Development of hybrid/active/passive silicon photonics for future technologies

Sia, Brian Jia Xu

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**DEVELOPMENT OF HYBRID/ACTIVE/PASSIVE SILICON
PHOTONICS FOR FUTURE TECHNOLOGIES**

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School of Electrical & Electronic Engineering

2020

DEVELOPMENT OF HYBRID/ACTIVE/PASSIVE SILICON PHOTONICS FOR FUTURE TECHNOLOGIES

JIA XU BRIAN, SIA

School of Electrical and Electronic Engineering

A thesis submitted to the Nanyang Technological University in partial
fulfillment of the requirement for the degree of Doctor of Philosophy

2020

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research, is free of plagiarized materials, and has not been submitted for a higher degree to any other University or Institution.

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Supervisor Declaration Statement

I have reviewed the content and presentation style of this thesis and declare it is free of plagiarism and of sufficient grammatical clarity to be examined. To the best of my knowledge, the research and writing are those of the candidate except as acknowledged in the Author Attribution Statement. I confirm that the investigations were conducted in accord with the ethics policies and integrity standards of Nanyang Technological University and that the research data are presented honestly and without prejudice.

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Associate Professor Wang Hong

Authorship Attribution Statement

This thesis contains material from 8 manuscripts, in the publication process/published in the following peer review journals which I am listed as an author.

Chapter 3 is published as J. X. B. Sia, W. Wang, X. Guo, J. Zhou, Z. Zhang, M. S. Rouifed, X. Li, Z. Qiao, C. Liu, C. Littlejohns, G. T. Reed, and H. Wang, “Mid-Infrared, Ultra-Broadband, Low-Loss, Compact Arbitrary Power Splitter Based on Adiabatic Mode Evolution,” *IEEE Photonics J.*, vol. 11, no. 2, p. 6601111, 2019.

The contributions of the co-authors are as follows:

- Dr. *Wang Wanjun* and *I* conceptualized the device.
- *I* designed the device via the Lumerical simulation suite.
- Miss *Zhou Jin* and *I* fabricated the device.
- Miss *Guo Xin* and *I* characterized the device experimentally.
- *I* drafted the manuscript, which was revised by Professor *Wang Hong*, Dr. *Wang Wanjun*, Professor *Graham T. Reed*, Dr. *Callum Littlejohns*, Dr. *Zhang Zecen*, Dr. *Mohamed Said Rouifed*, Dr. *Liu Chongyang*, Dr. *Li Xiang* and Dr. *Qiao Zhongliang*.

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- Dr. *Wang Wanjun* and *I* conceptualized the platform.
- *I* designed the device via the Lumerical simulation suite.
- Miss *Guo Xin*, Miss *Zhou Jin* and *I* characterized the device experimentally.
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Chapter 6 is in the publication process as W. Wang, J. X. B. Sia, X. Guo, X. Li, Z. Qiao, J. Zhou, C. G. Littlejohns, C. Liu, G. T. Reed, and H. Wang, “Spatial Multiplexing + Optical Modulation on the SiN-SOI Multilayer Platform at 2 μm,” submitted to *J. Lightwave Technol.*.

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- *I* drafted the manuscript, which was revised by Professor *Wang Hong*, Dr. *Wang Wanjun*, Professor *Graham T. Reed*, Dr. *Callum Littlejohns*, Dr. *Liu Chongyang*, Dr. *Li Xiang* and Dr. *Qiao Zhongliang*.

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The contributions of the co-authors are as follows:

- Professor *Wang Hong* and Dr. *Liu Chongyang* initiated the project.
- *I* designed the device via transfer matrices and Lumerical simulation suite.
- Miss *Zhou Jin* and *I* fabricated the silicon photonic chip.
- Dr. *Liu Chongyang*, Dr. *Li Xiang* and Dr. *Qiao Zhongliang* fabricated the III-V chip.
- Miss *Guo Xin* and *I* built the test setup for hybrid integration between the silicon photonic and III-V chips.
- Dr. *Li Xiang*, Dr. *Qiao Zhongliang* and *I* performed the hybrid integration between the silicon photonic and III-V chips.
- Dr. *Li Xiang* and *I* built the test setup for laser linewidth and relative intensity noise characterization.
- *I* drafted the manuscript, which was revised by Professor *Wang Hong*, Dr. *Wang Wanjun*, Professor *Graham T. Reed*, Dr. *Callum Littlejohns*, Dr. *Liu Chongyang*, Dr. *Li Xiang* and Dr. *Qiao Zhongliang*.

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*Things are not always right
because they are hard,
but if they are right,
one must not mind,
if they are also hard.*

-Sir Winston Churchill

To

My fiancé, Jin Qian Wei.

My parents, Zhu Meng Shuang and Sia Hai Chew.

My Siblings, Sia Jin Yang, Crystal and Sia Tian Wa, Jeremy Marc.

My Grandparents, Ng Shooi Ying and Sia Lian Huat.

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DEVELOPMENT OF HYBRID/ACTIVE/PASSIVE SILICON PHOTONICS FOR FUTURE TECHNOLOGIES

by

JIA XU BRIAN, SIA

Presented to the Department of Electrical and Electronic Engineering on October 2, 2020,
in partial fulfillment of the requirements for the degree of
Doctor of Philosophy in Electrical and Electronic Engineering

Summary

As a corollary of silicon manufacturing, silicon photonics has emerged as a viable photonic platform that has attracted the attention of many. The commercialization efforts of this technology, however, have remain somewhat limited due to several obstacles, technical and cost-related.

As silicon is a poor emitter of light, the realization of an electrically-pumped monolithic laser source is unlikely. However, one may argue that the above have been satisfactorily resolved with the hybrid/heterogenous III-V/silicon photonic platform. In fact, the poor electro-optic conversion of silicon is one of the main factor that enables high performance hybrid/heterogenous III-V/silicon photonic laser diodes, resulting in significant improvement in performance over its III-V counterparts.

While silicon photonics promises low cost, the premise is that the economies of silicon manufacturing is exploited. The inception of silicon photonics is mainly driven by the “interconnect bottleneck” in telecom and datacom. The data center transceiver market is attractive. However, there is a lack of a singular solution to all requirements in terms of reach, multisource agreement and standards. This implies that the cost of developing silicon photonics technology will be high unless the optical industry makes a concerted effort for standardization. As of now, the volumes required by silicon photonics are too low to draw commitment from large chip-making foundries. This work posits that for silicon photonics to be commercially viable, its range of applications must be widespread. The greater the adoption of silicon photonics in industry, the lower its cost. The condition is that firms must make the first step towards choosing silicon photonics for their applications.

This work focuses on the development of silicon photonics technology beyond the traditional O and C bands. As a proof of concept to the broadband properties of the silicon-on-insulator platform, a high-performance arbitrary power splitter is realized at the longer transparