

or in terms of corresponding quality factors

\[
\frac{1}{Q} = \frac{1}{Q_{rad}} + \frac{1}{Q_{coup}} + \frac{1}{Q_{TPA}} + \frac{1}{Q_{FCA}}, \quad (3.5)
\]
Figure 3.9: Schematic representation of a short cavity laser with a coupled PhC cavity + waveguide system as a resonant mirror. The major fraction of light generated by the RSOA passes through the SU-8 waveguide unaffected (black arrow). The red line depicts lasing at the PhC resonant wavelength. \( R_1 \) - high reflection coating of RSOA, \( R_2 \) - integral reflection from PhC - waveguide block.

where \( Q \) - quality factor of the PhC cavity, \( Q_{rad} \) - decay due radiation losses, \( Q_{coup} \) - total energy decay rate from the PhC cavity to the waveguide which depends on coupling between them, \( Q_{TPA} \) - decay due two photon absorption, \( Q_{FCA} \) - decay due free carrier absorption. Based on the above discussion, the absorbed optical power in the modal volume of a PhC cavity was given by

\[
p = h\nu (\Gamma_{TPA} + \Gamma_{FCA}).
\]  

(3.6)

If we define \( \frac{1}{Q_{rad}} + \frac{1}{Q_{TPA}} + \frac{1}{Q_{FCA}} \) as \( \frac{1}{Q_0} \), the equation 3.5 could be rewritten in a more common form as

\[
\frac{1}{Q} = \frac{1}{Q_0} + \frac{1}{Q_{coup}},
\]  

(3.7)

where \( Q_0 \) is an intrinsic quality factor of the PhC.

The recombination of the generated free carriers ultimately resulted in heat dissipation in the PhC cavity. The region in which heat was generated matches very closely the spatial distribution of the optical mode (with carrier diffusion and thermal diffusion slightly enlarging that region), automatically constituting one of
the most efficient localized heating mechanisms possible.

As the PhC cavity temperature set the resonant wavelength, and hence the emitted wavelength in the studied laser architecture, the tuning of the wavelength through the laser output power could be realised, a technique that we have named Power Tuning. More specifically, wavelength stability can be realised by balancing the variation in the ambient temperature with changes in the PhC cavity heating due to carrier recombination. If, as higher operating temperatures are experienced, the laser power is appropriately decreased, the two effects can be made to cancel each other, giving a zero net shift of the emitted wavelength. For a fixed laser output power, the ratio between the absorptive decay rates and the total decay rate determines the amount of power dissipated as heat in the cavity. \( \Gamma_{\text{coup}} \) can be controlled by the separation between the waveguide and the PhC cavity, whereas the other terms are fundamental or technological constants. In this initial experiment, \( \Gamma_{\text{coup}} \) was chosen so that the dissipated power is of the order of a few milliwatts.

Figure 3.10: (a) Laser waveguide coupled output power vs injected electrical power. (b) Wall-plug efficiency (WPE) as a function of injected current. All measurements were taken at room temperature.

Following the process described in the Materials and Methods section, the CW characteristics of multiple lasers were measured at room temperature, without active cooling, for driving currents up to 100 mA. Single longitudinal mode lasing was achieved by aligning a longitudinal mode of the laser cavity with the reflector
band. Typical laser threshold currents were in the 10 mA to 20 mA range and close to the 9.4 mA for flip-chip bonded laser reported in [57] and 13-15 mA in [58]. Output powers of several mW were measured in every case, with a maximum waveguide-coupled wall-plug efficiency of 8% at 45 mA (Fig. 3.10b), which is comparable to 7.6% 70 mA reported in [57] and 9.6% 52mA in [58]. Fig. 3.11 shows data from an indicative device. The measured side-mode suppression ratio (SMSR) was in excess of 40 dB over the full current range considered, with a maximum value of 50 dB. The single mode laser linewidth above threshold was determined to be 4.5 MHz, by a delayed self-heterodyne linewidth measurement (Fig. 3.11d). Fig. 3.11a shows the LI curve for the laser under consideration, which exhibited a series of kinks (also present in [58]), attributed to mode-hoping. It should be noted that mode-hopping occurred as sharp transitions between adjacent longitudinal modes of the laser cavity, and is not to be associated with transitions between different modes of the PhC cavity, the FSR of which (8 nm [91, 95]) is much larger than the observed hops. This problem could be solved by incorporating of a narrow-band filter, such as ring resonator, into laser cavity. Such approach was used by Tanaka et al. [57] and provided SM lasing for the whole range of pumping currents within 20°C - 60°C temperature range.

As the driving current was swept from threshold to 80 mA (without active cooling), the resonant wavelength of the PhC reflective filter was nonlinearly red-shifted due to absorptive heating by \( \sim 3 \) nm, which corresponded to multiple longitudinal mode spacings of the laser cavity. Such phenomena is not typical to the Si grating reflectors, where shit was around 0.3 nm in [58]. The transitions between different longitudinal modes can also be seen in the time averaged optical spectra (Fig. 3.11c) of the device under test. At transition, the coexistence of two modes with weak sidebands was observed, which we attribute to the averaging of the temporally unstable longitudinal modes. A comparison of the lasing wavelength stability versus corresponding power output for DFB and PhC hybrid lasers shown in Fig. 3.11e.

In order to explore new features of the hybrid laser through Power Tuning, a comparison of its wavelength response to changes in ambient temperature with that of a Distributed Feedback (DFB) laser, the most commonly employed light source
Figure 3.11: (a) LI-curve without temperature stabilisation and (b) Single mode (SM) lasing at 80 mA for 20 - 80°C temperature range, without Power Tuning. (c) False colour plot of the time averaged optical spectrum as a function of upswept drive current, with the x-axis matched to that of (a). From the change in the lasing wavelength an increase of PhC temperature by 15°C can be deduced. (d) Delayed self-heterodyne measurement of the laser linewidth in a single mode region. The central frequency of the Acousto-Optic Modulator (AOM) was 55 MHz, the measured linewidth $\Delta \nu = 4.5$ MHz. (e) Emitted wavelength as a function of the fiber-coupled output power for DFB (black) and compact PhC hybrid lasers measured at 20°C.

In applications that require a high spectral purity, was made. For this comparison, the temperature of both the RSOA and the silicon chips were reduced from 80°C to 20°C in steps of 10°C via Peltier elements. As the temperature of the substrates
was decreased, the blue-shift of the reflection peak was compensated by an increase in the drive current, which led to an increase of the absorptive heating in the PhC cavity. In this way, a variation of only ±0.38 nm around the central lasing wavelength (\(\lambda_0 = 1550.85\) nm) was achieved over the entire considered temperature range (green rhombi on Fig. 3.12a). In order to acquire optical spectra at each temperature a realignment was required (a 10°C change is enough to significantly change the linear sizes of the Al mounts to ruin the coupling between the active and the passive components of the device). Thus, a different longitudinal mode of the laser was probably lasing at each temperature, giving a residual variation. As a reference, the change in the wavelength of a JDS Uniphase CFQ935 DFB laser as a function of its substrate temperature was examined. A shift of ~6 nm was measured for the same 60°C variation, more than an order of magnitude larger than in the Power Tuned PhC laser. The wavelength change in the DFB laser was a result of the effect of temperature on the grating, which determines the lasing frequency through the Bragg condition, and is related to the temperature sensitivity of the grating material. The comparative results are summarized in Fig. 3.12.

For the further understanding of the Power Tuning mechanism in the PhC laser configuration, the temperature of the PhC as a function of dissipated optical power was modelled, and is shown in red in Fig. 3.12b. For conditions corresponding to those in the experiments reported here, simulations predicted a temperature rise of 10°C per milliwatt of dissipated power. Indicatively, Fig. 3.12c presents the thermal profile of a DA PhC cavity on SOI for 2 mW of power dissipated in it. As explained previously, the absorptive heat is generated in the 0.495 \(\mu\)m\(^3\) volume of the mode of the PhC cavity, very effectively raising the temperature of the resonator. This heating mechanism is more than twice as efficient as a conventional metal micro-heater [104], which has to be located at some distance (>1\(\mu\)m) from the optical mode to avoid optical absorption losses. Such a high heating efficiency enables strong variation of the PhC cavity temperature as a function of coupled power, and by extension of the intra-cavity power of the laser. In these experiments, the stability of the emitted wavelength over a 60°C span of substrate temperature (from 20°C to 80°C) was achieved by a change of the output power by 2.3 mW, corresponding to an approximately 6.5 mW change in the power dissipated in the
PhC cavity. This variation in the laser output as the temperature changes, implies a requirement for a receiver to handle a variation in the average power level.

The Power Tuning technique is a result of the non-linear absorption in silicon, combined with the exceptionally high power density in the wavelength-selective element of the laser cavity. Offering the ultimate Q/V ratio, silicon PhC cavities can exhibit a Power Tuning performance superior to that of other systems. For example, ohmic heating can result in changes in the lasing wavelength of a DFB laser, as the drive current is varied. However, as the energy densities in the Bragg gratings are much lower than in PhC cavities, the emitted wavelength dependence of such a laser on output power is much weaker (and typically linear), implying that
an impractically large charge in drive current would be required to achieve stability via Power Tuning over the considered 20-80°C range. Indicatively, an increase in pump current from 50 mA to 200 mA had to be used in the above CFQ935 DFB laser to compensate for a substrate temperature change of only 10°C. Another interesting scheme for silicon-compatible single mode lasing sources are the recently demonstrated hybrid III-V/silicon ring resonator lasers [57]. Ring resonators can provide significant field enhancement and, similar to Photonic Crystal cavities, nonlinear optical transmission and bistability have been reported in these devices [105]. Nonetheless, the mode volume of a typical ring resonator is ten times larger than that of a PhC cavity (\(\sim 5.6 \mu m^3\) for a ring resonator with a 10\(\mu m\) radius, following [106] as compared to \(\sim 0.495 \mu m^3\) of the PhC cavity used here) and thus the relative field enhancement is much smaller. As two-photon absorption is proportional to the square of the light intensity, for the same Q-factor and input power the TPA rate in such a ring resonator will be a factor of one hundred less than in the PhC. Coupled with the larger heat capacity, the dependence of the output wavelength on power for a ring resonator hybrid laser will be very weak, and the potential for Power Tuning insignificant.

To further reduce the requirement on the dissipated power and the output power variation for the realisation of Power Tuning in the hybrid PhC laser architecture, a situation could be considered in which the silicon substrate has been removed from underneath the PhC cavity by, for example, xenon difluoride (XeF\(_2\)) etching [106]. The red curve in Fig. 3.12b shows the simulated temperature variation as a function of power dissipated in the cavity in this case. As the thermal isolation is now higher, the heating of the PhC cavity is even more efficient, giving a change of 33°C/mW, as compared to the 10°C/mW change in the case of a reflector with a silicon substrate. In this new scenario, the coupling between the waveguide and the PhC cavity (\(\Gamma_{\text{coup}}\)) must be re-optimised to reflect this increased sensitivity. As a result, the heating power range required for Power Tuning over the same substrate temperature span (80°C to 20°C) can be reduced to \(\sim 2\) mW and the slope efficiency of the laser improved by virtue of the lower reflectivity of the PhC reflector in this case.
Such hybrid lasers are compatible with mass production techniques. While the hybrid integration vision of [107] is preferred, the wavelength stabilisation technique presented is equally applicable to other integration schemes, for example the heterogeneous integration approach of [60, 71]. The technique simply requires a high Q/V optical resonator (e.g. a PhC cavity), which can be well realised in those technologies. Chip bonding [70] and transfer printing [108] are particularly appropriate to realise the hybrid PhC polymer RSOA. The simulated mode area of the polymer waveguide is 4.5\(\mu\)m\(^2\), a close match to the 4.6\(\mu\)m\(^2\) mode area of the RSOA used here, with slight differences in the shape. Such mode areas give a good tolerance to misalignments with a reduction of coupling efficiency of 15% predicted for a 500 nm misalignment and a 5 mA increase in threshold current experimentally measured. Through the use of deposited solder and vertical alignment features, precise, sub-micron, vertical alignment has been demonstrated [109]. After thorough calibration, state-of-the-art flip-chip bonding and transfer printing can achieve similar placement accuracies in terms of lateral alignment e.g. 3\(\sigma\) of 1.5\(\mu\)m reported with transfer printing [110].

3.5 Conclusion

To conclude, a novel hybrid Photonic Crystal laser for dense WDM links in data centre applications has been demonstrated. This configuration leads to very high stored energy densities, unprecedented in a PhC cavity, making the lasing wavelength a sensitive function of the laser power, through the mechanism of silicon non-linear absorption. A lasing wavelength stability of \(\pm 0.38\) nm was achieved over the full temperature range 20-80\(^\circ\)C range. In the future silicon chips could be platforms comprising arrays of PhC cavities with densely spaced wavelengths coupled to an array of standardized RSOAs, giving a dense grid of transmitters. This geometry would efficiently utilise available space, on the order of 100\(\mu\)m x 500\(\mu\)m for both silicon and III-V chips, with a demonstrated output power in the milliwatt range. This mechanism to balance ambient temperature changes with controlled absorptive heating in the PhC, thereby providing a route to high capacity interconnects in the datacentre by means of cooler-less dense WDM has
been exploited. The presented laser platform also has applications in optical sensing and in nonlinear optics.

The hybrid laser configuration allows the independent optimization, fabrication and pre-testing of the active and the passive regions, while making cost-effective use of III-V materials [111]. This alleviates problems commonly met in wafer-bonded or heterogeneously integrated lasers, which arise from the difficulties in simultaneously achieving evanescent coupling, good thermal conductivity and high gain. Both the silicon and gain chips can be tested and screened prior to assembly, improving yields.

The PhC laser is compatible with low loss waveguiding platforms, such as siloxane polymers [112] and silicon nitride [100], making the devices suitable for integration with active and passive components previously demonstrated in the vertically coupled PhC platform [14, 95, 113] for the realization of more complex, power-efficient Si photonic systems.
Chapter 4

Thermally induced frequency modulation

4.1 Introduction

Frequency modulated (FM) lasers play a key role in various applications such as biomedical imaging [114], wide-band communications technology [115, 116], radar and sensing [117]. There are several realisations of FM semiconductor lasers that have been reported with widely used monolithic solutions such as Distributed Bragg Reflector Super Structure Gratings (DBR-SSG) [115, 118, 119] and Distributed Feedback (DFB) lasers which employ direct modulation of the laser injection current that modulates the laser intensity and frequency simultaneously. A wide tuning range (\(\sim 5\) nm) with DFB lasers has been demonstrated for gas sensing [120] utilising a concept of FM laser with wavelength scanning absorption. While offering the convenience of a monolithic source with a remarkable range of emitting wavelengths, these devices also require a certain degree of fabrication complexity and demonstrate high power consumption during operation. With direct modulation, the simultaneous intensity modulation (IM) combined with the FM affects the sensitivity of the measurements and this is an undesired feature of these devices. Numerous methods have been established to tackle this problem such as extracting the frequency scan information using second harmonic detection and subtraction techniques [121, 122]. In the optical communications field the Chirp Managed Laser (CML) used FM to IM conversion to exploit the effect of
frequency chirp in Directly Modulated Lasers (DML) and used this for extended transmission distance. A pure FM laser is also effective and in [115] we see an extended transmission reach (∼ 10 GHz) with a FM laser while maintaining constant output power with a SSG-DBR multi-section laser.

In this chapter, we describe a compact FM hybrid external PhC reflector laser, with an architecture very similar to that described in Chapter 3 (Fig. 4.1a). The main difference lies in the ability to tune the reflection phase of the external reflector via changes of the refractive index of the Si PhC cavity. The modulation of the index could be realised by two mechanisms: either by plasma dispersion modulation induced by carrier depletion through a pn diode formed in the PhC cavity region; or by thermal effects emanating from carrier injection and Joule heating.

The frequency modulation in this chapter was realised by the application of a periodic signal from a function generator either to a pn diode or to a NiCr microheater. The RSOA was always driven by constant current, which potentially leads to a reduced modulation power consumption in comparison to conventional lasers. The main reason for that is the significant (∼ 10^2 - 10^3 times) reduction of the laser volume where we apply the periodic signal. The volume of the intrinsic region of PhC cavity is as small as 2.2 µm^3, enabling fJ/bit switching energies [14], the requirement that was highlighted earlier in Introduction section.

### 4.2 Frequency Modulated PhC Laser Concept

As discussed in Chapter 2, the emitted wavelength of the PhC EC laser is set by the overlap of the longitudinal mode of the laser cavity, the reflection band of the PhC resonant reflector and a local maximum of the gain ripple, originating from FP modes of the RSOA due to limitations in AR coatings. There are several reports [123–125] of experimentally measured phase change over the reflection band for photonic crystals. In general, the value of the phase change across the stop-band ∆φ approaches π. Following the same principle of realising frequency modulation (FM), which was evaluated by Mork et al [126] in their
Figure 4.1: (a) Schematic representation of the compact external cavity FM laser configuration. The laser cavity is formed by butt-coupling a III-V-based RSOA to an external reflector chip, comprising a waveguide vertically coupled to a Silicon PhC cavity embedded in a pn junction, that provides tuneable wavelength-selective optical feedback. (b) 3D representation of the chosen external resonant reflector. A waveguide is vertically coupled to a PhC cavity with a pn junction extending in its defect. The blue and red regions represent the p- and n-doped regions of the pn junction. (c) A cross section of (b) with Al - aluminum contacts for voltage application and FOx - layer of flowable oxide.

Simulation of the FM photonic crystal Fano laser, a model of a frequency modulated photonic crystal laser was developed with it’s subsequent experimental confirmation.

Assuming a Lorentzian shape for PhC reflector (Fig. 4.2), in the vicinity of a central frequency corresponding to the maximum reflectance, the reflection phase is given by:

\[ \varphi_r = \arctan \left( \frac{2\pi \nu}{\Gamma} \right) \approx \frac{2\pi \nu}{\Gamma}, \quad (4.1) \]

where \( \Gamma \) is the reflection band width in radians, \( \nu \) is the optical frequency and the linear approximation is valid, close to the center of the filter. The propagation phase \( \varphi_{prop} \) increases linearly with increasing optical frequency as given by \( 2\pi \nu T \), where
Figure 4.2: A schematic illustration of the frequency modulation mechanism realised in FM PhC laser. Solid curves represent an initial solution for the reflection peak (blue), reflection phase $\varphi_r$ (red) and total accumulated phase $\varphi_{tot}$. The dashed curves depict each parameter for a shifted reflection peak position by $\Delta F$. Orange arrows indicate lasing frequency for the same $m$-th laser cavity mode showing a shift by $\Delta \nu$ for the shifted solution, where $\Delta \nu < \Delta F$. Pink points 1 and 2 illustrate that the total accumulated phase doesn’t change with lasing frequency being tuned.

T is the cavity roundtrip time. Therefore,

$$\varphi_{prop} = \frac{2\pi \nu}{FSR},$$

(4.2)

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:

$$\varphi_{prop} + \varphi_r = 2\pi m,$$

(4.3)

where $m$ is an integer. Figure 4.2 schematically demonstrates how the central
frequency value influences the lasing wavelength. The solution exists at the intersection of a laser cavity mode and the total accumulated phase, that lies within the reflection band. By tuning the reflection band by $\Delta F$, the phase at every frequency near the reflection band center will change by

$$\Delta \varphi = -\Delta F \frac{2\pi}{\Gamma}.$$  \hfill (4.4)

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

$$-\Delta F \frac{2\pi}{\Gamma} + \Delta \nu \frac{2\pi}{\Gamma} + \Delta \nu \frac{2\pi}{FSR} = 0.$$  \hfill (4.5)

From 4.5 for $\Gamma < FSR$ we can write an expression for the modal frequency shift $\Delta \nu$, which is required to retain the phase matching condition:

$$\Delta \nu = \Delta F \left[ \frac{1}{1 + \frac{\Gamma}{FSR}} \right].$$  \hfill (4.6)

This linear approximation shows that the lasing frequency shift $\Delta \nu$ is less than the reflector shift $\Delta F$ 4.2, and with a larger FSR to filter width ratio, the laser mode frequency follows the filter center frequency more closely.

### 4.3 Experimental Set-up and Design Considerations

For the proof-of-concept FM PhC laser experimental realisation, three different external reflector designs were tested. Each configuration utilised reflection peak red-shift through heat localisation in the small volume of the PhC cavity. The differences lay in the mechanism of the heat generation (pn diode and NiCr microheater) and in the material utilised for the waveguide of each sample. The first sample was tuned by carrier injection, and the waveguide medium is a low-refractive-index $\text{Si}_3\text{N}_4$ (Sample 1). A low-refractive-index SU-8 polymer was used for the vertically coupled waveguide to the PhC cavity with the reflection phase being tuned in second case with carrier injection (Sample 2), in third case with a NiCr heater (Sample 3). The main parameters of these reflectors are
presented in Table 4.1.

<table>
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<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
</tr>
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<td>SU-8</td>
</tr>
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<td>angled</td>
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<td>3.1 x 2.1</td>
<td>3.1 x 2.1</td>
</tr>
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<td>pn</td>
<td>NiCr</td>
</tr>
<tr>
<td>RSOA length (µm)</td>
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<td>250</td>
<td>400</td>
</tr>
</tbody>
</table>

Table 4.1: General parameters of the tested reflector samples.

Each case will be described in more detail below.

4.3.1 Sample 1: Thermal PhC - Si$_3$N$_4$ Reflection Phase Tuning via Carrier Injection

Considering CWDM as a target application for the FM hybrid III-V - Si laser the mechanism for frequency modulation should be able to deliver $\sim$ 10 Gb/s modulation speed. The most obvious solution to satisfy this condition is a direct frequency modulation through carrier depletion induced by reverse bias. However, due to the high resistance of the pn diodes in the fabricated samples a forward bias has been used instead. Therefore, PhC cavity reflection phase tuning was induced by the heat locally generated by the pn junction. A number of Si PhC samples were fabricated and tested in conjunction with standard 250µm long InP-based reflective semiconductor optical amplifiers (RSOA)(Fig. 4.1a). The reflector sample comprises a low-refractive-index polymer SU-8 or Si$_3$N$_4$ waveguide vertically coupled to Si PhC dispersion adapted (DA) [91] PhC cavity through thin oxide layer, enabling the evanescent exchange of light between the PhC mode and the laser cavity mode.

Fabrication and Characterisation

To create the pn junction, four different levels of doping were implanted and annealed. The low doped p and n regions are designed to overlap with the DA
cavity to achieve maximum electro-optic efficiency and were created using the ion implantation of boron and phosphorous ions to realise the targeted doping concentration of $10^{16}$ cm$^{-3}$. The heavy doped p+ and n+ regions were designed to be 2 µm away from the center of the cavity.

On the next step, Si$_3$N$_4$ waveguides were formed on top of the DA PhC nanocavities. The width and height of these waveguides were 1 µm and 0.5 µm respectively, providing the best mode matching between the RSOA and the resonant reflector structure.

After the fabrication stage had been completed the diodes of the resonant mirrors were characterized by sweeping the forward bias voltage through the pn junction. An up-sweep voltage up to 8 V was applied and indicative IV curves can be seen on Fig. (4.3).

Finally, optical characterization was carried out comprising reflection and transmission spectra collection, and power transmittance level measurement i.e. the waveguides optical quality was influenced not only by the selected material, but also by small unavoidable defects such as scattering centers inside the SU8 waveguide. The output power was collected through lensed fiber and coupled to a 3 x 3 coupler enabling simultaneous power monitoring through a power meter (PM), optical spectra with an optical spectrum analyzer (OSA) and the heterodyne beating signal with a fast digital oscilloscope (OSC) through a fast photo receiver with 35 GHz bandwidth. The main reason behind employment of the narrow-linewidth tunable

Figure 4.3: A $VI$ curve of the pn juction measured in forward bias.
Figure 4.4: A schematic of the experimental setup for FM PhC laser characterization. RSOA was driven by constant current. A periodic signal from the function generator was applied to the PhC reflector pn diode. The red dashed line indicates the whole PhC laser. Output laser power was coupled through a lensed fiber into a 3 x 3 coupler, where it mixed with the polarization matched light from a narrow linewidth (<300 kHz) tuneable laser source to generate a heterodyne beating signal. The time trace of the signal was collected by the fast oscilloscope (OSC) through a 35 GHz fast photoreceiver. The power meter (PM) and optical spectrum analyzer (OSA) were used for alignment purposes.

Laser source (TLS) was necessity to record an evolution of the instantaneous beating frequency relatively to some reference point (initial beating frequency between TLS and device under test (DUT)). In this aspect self-heterodyne technique could not be used as the instantaneous frequency always equals to the driving frequency of the AOM.

Laser Characterisation

The laser comprised a 250 µm (group refractive index $n_{gRSOA} = 3.6$) long RSOA and a Si chip with a Si$_3$N$_4$ (group refractive index $n_{gSi_3N_4} = 1.94$) waveguide 2240 µm long, measured from the input facet up to the PhC cavity. The total laser cavity optical length, calculated as $n_{gRSOA}L_{RSOA} + n_{gSi_3N_4}L_{Si_3N_4}$, was 5246 µm long with FSR = 28.6 GHz. The measured reflector width at FWHM was 0.93 nm or 116 GHz (Fig 4.5a). Clearly, the condition for single mode (SM) operation of the laser, (FSR being greater than the one of the reflector width) is not satisfied. But, as in section 2, there are parasitic Fabry-Perot fringes that modulate the reflection spectrum, thus resulting in several “reflectors” with spacing corresponding to the FSR of the cavity formed by the input facet of the Si$_3$N$_4$ waveguide and the PhC. Therefore,
Figure 4.5: (a) An example of measured PhC transmission resonance, FWHM $\Delta \lambda = 0.93$ nm or 116 GHz. (b) The measured dependency of the transmission peak central frequency shift $\Delta F$ versus applied voltage on the pn diode; the slope value is 400 GHz/V. (c) Single mode lasing spectrum measured at 65 mA pumping current. The measured side mode suppression ratio $> 45$ dB.

the center frequencies of the “reflectors” are separated by 220 pm or 27.5 GHz and that is the mechanism which provides a possibility of SM lasing (Fig. 4.5c) with subsequent mode hop free FM operation (Fig. 4.6).

From Figure 4.5b it is clear that the tunability of the reflector central frequency is 400 GHz/V. This value represents the reflection peak frequency shift and is not related to the parasitic fringes, occurring due to the poor AR coating on the Si$_3$N$_4$ waveguide facets. The value for the fringe “tuning” is much smaller and equal to $\Delta \lambda = 0.2160$ nm/V or 27 GHz/V. This is to be expected, as a change in the PhC reflection phase doesn’t directly influence the $L_{\text{waveguide}}$ (Fig. 4.7e). However, the lasing frequency tuning occurs due to the superposition of the PhC cavity thermal tuning and thermal expansion of the waveguide portion, which is located in close proximity to the PhC cavity region and thus, due to the slight change in the
total length of the laser cavity, a red-shift of the Fabry-Perot (FP) fringe takes place.

To maximise SM operation range the laser cavity should be as short as possible. The main condition is that the laser FSR should be bigger than the FWHM of the PhC reflector. A simple calculation using this reflector suggests the Si$_3$N$_4$ waveguide length should be less than $200\,\mu$m. With the distance from the input facet up to the PhC reflector being $200\,\mu$m the laser FSR is 116.5 GHz. Practically, precise cleaving of the reflector sample could be realised as was suggested in chapter 2, i.e. a crack trench on the bottom part of the Si substrate at the desired distance from the PhC structure.

Figure 4.6 demonstrates a direct frequency modulation of the designed laser at 10 kHz. The PhC laser drive current was kept at 65 mA (single mode operation with SMSR $>45$ dB) and forward DC bias of $V_{DC} = 3.35$ V was used. The amplitude modulation of $I_{pp} = 22.32\,mV$ or 1.85 dB and frequency modulation $\Delta \nu = 4$ GHz was observed. The emission of the laser was collected by lensed fiber and mixed with the uncorrelated light from a narrow linewidth ($> 300$ kHz) tuneable laser source.
Figure 4.7: (a) Schematic representation of the PhC cavity and pn junction. The different doping regions are shown in different colours: p+ in red, n+ in dark blue, p in light red, n in light blue. (b) Sketch of a tuneable FM resonant reflector structure. The doping regions are designed to keep the electrical vias (gold area) and metal electrodes on the same side of the waveguide (in light green). (c) An example of the fabricated PhC structure. (d) Microscope image of needle probes applied to the contact pads on Si PhC reflector sample with vertically coupled with Si$_3$N$_4$. (e) Schematic illustration of the PhC FM laser geometry. $L_{gain} = 250\, \mu\text{m}$, $L_{waveguide} = 2240\, \mu\text{m}$. Total optical length with $n_{g\text{RSOA}} = 3.6$ and $n_{g\text{Si$_3$N$_4$}} = 1.94$ is $5246\, \mu\text{m}$. The red dashed rectangle represents the small region of the cavity affected by Joule heating from the pn region under carrier injection operation in forward bias.
Figure 4.8: (a) Microscope image of the FM PhC laser. Total optical length with $n_{g\text{RSOA}} = 3.6$ and $n_{g\text{SU-8}} = 1.59$, is $1894 \mu m$ and FSR 79 GHz. (b) Single mode lasing spectrum with SMSR > 45 dB and maximum waveguide coupled output power (inset) 3.5 mW. All data was acquired without temperature stabilisation at room temperature.

TLS) resulting in a heterodyne beating signal, detected by a 33 GHz photoreceiver and recorded by a fast digital oscilloscope (Fig. 4.4). A real-time observation of the collected power and optical spectrum was also possible through a 3 x 3 coupler with power meter (PM) and a digital optical spectrum analyzer, respectively.

4.3.2 Sample 2: Thermal PhC - SU-8 Reflection Phase Tuning via Carrier Injection

The Sample 2 was similar to the one described in previous section except the material selected for the waveguide. The general geometry of the sample was the same as used for the thermal stability study described in chapter 3. The only difference was the presence of a pn region formed within the Si PhC cavity and the length of the SU-8 waveguide, measured from the input facet up to the reflecting structure (Fig. 4.8a).

The height and width of the waveguide were $3.1 \mu m$ and $2.1 \mu m$ respectively, 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 $\sim 130 \text{ nm}$ thick layer of flowable oxide (Accuglass by Honeywell) was used as a buffer layer. Both facets of the reflector chip were AR-coated (with a single layer MgF$_2$ coating) to minimize back-reflections.
The same setup and methods were used for experimental data collection and analysis as was presented in Section 4.3.1. The main interesting aspect which is specific for the SU-8 polymer, is a negative refractive index change with temperature increase, i.e. negative thermo-optic coefficient (TOC) $dn_{SU-8}/dT = -1.1 \times 10^{-4} \text{K}^{-1}$ [127]. The wavelength for the mode $m$ is defined as

$$\lambda_m = \frac{2(l_{gain}n_{gain} + n_{wg}l_{wg} + l_{eff}n_{grat})}{m}.$$  (4.7)

It is apparent that $\Delta \lambda_m$ is proportional to the optical length of the laser cavity and in the case of the negative $dn_{wg}/dT$ term the expected lasing wavelength red-shifting smaller. Therefore, with the application of the same amount of heating power, a slightly less amount of frequency shift is expected, compared to the samples with the Si$_3$N$_4$ waveguide. This phenomena takes place due to the influence of the dissipated heat from the pn region on the polymer waveguide fraction just above the PhC structure, resulting in a slight reduction in cavity length. Or, from the other hand, to achieve the same depth of frequency modulation a high thermal, therefore, electrical power, should be applied.

Figures 4.9a and 4.9b illustrate an optical frequency modulation at 10 kHz and 100 kHz respectively. Even though the DC bias voltage and $V_{pp}$ are kept the same, due to the high thermal time constant a reduction in frequency shift of the studied laser from $\Delta \nu = 4.3 \text{ GHz}$ at 10 kHz to $\Delta \nu = 2.2 \text{ GHz}$ at 100 kHz ($\sim 2$ times) was measured. A further increase of the driving sine waveform frequency resulted in an even smaller $\Delta \nu$. Even though the carrier injection frequency modulation approach is limited by the thermal time constant, the photon lifetime in the employed PhC cavities with oxide cladding is of the order of hundreds of picoseconds [128], corresponding to the GHz range of modulation speeds.

From the dependency of $I_{pp}$ vs $V_{pp}$ a maximum value of peak-to-peak amplitude modulation of 14% was achieved, which is relatively small. Apart from the obvious influence from the nonlinear spectral shape of the reflection peak, the gain spectrum, modulated by FP fringes corresponding to the RSOA cavity, also
makes a contribution to the intensity modulation. Ideally, for both the reflector sample and the gain die, the AR coating should be optimized for the reflector resonant frequency (wavelength) in order to minimize intensity fluctuations under FM operation.

4.3.3 Sample 3: Thermal PhC - SU-8 Reflection Phase Tuning via Microheater

The possibility of thermal PhC reflection phase modulation with heat generated by a microheater has been studied with sample 3 as a reflector. In comparison with the carrier injection scheme (Sample 2), with the same electrical power applied, the
thermal power density is lower, due to the larger size of the heater. Additionally, a larger portion of the waveguide is also heated, thus significantly perturbing the laser cavity length and, as was described above, in the presence of the parasitic Fabry-Perot fringes, FM operation could not be considered as purely induced by a PhC reflection phase shift.

From the FM point of view, the PhC SU-8 microheater sample as a candidate for high speed modulation applications is not valuable. The focus of this section is mainly the description of the reflector chip structure and the laser operation parameters, which is valuable from an application point of view.

**Reflector Chip Design and Characterisation**

The metal contacts were formed on the oxide layer (Fig. 4.10b) by a 220-nm-thick layer of Ni on top of a 20 nm layer of Cr (used for better adhesion). The contact pads were designed to prevent the losses that the proximity of the metal would induce on the propagating optical field. Thermal tuning of the PhC cavity resonance was triggered by a local change in temperature caused by the application of a voltage to the contact pads. The width of the conductor was reduced in the vicinity of the PhC cavity to ensure increased resistance (and therefore a larger localized temperature change for a given voltage), while trenches were defined on the Silicon layer around the PhC cavity (Fig. 4.10a) for improved thermal isolation (that would consequently increase the efficiency of the thermo-optic effect).

In order to mitigate FP fringes influence, an angled (6°) 400µm long RSOA was selected as the gain section. Accordingly, the reflector was designed and fabricated in an angled (∼ 12°) waveguide configuration. Even though the introduced angle was not expected to decrease the coupling efficiency between the RSOA and SU-8 waveguides (given that the sample angle is abiding Snell’s law), judging by the output power of the studied laser it is thought otherwise. This could be explained if we consider the mechanical properties of the SU-8. In comparison with the Si₃N₄ case, which has an oxide overcladding, making the waveguides mechanically...
Figure 4.10: (a) SEM image of the PhC cavity surrounded by trenches (light gray area indicated by red dashed line) on silicon designed to decrease heat dissipation from the PhC region. (b) Microscope image of the PhC reflector with needles applied to the NiCr microheater contact pads. (c) Microscope image of the PhC reflector (green rectangle) and phase tuning (PT) section (purple rectangle) placed in-line. Both sections contain microheaters in order to provide a possibility for thermally induced cavity length/phase tuning (PT) and reflection phase (PhC) modulation. (d) Microscope image of the RSOA-PhC SU-8 with heaters laser. (e) VI curve of the microheater, measured resistance 50 $\Omega$ at room temperature.
robust, the SU-8 polymer demonstrates worse adhesion with a FOX layer. This circumstance leads toward low yield in the number of the waveguides with facets of an acceptable quality after the wafer cleaving process (which is directly influencing coupling efficiency). In other words, due to the poor adhesion between SU-8 and FOX layer, the polymer waveguide is slightly shorter than the Si chip. Thus, the distance between RSOA and input facet of the waveguide was increased and coupling of the light from optical amplifier was degraded.

The collection of the output power and subsequent characterization were performed by using the same set-up which was described earlier (Fig. 4.10d). Figure 4.10e demonstrates the VI curve of the heater with an increase in resistance after 3V, which is expected according to $R = R_0[1 + \alpha(T-T_0)]$, where $R_0$ is the resistance at room temperature, $T_0$ - room temperature, $\alpha$ - Ni resistance temperature coefficient.

**Laser Operation**

Short cavity butt coupled laser performance data has been collected using the same set-up as in Section 4.3.1. The main difference here is the utilization of the angled RSOA and waveguides on top of the reflection sample. Even though a lasing threshold as low as 9 mA has been seen in the “straight” waveguide configuration (static pn SU8 reflector characterisation from Chapter 3), the lowest threshold achieved was 30 mA (Fig. 4.11b) (which again was mainly linked to lower coupling efficiency). A typical SMSR slightly higher than 30 dB has been observed (Fig. 4.11c).

The frequency modulation results were not as promising as in the case of PhC with Si$_3$N$_4$ waveguides, with maximum $\Delta \nu = 2.2$ GHz at 5 kHz driving frequency (Fig. 4.11d) and reaching a value below 0.1 GHz at 300 kHz (Fig. 4.11e). From these measurements, an estimated response time was approximately $5\mu$s. This is comparable with other thermo-optics devices based on SOI, which had rise times 5 - 60$\mu$s [104, 129–131]. The key limiting factor for response time reduction was likely poor heat diffusion through the (insulating) layers of silica and FOx.
Figure 4.11: Lasing characteristics of the FM PhC laser with microheaters. (a) Optical spectrum measurement at different values of injection current. (b) Waveguide coupled LI curve with lasing threshold at 30 mA. (c) Single mode lasing with SMSR > 30 dB measured at 78.5 mA, 20°C. (d) A spectrogram of a heterodyne beating time trace acquired at modulating frequency of 5 kHz, $\Delta \nu = 2.2$ GHz. (e) Depth of modulation $\Delta \nu$ measured as a function of modulation frequencies.
4.4 Conclusion

A frequency modulated PhC laser by means of the thermo-optic effect in silicon has been presented. Three sample configurations have been tested, which could be named as PhC - Si$_3$N$_4$ pn straight, PhC - SU-8 pn straight and PhC - SU-8 microheater angled.

The maximum waveguide coupled power output of 2 mW at 50 mA, 20°C has been achieved in the first case, which is on par with the solution presented by Tanaka et al. [57](3 mW at 50 mA, 20°C). Comparing the length of the RSOA (600 µm long) they utilized with the one in our studied case (250 µm long) the result is quite good. The main shortfall of the shown prototype is the absence of robust packaging, which lies beyond the scope of the presented thesis.

The second type demonstrated promising results towards GHz level modulation speeds, with a $\Delta\nu$ maximum value of 100 kHz. First of all, the recipe for the pn junction requires an optimization in order to employ carrier depletion modulation, which potentially will eliminate the limitation of the thermal time constant. Also, in order to enable GHz range modulation speed characterisation, a modification of the experimental setup is required, i.e. a necessity to introduce a tunable narrow-band filter to perform frequency to amplitude conversion.

The third type, being inferior to the previous cases in terms of output power and maximum achievable modulation speed, hasn’t demonstrated any outstanding performance from an engineering or application point of view. However, these devices shown an interesting fast dynamics results due to the silicon non-linear behavior in conjunction with the high power density ($\sim$ 1 mW/µm$^3$) provided by the nature of the PhC cavity (high Q/V ratio). These results will be discussed in detail in the next chapter.
Chapter 5

Modal dynamics of PhC laser

5.1 Introduction

The PhC laser with microheaters (described in Chapter 4), demonstrated a number of regimes, dependent on the total propagation phase in the cavity. Thermal tuning applied on a small fraction of SU-8 waveguide between the RSOA and the PhC cavity allowed the phase to be controlled. The goal of this chapter is a description of the observed fast and slow dynamics without insight for the fundamental mechanism behind them.

As was described previously the Si PhC cavity accommodates a high energy density which leads to nonlinear behavior of the reflector, depending on the amount of coupled energy. If we envisage phase tuning as a fine-tune mechanism for coupling between the lasing cavity mode and PhC resonant frequency, we can assume that unstable behavior initiates when a point of bifurcation is approached, i.e. a new value of the total propagation phase could not support the initial stable state and simultaneously introduced a phase detuning not sufficient to reach a new stable state solution.
5.2 Photonic Crystal Laser with Phase Tuning

Section: Brief Description and Static Characterization

The schematic of the studied laser shown in Figure 5.1. It is the same laser as described in section 4.3.3 with the possibility for frequency modulation by a microheater (indicated as I) induced thermal effect, but here the PhC reflector remains unmodulated. Instead, a second microheater (II) is employed as a phase tuning tool.

![Figure 5.1: Schematic representation of the hybrid PhC laser with phase tuning section. Laser cavity phase tuning performed by DC bias application on the NiCr microheater II (microheater I is not used in this experiment). The material of the waveguide, vertically coupled to the PhC cavity, is an SU-8 polymer with negative thermo-optical coefficient. \( L_{\text{gain}} = 0.4 \text{ mm}, L_I = 3.66 \text{ mm}, n_{\text{gain}} = 3.22 \) and \( n_{\text{SU-8}} = 1.59 \) at 1550 nm, at 20°C.]

The Si dispersion adapted (DA) PhC cavity which has been studied in this work was 14\( \mu \text{m} \) long and that length corresponded to an FSR \( \sim 7 \text{ nm} \) (spectral distance between 2 adjacent resonances). However, the reflection coefficient was varying from resonance to resonance. In this particular case the highest reflectance was shown by the peak at 1535 nm, next was the 1550 nm peak and the weakest one was at 1543 nm (no linear dependency) (Fig. 5.2a). In addition to the lasing condition of coincidence between a resonance peak and a cavity mode, the preferred lasing wavelength (1535, 1543 or 1550) was determined by the position of the RSOA gain ripple (arising from a non-optimized AR coating) within the peak and optical feedback (Fig. 5.2b). Therefore, through the change of one of these conditions a
lasing on the other resonances is possible to achieve.

The total laser cavity propagation phase is the most straightforward parameter for the control of detuning. In this experiment a DC voltage in the range 0.58 - 1.73 V (6.7 - 60 mW of electrical power applied on 50 Ω heater) with steps of 0.29 V has been applied to the phase tuning section and was kept constant until time traces containing fast dynamical processes were recorded. Due to translation symmetry, the cavity mode structure is $2\pi$ invariant in terms of propagation phase. A full swing of $2\pi$ corresponds to $\Delta U = 1.15$ V, where $\Delta U$ is the difference between the initial and final voltage (Fig. 5.2c). The injection current on the RSOA was 100 mA (with a threshold at 30 mA). The time traces were acquired through a New Focus...
1544-B 12 GHz bandwidth photoreceiver and DPO73304DX fast digital oscilloscope with 33 GHz bandwidth, meaning that the cut-off acquisition frequency is 12 GHz.

Even though an effort was made to collect data in a systematic manner, due to the unpackaged configuration of the laser (RSOA and Si chip resting on separate translation stages) a small laser cavity length variation (fractions of a nm) still affected laser performance over a time frame greater than 10 minutes. This circumstance created a situation where we can not get the same regime at exactly the same microheater voltage after realignment of the RSOA in respect to Si chip (in order to restore coupling between them) as it resulted in a laser with a slightly different cavity length thus different offset of the propagation phase. In spite of that, the first four regimes are given in the order corresponding to the ascending value of the microheater voltage because it is valid for the same RSOA - Si reflector coupling conditions. The fifth regime was recorded separately in a non-consistent manner.

5.3 Single mode “Quiet” Lasing

The first regime is what is desired in most engineering applications, stable single mode lasing (Fig. 5.3a) without any dynamics on the background (Fig. 5.3b and 5.3c). The microheater bias voltage was 0.58 V (6.7 mW) and it can be viewed as an initial voltage corresponding to $0\pi$ shift of the total propagation phase. Similar to conventional DFB sources, the PhC laser showed monotonous SM operation for the majority of the pumping current values.

The absence of a peak in the RF Fourier spectrum (Fig. 5.3c) which would correspond to a relaxation oscillation frequency (ROF) is unexpected. However, such phenomena could be observed under certain conditions which was previously reported in literature. For example, in [132] shown that in the conventional laser with weak optical feedback when the product of ROF $\nu_{ROF}$ and delay time $\tau_{delay}$ equals an integer ($\nu_{ROF}\tau_{delay} \approx 0, 1, 2...$), the ROF were damped and suppressed. Therefore, such condition might have been met accidentally when this particular SM regime was recorded. The other explanation could be an effect described in [133], where each isolated mode of the multimode laser had a distinct peak in power.
Figure 5.3: (a) Optical spectrum of the “Quiet” single mode regime at single resonance (1535 nm). (b) Time trace of (a) without any dynamics. (c) Fourier spectrum of (b) shows that this is indeed eventless regime.

spectrum, but the power spectrum of the time trace for the combined multimode spectrum was ”flat”. On Fig. 5.3a we can clearly see a SM operation. However, due to poor stability of the coupling between RSOA and Si reflector a second mode could temporally emerge from second PhC resonance, which generated anti-phase ROF and thus power spectrum was flat (Fig. 5.3c).

5.4 Two-color Lasing

The second regime was a simultaneous lasing on two resonances - 1535 nm and 1550 nm and the corresponding voltage (electrical power) on the microheater was 1.16 V (27 mW) which introduced a π shift (Fig. 5.4a). The associated time trace appeared nearly periodic (Fig. 5.4c). In order to relate light from each resonance with their respective contribution to the time trace, a heterodyne beating signal at both wavelengths was recorded (Figs. 5.4e and 5.4f). For instance, on
Figure 5.4b, a tunable laser source was positioned in the vicinity of the lasing peak at 1550 nm and the corresponding time trace appeared as shown on Figure 5.4d. The fast oscillating regions of the time trace were denoting the time periods when the mode at 1550 nm was dominant. In the same way it was possible to locate the contribution of the 1535 nm mode (or short wavelength mode) (Fig. 5.4e).

After acquisition of the heterodyne beating signal for each mode an attempt to reconstruct the temporal behavior of standalone modes was made (Figs. 5.4e and 5.4f). Unfortunately, the duty cycle of the integrated periodic signal is “breathing” and therefore, a phase mismatch between 2 heterodyne signals emerges making reconstruction of each standalone time trace not reliable. The difference in shapes represented on Figures 5.4e and 5.4f clearly proves this statement. Ideally, a pair of tuneable filters could be used for simultaneous observation of each lasing mode through 2 channels on an oscilloscope via 2 identical photoreceivers.

The antiphase dynamics is a direct indication of coherence in a two color regime. In general, antiphase dynamics in a N-mode laser manifests itself as a periodic regime in which all modes oscillate with nearly the same wave pattern but the phase of each mode amplitude is shifted by $2\pi/N$ from the previous mode. Antiphase states are also known as splay-phase states [134, 135] or ponies on a merry-go-round [136], and were found in different fields of science and engineering such as coupled Josephson junctions [137, 138], coupled chemical oscillators [139], and coupled laser arrays [134]. Antiphase dynamics in two mode lasers were studied experimentally and theoretically in intracavity frequency-doubled lasers [140], bidirectional class B ring lasers [141] and two state quantum dot lasers [142]. Spectral properties of two mode anti-phase oscillations in lasers were revealed by Mandel et al. [143].

In general, this regime requires a more thorough study and systematization. For example, a dependency of duty cycle and peak-to-peak amplitude versus pumping current, stability of the pulsing regime, its reproducibility from sample to sample etc.
**Figure 5.4:** (a) Optical spectrum of the simultaneous lasing on two PhC resonances - 1535 nm and 1550 nm. (b) Optical spectrum of two-color lasing with TLS placed at 1550 nm for heterodyne beating measurement. (c) Time trace corresponding to Figure (a). (d) Time trace corresponding to Figure (b). (e) Beating signal from the mode at 1535 nm (black); filtered time trace (red); filtered time trace (light green) without offset introduced by TLS; envelope function (dark orange) of the heterodyne signal after subtraction of filtered signal; blue - reconstructed time trace of the mode at 1550 nm. (f) Same as (e), but time trace reconstruction performed for the mode at 1535 nm.
5.5 Multi-mode “Quiet” Lasing on a Single Resonance

As the DC voltage on the microheater is increased up to 1.39 V (38.5 mW), introducing a $1.4\pi$ shift in the propagation phase relative to the SM operation, a third regime emerges which could be referred to as “quiet” multi-mode lasing from the same PhC peak (Fig. 5.5a). It has been named as “quiet” due to the absence of any prominent dynamics on a 12 GHz bandwidth (Fig. 5.5c). The possibility of some interplay between side bands exists, but as the spectral distance between them is 0.14 nm or 17.8 GHz a faster photoreceiver would need to be employed. Moreover, the absence of any prominent peaks in the Fourier spectrum can be explained by the antiphase dynamics effect reported in [133]. Due to this effect the individual modes may show large amplitude pulsations, but the total output will remain constant. Also, as in the SM regime the peak corresponding to the ROF was absent. The choice of photoreceiver has been dictated by it’s high V/W optical signal conversion as the power output on this particular Si PhC reflector sample was poor.

This regime is typical for the short cavity RSOA - PhC laser and was always observed when an optical spectrum vs injected current measurement has been performed. The PhC reflection bandwidth was 98 GHz measured at FWHM and all 5 modes were accommodated within a 71 GHz span (Fig. 5.5a). As was shown in Chapter 3, the spectral position of the PhC reflector is intracavity power dependent thus the simultaneous acquisition of the reflection spectrum and laser output is necessary in order to relate the two.

However, in this particular case, we fix all the laser parameters except the total propagation phase (this is valid only for the single $2\pi$ sweep), thus simplifying the road towards exploration of the mechanism triggering one or the other non-trivial regimes. As for why this closely-spaced multimode lasing occurs, it can be tentatively explained by the transient state of the lasing solution, where neither the previous cavity longitudinal mode ($m$) nor the next one ($m+1$) satisfy the
Figure 5.5: (a) Optical spectrum of the “Quiet” multimode regime at single resonance (1535 nm). The separation between lasing lines is 0.14 nm or 17.8 GHz. (b) Time trace of (a) without any particular feature (thus quiet). (c) Fourier spectrum of (b) proving absence of any oscillation within 12 GHz bandwidth (photoreceiver bandwidth).

reflector’s newly shifted central frequency value.

5.6 Multi-mode “Modulated” Lasing on a Single Resonance

The system reaches the fourth, multi-mode “modulated” state with the further increase of voltage on the phase tuning section up to 1.62 V (52.4 mW) corresponding to a $1.8\pi$ shift from the first SM regime. It has a similar optical spectrum to the previous case, but each side band accommodates a fast modulation on top of it (Fig. 5.6a). Furthermore, the optical spectrum (OS) is more asymmetric in comparison to the previous case of multi-mode “quiet” modulations, where due
to symmetric OS individual pulsation of each mode was compensated and total output was flat. This asymmetry might be the source of the train of periodic pulses similar in shape as it is violates the compensation rule (Fig. 5.6b).

A Fourier spectrum of the time trace proves that there is no intermix of any other pulsations. The repetition rate is 3.63 GHz corresponds to the left peak and the rest corresponds to the 2nd and 3rd harmonics constituting non-sinusoidal pulses. The measured 3.63 GHz is most likely a relaxation oscillation frequency.

**Figure 5.6:** (a) Optical spectrum of the “Modulated” multimode regime at single resonance (1535 nm). (b) Time trace of (a) comprising repeating pulses. (c) Fourier spectrum of (b) shows the repetition rate of the pulses is 3.63 GHz (first peak, 2nd and 3rd peaks are just harmonics).
5.7 Bursting Phenomenon: Switching Between “Quiet” and “Deep Modulation” modes

Lastly, a change between “quiet” and “deeply modulated” states has been observed. Unfortunately, the optical spectrum has not been collected, but nevertheless this regime is interesting from the chaotic dynamics research point of view.

The average repetition rate of the outburst regions was 14.4 MHz upon inspecting Figure 5.7e. However, apart from the peak in the Fourier spectrum at 14.4 MHz which can be associated with the thermal effect in the RSOA (Fig. 5.7c) there were no more distinct peaks. Comparing the Fast Fourier Transform (FFT) spectra of the 20µs long time trace and the time trace of a single bursting region (Fig. 5.7b), it is apparent that a continuous distribution of frequencies from 2 GHz up to cut-off at 12 GHz originates from the components of the named time trace part. Therefore, an absence of the distinguished peak in a frequency domain suggests a chaotic nature to these oscillations.

In this regime, the laser output takes the form of bursts of spiking oscillations separated by quiet periods. Since the discovery of the fact that neurons communicate via spiking of bursting dynamics, neuromorphic studies attract significant attention [144]. There is also a growing interest in the generation of bursting and spiking effects in photonic devices [145]. Coexistence of the fast and slow timescales in bursting dynamics suggests that two different mechanisms are needed to generate this activity. The mechanism which generates fast oscillations in our system can be clearly related to the field matter interaction in a form of the relaxation oscillations in GHz range. The mechanism responsible for the slow timescale can be attributed to the slow (MHz range or slower) change of the phase due to optothermal effects, which are unavoidable at high intensity operation as has been theoretically predicted in [146] where very similar bursting dynamics have been reported.
Figure 5.7: (a) Time trace showing switching between “quiet” and “deep modulation” regimes. (b) Zoom-in of the area depicted by the red rectangle on (a). (c) Fourier spectrum of (a). (d) Fourier spectrum of the modulation part of the time trace (red rectangle). Continuous down-heel pattern on (c) between 2 GHz and 12 GHz appears due to the deep modulation “packages”. (e) Zoom-in of the peak at 14.4 MHz on (c), which seems to be the mean repetition rate of the “packages”. (f) Magnified figure of (b) (green rectangle).

5.8 Conclusion

Several dynamical regimes have been briefly described that have been observed during a phase shifting of the PhC short cavity laser over $2\pi$. In order to generate
and record less speculative and repeatable results the studied laser needs a proper packaging. Overall approach where various dynamical regimes are triggered by the sole change in propagation phase of the laser is convenient, as a number of variables becomes smaller. Phase tuning section inside laser cavity allows to fine-tune longitudinal mode in respect to the central frequency of the PhC reflector and enables frequency modulation described in previous chapters in the vicinity of optimal DC bias voltage. It is particularly useful as thermal conductivity of silica were the main factor limiting thermal PhC modulation.

Also, as thermal phase tuning triggered multimode states, which were described above, it is safe to assume that the same mechanism could potentially help to avoid such states in order to sustain SM lasing. The most interesting regimes from the fast dynamics point of view are “two-color” lasing and “quiet - deep modulation” as a candidates for the further study in the road towards deeper insight in the non-linear systems in general and PhC laser in particular.
Chapter 6

Conclusion and Future Work

In this thesis we introduced and studied the potential of several electrically pumped hybrid Si/III-V external cavity (EC) laser designs suitable for Si photonics applications. The evaluated Si reflector structures can be described as photonic crystals with either unidirectional (1D) or planar (2D) modulation of the refractive index. Due to a relatively short laser cavity length, the lasers demonstrated single mode (SM) operation over a wide range of pumping currents, which is essential for applications as WDM data-communication systems. Also, EC design ensures a high yield and performance (due to the separate optimisation of active and passive components), as well as thermal management due to the spatial separation of the III-V and Si chips.

6.1 Si$_3$N$_4$ Grating

The first type of external Si reflector that we studied was a Si$_3$N$_4$ Bragg grating (1D photonic crystal), which together with the 250 µm long InP RSOA (Chapter 2) demonstrated a mode hop free SM operation for 47 mA at room temperature without active cooling with a typical SMSR of 47 - 49 dB, and a maximum waveguide-coupled (WC) output power of 3 mW. Such stability in the lasing wavelength was ensured by the low thermo-optical coefficient of the Si$_3$N$_4$ ($1.62 \times 10^{-5}/^\circ$C). The value of the wavelength measured at different ambient temperatures (20°C to 80°C) was within 1.1 nm, which, in comparison to the 6 nm
red-shift of the traditional InP DFB [72], is a significant improvement.

The initial concept of this laser was to implement the second order reflection peak of the Si$_3$N$_4$ grating as a wavelength-selective element and an output mirror. However, Fabry-Perot fringes, which were formed due to the imperfect Si chip facets anti-reflection (AR) coating, superimposed upon the grating’s reflection characteristic and gradually distorted it. In order to mitigate the influence of FP fringes, it is necessary to apply a multi-layer AR coating on the chip facets, optimised for the reflection peak central wavelength, and minimise the distance from the Si reflector input facet and resonant structure. Both approaches are applicable and necessary for every Si external reflector studied in this thesis.

6.2 Silicon Photonic Crystal reflectors

The second type of reflector that we studied was a Si PhC (2D photonic crystal) cavity vertically coupled to a low-refractive index waveguide. A short cavity laser, comprising a 250$\mu$m long gain section and PhC reflector, demonstrated a lasing threshold at 13 mA with a maximum output power up to 3 mW, and maximum wall-plug efficiency of 8.5% (at 41 mA) at the emitted wavelength of approximately 1550 nm. The laser linewidth was 4.5 MHz and the observed SMSR values were typically $> 40$ dB (the maximum observed was 50 dB). A thermal stability of the emitted wavelength in the span of 60°C (20°C to 80°C) was measured as a $\pm 0.38$ nm deviation from the central wavelength of 1550.85 nm through the power tuning technique discussed in Chapter 3. The overall performance of the device was equal to analogous hybrid EC lasers [57–59, 77, 95, 147].

As was mentioned in the Aims of the Thesis section, the next step for the studied EC laser configuration should be an implementation of RSOA arrays. Such laser arrays can be obtained by butt-coupling an RSOA bar with several waveguides to a silicon board with an array of resonant reflectors, thereby significantly reducing the power consumption per channel. This approach can be integrated in data communication solutions, for example, together with fast amplitude modulators or,
considering the continuous frequency modulation, via a pn diode or microheater, used as a multicolor light source for gas sensing applications.

The suitability of the proposed EC PhC laser design for a direct frequency modulation was discussed in Chapter 4. As the lasing wavelength is determined by the resonant wavelength (frequency) of the Si PhC cavity, the modulation of the laser output can be achieved by modulating the PhC cavity resonance. This method enables the implementation of low power consumption resonant modulators in practical applications by eliminating the requirement for wavelength matching between the laser source and the modulator. For the experimental proof-of-concept, two types of Si chips were tested: a pn junction that was extended into the PhC cavity; and a microheater that was positioned close to the PhC. In both cases, a thermal effect locally changed the refractive index of the PhC cavity, thereby tuning the reflector’s central frequency (wavelength) and resulting in an output wavelength change. Direct frequency modulation of the considered EC laser with the pn junction at a speed up to 100 kHz was achieved for an injection type modulation at a constant RSOA drive current of 30 mA. Although the demonstrated operation is not optimal (slow and power consuming due to a high resistance of the non-optimised pn diode), the implementation of the PhC cavity as a tuneable resonant mirror in reverse bias could potentially result in a power consumption in the sub-pJ/bit level due to a very low capacitance ($5.6 \times 10^{-18}$ F).

6.2.1 Improvements in Direct Frequency Modulation

There were several factors limiting the speed of the frequency modulation. The key limiting factor was the impedance mismatch resulting from the high resistance of the pn diode and employment of needle probes, which are obviously unsuitable for high speed modulation. To overcome this problem, the experiment could be repeated using a ground-signal-ground (GSG) microwave probe, especially designed for high frequency modulation. Also, the electrical design should be improved by contact resistance reduction.
Another limitation was the carrier injection type modulation, which immediately transformed into thermal modulation with the pn diode acting as a heat source localised inside the PhC cavity. However, in order to increase the modulation speed, a depletion type modulation should be considered. The observed frequency shift values of $\Delta \nu = 2.5 - 4.5$ GHz can be easily obtained in carrier depletion mode, which was already reported in [148]. In this mode the switching energy of the device determines the modulation power consumption, and can potentially be on the level of sub-fJ/bit for the studied EC configuration with a vertically coupled waveguide-PhC system [148].

6.3 Fast and Slow dynamics in External Cavity PhC laser

Finally, a laser cavity phase tuning experiment was carried out, which showed a set of interesting slow and fast dynamics (Chapter 5). The phase tuning (PT) was achieved through a local refractive index change of the Si chip polymer waveguide, which was induced by the heat generated by the microheater, positioned between the RSOA and PhC reflector. Due to the high power/volume ratio within the Si PhC cavity, strong non-linear effects emerged and resulted in a complex behavior. As the phase for the laser cavity was tuned from 0 to $2\pi$ (and initially optimal coupling conditions between the gain and reflector were slowly distorted), several regimes appeared. One particular regime with a simultaneous SM lasing on two PhC resonances (two color lasing) is of interest. The antiphase dynamics observed was a direct indication of the coherence between the two colors. As the two lines were separated by $\sim 1.7$ THz (15 nm), the system can be viewed as a pulsed THz source with a 10 ns repetition rate.

Robust coupling between the active and passive components of the EC laser with a PT section is essential in order to perform a thorough study and systematise the observed regimes. A butterfly package configuration will suffice for this task.

In conclusion, we studied several types of Si resonant reflectors in the EC laser
architecture under different conditions. The experimentally observed PhC EC laser performance, wavelength thermal stability, and a possibility for a direct frequency modulation show the potential of the proposed architecture to be a candidate for WDM implementation in silicon optical interconnects.
Bibliography


List of Figures

1.1 Comparison of direct InP (left) and indirect Si (right) band-gap diagrams (reproduced from [16]). ........................................ 3
1.2 Absorption coefficient versus wavelength in Si measured at 300 K [31]. 5
1.3 (a) Short cavity laser comprising an InP reflective semiconductor optical amplifier (RSOA) and Si$_3$N$_4$ Bragg grating. (b) Frequency modulated short cavity comprising an InP RSOA and tunable PhC reflector via pn diode carrier injection. Two types of samples tested which vary by the waveguide material (Si$_3$N$_4$ or SU-8 polymer). (c) Frequency modulated short cavity laser comprising an InP RSOA and thermally tunable PhC reflector via microheater. This type of sample also contains a laser cavity phase tuning section, which acted as a second in-line microheater. ........................................ 7
1.4 Schematic illustration of the possible employment of the RSOA bar with several PhC reflectors in conjunction with separate high-speed amplitude modulators for WDM application. .......................... 9
2.1 Schematic representation of 1D (a), 2D (b) and 3D (c) Photonic Crystals. .......................................................... 14
2.2 (a) Medium with one-dimensional periodicity in the z-direction. The high permittivity regions ($\varepsilon_1$) are shown in red and the low ones ($\varepsilon_2$) are shown in green. The distribution of the two possible modes at $k = \pm \pi/\alpha$ is depicted by the black and blue curves. The low-frequency mode $\omega_{\text{low}}$ tends to concentrate its energy in the high-$\varepsilon$ regions, while the higher frequency $\omega_{\text{high}}$ concentrates the majority of its energy in the low permittivity regions. (b) Dispersion relation ($\omega - k$) for propagation in the z-direction of a homogenous medium (solid lines). The assumed arbitrary periodicity leads to the periodic repetition of the dispersion curves at $k' = k + 2m\pi/\alpha$ (dashed lines). (c) Band diagram (dispersion relation) for propagation in the z-direction of a z-periodic medium. A photonic band gap (frequency region marked in yellow) arises due to the appearance of two modes with different frequencies ($\omega_{\text{high}}$ and $\omega_{\text{low}}$) at the same $k = m\pi/\alpha$. The red rectangle indicates the irreducible Brillouin zone.

2.3 (a) EC schematics of the hybrid EC laser based on the butt-coupled RSOA and Si$_3$N$_4$ mirror. The reflector comprises a Si$_3$N$_4$ waveguide with a Bragg grating etched on to it, on a silicon dioxide substrate and cladded in a low-index flowable oxide. (b) Schematic view of the Si$_3$N$_4$ Bragg grating. Where $l_{\text{grating}}$ - grating length, $l_{\text{grating}} = 1504$ $\mu$m; c - waveguide width, $0.9$ $\mu$m $\leq c \leq 1.1$ $\mu$m; b - corrugation depth of the grating, $b = 0.09$ $\mu$m. Red dashed line indicates a basic trapezoid element which constitute the complete grating.

2.4 Schematic view of the Si$_3$N$_4$ waveguide with single layer AR coating.

2.5 Reflectance as a function of wavelength from air ($n=1$)/Si$_3$N$_4$ ($n=1.94$) interface. a) Simulated reflectance without coating (black line), with single layer of theoretically ideal AR coating ($n = 1.41$) of 274 nm (red line), with MgF$_2$ ($n = 1.37$) of 282 nm (cyan line) and with MgO ($n = 1.71$) of 226 nm. b) Close-up comparison of the coatings described in “a)”. c) Part of Si$_3$N$_4$ blank waveguide normalised transmission spectrum, where blue line - transmission spectrum before deposition of AR coating, red line - spectrum after single layer deposition of 227 nm of MgO.
2.6 Simulated reflection and transmission spectra for the 1st and 2nd order triangular Bragg grating ($\Lambda_1 = 460$ nm and $\Lambda_2 = 920$ nm respectively). Number of periods $N = 1600$. . . . . . . . . . . . . . . 23

2.7 Simulation results for the Bragg grating with triangular effective index modulation. a) Simulated dependence of the grating reflectance and corresponding central peak FWHM bandwidth vs corrugation width. b) Simulated dependence of the grating reflectance and corresponding central peak FWHM bandwidth vs grating length. . . . . . . . . . . 24

2.8 Simulated mode profiles: a) Simulated near-field profile of the mode on the facet of the RSOA. b) Simulated near-field profile of the mode on the facet of the Si$_3$N$_4$ waveguide. c) Simulated coupling efficiency vs. misalignment between the Si$_3$N$_4$ waveguide and the butt-coupled RSOA. The maximum power coupling coefficient was found to be $K = 0.48$. d) Simulated coupling efficiency vs. gap distance between the Si$_3$N$_4$ waveguide and the butt-coupled RSOA. . . . . . . . . . . . 25

2.9 Schematic view of the set-up used for passive characterisation of the reflector sample. SR - silicon reflector chip; SMF - single mode fiber; IRC - infra-red camera; PBM - polarising beam splitter; OSA - optical spectrum analyser; TLS - tunable laser source; L1-L5 - aspheric lenses; ASE - amplified spontaneous emission broadband source. Collection of the transmission and reflection spectrum was carried out separately. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 26

2.10 (a) Tilted SEM view of the 600 nm thick patterned silicon nitride before encapsulation. (b) The reflection spectrum of the 1505 µm long Si$_3$N$_4$ grating acquired at 20°C. Blue curve - real reflection spectrum; red curve - lorentzian approximation excluding Fabry-Perot influence. (c) Plot of the measured reflection peaks central wavelengths of the 4 devices on all 20 chips. Waveguide widths are 0.9 µm (blue curve), 1.1 µm (red curve), 1.3 µm (yellow curve) and 1.5 µm (purple curve). (d) Blue axis shows the most frequent resonant wavelengths over all 20 chips at each waveguide width and the red axis shows the resonant wavelength standard deviation over all chips at each waveguide width. 27
2.11 Plot of the central wavelength of the Bragg grating reflection peak as a function of operating temperature. The device displays a constant shift of 12.4 pm/°C. 

2.12 Schematic view of the set-up used for the active characterisation of the hybrid laser. IRC - infrared camera, OSA - optical spectrum analyser, DSO - digital sampling oscilloscope, PR - photoreceiver, TLS - tunable laser source, MFPC - manual fiber polarisation controller, OI - optical isolator. 

2.13 Power vs. Wavelength plot, showing the spectral overlap of the gain ripple (blue curve), the Si$_3$N$_4$ Bragg mirror (red curve) and the total cavity laser spectrum (black curve). 

2.14 Laser characterization. (a) False colour plot of the optical spectrum of the laser, averaged in time, with increasing driving current. (b) Normalized reflection spectrum of the Bragg gratings, with the wavelength axis matched to that on the left, (c) L-I curve of the EC laser. (d) Optical spectrum of the EC laser at room temperature and 85 mA of driving current. The laser line shows 49 dB of SMSR. (e) Linewidth of the hybrid EC laser (blue) equal to 1.7 MHz and fit (dashed red). (f) Multi-mode regime spectrum at 67 mA. 

2.15 Plot of the single mode lasing wavelength against temperature with a controlled driving current of 50 mA. 

2.16 A representation of the lasing condition for the short cavity laser. Red - a calculated longitudinal cavity modes, black - Bragg grating reflection spectrum modulated by Fabry-Perot fringes, blue - gain spectrum from real III-V RSOA 250 µm long. 

2.17 Plot of the single FP fringe width (red) and corresponding number of fringes accommodated within the designed Bragg grating reflection peak (blue) against Si$_3$N$_4$ waveguide length, measured from the input facet up to the reflector ($l_{passive}$).
2.18 Representation of the SiN hybrid laser longitudinal mode drift at different temperatures for 4 different SiN bare waveguide lengths. Red lines represent FP fringe width superimposed with Bragg grating reflection peak. Black dashed line represents longitudinal mode with the same number. (a) Waveguide 80µm long, SM mode hop free lasing ensured for ΔT = 6.54°C. (b) Waveguide 800µm long, SM mode hop free lasing ensured for ΔT = 8.92°C. (c) Waveguide 1000µm long, SM mode hop free lasing ensured for ΔT = 9.08°C. (d) Waveguide 1500µm long, SM mode hop free lasing ensured for ΔT = 7.4°C. It is apparent that the optimal length is 1000µm.

3.1 a) Birds-eye view and b) cross-sectional schematics of heterogeneously integrated LEAP laser and Si waveguide. Reproduced from [83].

3.2 The photonic band diagram for the modes of a triangular array of air cylinders (ε=1) in a dielectric membrane (ε=13), reproduced from [61]. The blue lines represent TM bands and the red, TE Bands. An inset shows the unit cell of the photonic crystal lattice. The band diagram calculated for the wave vectors in the irreducible Brillouin zone, formed by high symmetry points Γ, M and K. A photonic band gap exists only for TE modes.

3.3 A schematic representation of the light cone: a) blue line is a light line for the case of the waveguide submerged in air, red line - light line for n > 1; b) gray shade represents the light cone of continuum of states that extended both to waveguide and air, orange shade the same as gray one, but due to a smaller contrast between overloading media and waveguide the volume of the cone is bigger.
3.4 a) Schematic representation of the light confinement in the z-axis realized by total internal reflection. b) Schematic representation of the electric field (blue) distribution in a cavity with a rectangular envelope function (red dashed line). c) Schematic representation of the electric field distribution in a cavity with a Gaussian envelope function (dashed red line), \( n_1 > n_2 \). d) Spatial Fourier transform of the field in b). e) Spatial Fourier transform of the field in c). The gray rectangle in d) and e) indicates a leaky region inside the light cone.

3.5 (a) Double heterostructure cavity formed by the integration of a PhC structure with lattice constant \( a_2 \) into one with \( a_1 \) and its schematic band diagram [89]. (b) Width-modulated line-defect PhC cavity. “Red” holes sustain the biggest shift while the distance for the “blue” ones is smallest (reproduced from [90]). (c) Dispersion adapted (DA) cavity with confined first order mode. Green circles indicate the holes that have been shifted (reproduced from [91]).

3.6 (a) An example of the fabricated PhC structure. (b) Typical reflection and transmission spectra of the DA PhC cavity reflectors at 20°C used in this work. (c) Measured PhC resonance peak position versus temperature set by a Peltier element. Measured thermal sensitivity \( d\lambda/dT \) is 61 pm/°C.

3.7 The hybrid PhC laser configuration comprising a RSOA and a Si PhC based resonant mirror. A schematic representation of the device is given in (a) and a microscope view is shown in (b). The employed reflector consisted of a low index dielectric waveguide located vertically over a PhC cavity on silicon-on-insulator (SOI), the two separated by a thin buffer layer of oxide allowing their evanescent coupling [95]. The laser cavity was formed by butt-coupling the RSOA to the waveguide on the silicon chip, which acted as a narrowband reflector at the resonant wavelengths of the PhC cavity, as described in [100]. Filter reflection spectrum (black curve) and laser spectrum (red curve) superimposed in (c).
3.8 Self-heterodyne linewidth measurement set-up. The output light collected by the lensed fiber, passes through a 1550 nm fiber coupled optical isolator, then split by 50/50 coupler. One arm is sent to the acousto-optic modulator (AOM) driven at constant frequency of 55 MHz, the other one through a 10 km fiber delay to achieve incoherence with respect to the AOM branch. The two uncorrelated parts were combined with a 90/10 coupler with 90% directed to the electrical spectrum analyser (ESA) and 10% to the optical spectrum analyser (OSA). The polarisation matching condition was achieved by a manual polarisation controller.

3.9 Schematic representation of a short cavity laser with a coupled PhC cavity + waveguide system as a resonant mirror. The major fraction of light generated by the RSOA passes through the SU-8 waveguide unaffected (black arrow). The red line depicts lasing at the PhC resonant wavelength. \( R_1 \) - high reflection coating of RSOA, \( R_2 \) - integral reflection from PhC - waveguide block.

3.10 (a) Laser waveguide coupled output power vs injected electrical power. (b) Wall-plug efficiency (WPE) as a function of injected current. All measurements were taken at room temperature.

3.11 (a) LI-curve without temperature stabilisation and (b) Single mode (SM) lasing at 80 mA for 20 - 80°C temperature range, without Power Tuning. (c) False colour plot of the time averaged optical spectrum as a function of upswept drive current, with the x-axis matched to that of (a). From the change in the lasing wavelength an increase of PhC temperature by 15°C can be deduced. (d) Delayed self-heterodyne measurement of the laser linewidth in a single mode region. The central frequency of the Acousto-Optic Modulator (AOM) was 55 MHz, the measured linewidth \( \Delta \nu = 4.5 \) MHz. (e) Emitted wavelength as a function of the fiber-coupled output power for DFB (black) and compact PhC hybrid lasers measured at 20°C.
3.12 Temperature stable operation. (a) Emitted wavelength as a function of temperature for a packaged DFB laser at a drive current of 80 mA (black crosses), a PhC laser at 80 mA without power tuning (red circles), and the same PhC laser with power tuning realized by drive current tuning (from 150 to 50 mA, for 20 - 80°C, respectively (green rhombi). (b) Simulated temperature as a function of dissipated power for the SOI PhC (red) and the undercut PhC (black). (c) Thermal profile of the PhC cavity on the SOI resonant reflector chip for a dissipated power of 2 mW. (d) Thermal profile of an undercut PhC cavity for a dissipated power of 2 mW.

4.1 (a) Schematic representation of the compact external cavity FM laser configuration. The laser cavity is formed by butt-coupling a III-V-based RSOA to an external reflector chip, comprising a waveguide vertically coupled to a Silicon PhC cavity embedded in a pn junction, that provides tuneable wavelength-selective optical feedback. (b) 3D representation of the chosen external resonant reflector. A waveguide is vertically coupled to a PhC cavity with a pn junction extending in its defect. The blue and red regions represent the p- and n-doped regions of the pn junction. (c) A cross section of (b) with Al - aluminum contacts for voltage application and FOx - layer of flowable oxide.

4.2 A schematic illustration of the frequency modulation mechanism realised in FM PhC laser. Solid curves represent an initial solution for the reflection peak (blue), reflection phase \( \phi_r \) (red) and total accumulated phase \( \phi_{tot} \). The dashed curves depict each parameter for a shifted reflection peak position by \( \Delta F \). Orange arrows indicate lasing frequency for the same m-th laser cavity mode showing a shift by \( \Delta \nu \) for the shifted solution, where \( \Delta \nu < \Delta F \). Pink points 1 and 2 illustrate that the total accumulated phase doesn’t change with lasing frequency being tuned.

4.3 A VI curve of the pn junction measured in forward bias.
4.4 A schematic of the experimental setup for FM PhC laser characterization. RSOA was driven by constant current. A periodic signal from the function generator was applied to the PhC reflector pn diode. The red dashed line indicates the whole PhC laser. Output laser power was coupled through a lensed fiber into a 3 x 3 coupler, where it mixed with the polarization matched light from a narrow linewidth (<300 kHz) tuneable laser source to generate a heterodyne beating signal. The time trace of the signal was collected by the fast oscilloscope (OSC) through a 35 GHz fast photoreceiver. The power meter (PM) and optical spectrum analyzer (OSA) were used for alignment purposes.

4.5 (a) An example of measured PhC transmission resonance, FWHM $\Delta \lambda = 0.93$ nm or 116 GHz. (b) The measured dependency of the transmission peak central frequency shift $\Delta F$ versus applied voltage on the pn diode; the slope value is 400 GHz/V. (c) Single mode lasing spectrum measured at 65 mA pumping current. The measured side mode suppression ratio > 45 dB.

4.6 Frequency modulation of the hybrid III-V - Si PhC laser at 10 kHz modulation frequency, detected as a heterodyne beating with narrow linewidth tuneable laser source. Black inset - driving signal with peak to peak $V_{pp} = 1.3$ V and offset 3.35 V. Red inset - amplitude modulation of the optical signal intensity with $I_{pp} = 22.32$ mV (1.86 dB). Yellow inset - frequency modulation of the lasing frequency $\Delta \nu = 4$ GHz.
4.7 (a) Schematic representation of the PhC cavity and pn junction. The different doping regions are shown in different colours: p+ in red, n+ in dark blue, p in light red, n in light blue. (b) Sketch of a tuneable FM resonant reflector structure. The doping regions are designed to keep the electrical vias (gold area) and metal electrodes on the same side of the waveguide (in light green). (c) An example of the fabricated PhC structure. (d) Microscope image of needle probes applied to the contact pads on Si PhC reflector sample with vertically coupled with Si$_3$N$_4$. (e) Schematic illustration of the PhC FM laser geometry. $L_{\text{gain}}=250\, \mu\text{m}$, $L_{\text{waveguide}}=2240\, \mu\text{m}$. Total optical length with $n_{g\text{RSOA}}=3.6$ and $n_{g\text{Si}_3\text{N}_4}=1.94$ is $5246\, \mu\text{m}$. The red dashed rectangle represents the small region of the cavity affected by Joule heating from the pn region under carrier injection operation in forward bias.

4.8 (a) Microscope image of the FM PhC laser. Total optical length with $n_{g\text{RSOA}}=3.6$ and $n_{g\text{SU-8}}=1.59$, is $1894\, \mu\text{m}$ and FSR $79$ GHz. (b) Single mode lasing spectrum with SMSR $>45$ dB and maximum waveguide coupled output power (inset) $3.5$ mW. All data was acquired without temperature stabilisation at room temperature.

4.9 (a) Spectrogram of the time trace for a $10$ kHz driving frequency; depth of modulation $\Delta\nu=4.3$ GHz, DC offset $V_{\text{DC}}=2.6$ V, $V_{\text{pp}}=2.5$ V. (b) Spectrogram of time trace for $100$ kHz driving frequency; depth of modulation $\Delta\nu=2.2$ GHz, DC offset $V_{\text{DC}}=2.6$ V, $V_{\text{pp}}=2.5$ V. (c) A dependency of the Intensity modulation $I_{\text{pp}}=(I_{\text{max}}-I_{\text{min}})/0.5(I_{\text{max}}+I_{\text{min}})$ from $V_{\text{pp}}$. (d) Measured frequency modulation amplitude $\Delta\nu$ versus the modulation frequency.
4.10 (a) SEM image of the PhC cavity surrounded by trenches (light gray area indicated by red dashed line) on silicon designed to decrease heat dissipation from the PhC region. (b) Microscope image of the PhC reflector with needles applied to the NiCr microheater contact pads. (c) Microscope image of the PhC reflector (green rectangle) and phase tuning (PT) section (purple rectangle) placed in-line. Both sections contain microheaters in order to provide a possibility for thermally induced cavity length/phase tuning (PT) and reflection phase (PhC) modulation. (d) Microscope image of the RSOA-PhC SU-8 with heaters laser. (e) VI curve of the microheater, measured resistance 50 Ω at room temperature.

4.11 Lasing characteristics of the FM PhC laser with microheaters. (a) Optical spectrum measurement at different values of injection current. (b) Waveguide coupled LI curve with lasing threshold at 30 mA. (c) Single mode lasing with SMSR > 30 dB measured at 78.5 mA, 20°C. (d) A spectrogram of a heterodyne beating time trace acquired at modulating frequency of 5 kHz, Δν = 2.2 GHz. (e) Depth of modulation Δν measured as a function of modulation frequencies.

5.1 Schematic representation of the hybrid PhC laser with phase tuning section. Laser cavity phase tuning performed by DC bias application on the NiCr microheater II (microheater I is not used in this experiment). The material of the waveguide, vertically coupled to the PhC cavity, is an SU-8 polymer with negative thermo-optical coefficient. L_{gain} = 0.4 mm, L_1 = 3.66 mm, n_{gain} = 3.22 and n_{SU-8} = 1.59 at 1550 nm, at 20°C.
5.2 (a) Transmission (dark blue) and reflection (red) spectra of the PhC cavity with 3 resonances. The resonances could be arranged by reflectance in the following way (from high to low): 1535 nm, 1550 nm, 1543 nm. (b) Single mode lasing at 78 mA (red) at 1535 nm resonance peak (lasing wavelength 1535.48 nm), RSOA gain spectrum (green) at 78 mA. (c) Optical spectrum of the PhC laser operated below threshold versus bias voltage applied on microheater. The fringes with $\sim 0.18$ nm spacing correspond to the FSR of the laser cavity. $2\pi$ propagation phase shift corresponds to $\Delta U = 1.15$ V ($\Delta P = 53.3$ mW).

5.3 (a) Optical spectrum of the “Quiet” single mode regime at single resonance (1535 nm). (b) Time trace of (a) without any dynamics. (c) Fourier spectrum of (b) shows that this is indeed eventless regime.

5.4 (a) Optical spectrum of the simultaneous lasing on two PhC resonances - 1535 nm and 1550 nm. (b) Optical spectrum of two-color lasing with TLS placed at 1550 nm for heterodyne beating measurement. (c) Time trace corresponding to Figure (a). (d) Time trace corresponding to Figure (b). (e) Beating signal from the mode at 1535 nm (black); filtered time trace (red); filtered time trace (light green) without offset introduced by TLS; envelope function (dark orange) of the heterodyne signal after subtraction of filtered signal; blue - reconstructed time trace of the mode at 1550nm. (f) Same as (e), but time trace reconstruction performed for the mode at 1535 nm.

5.5 (a) Optical spectrum of the “Quiet” multimode regime at single resonance (1535 nm). The separation between lasing lines is 0.14 nm or 17.8 GHz. (b) Time trace of (a) without any particular feature (thus quiet). (c) Fourier spectrum of (b) proving absence of any oscillation within 12 GHz bandwidth (photoreceiver bandwidth).

5.6 (a) Optical spectrum of the “Modulated” multimode regime at single resonance (1535 nm). (b) Time trace of (a) comprising repeating pulses. (c) Fourier spectrum of (b) shows the repetition rate of the pulses is 3.63 GHz (first peak, 2nd and 3rd peaks are just harmonics).
5.7 (a) Time trace showing switching between “quiet” and “deep modulation” regimes. (b) Zoom-in of the area depicted by the red rectangle on (a). (c) Fourier spectrum of (a). (d) Fourier spectrum of the modulation part of the time trace (red rectangle). Continuous down-heel pattern on (c) between 2 GHz and 12 GHz appears due to the deep modulation “packages”. (e) Zoom-in of the peak at 14.4 MHz on (c), which seems to be the mean repetition rate of the “packages”. (f) Magnified figure of (b) (green rectangle).
List of Tables

1.1 Parameters of short-wavelength directly modulated VCSELs. . . . . . . 4

2.1 Simulation parameters close to those of the real system . . . . . . . . . . 36

4.1 General parameters of the tested reflector samples. . . . . . . . . . . . 70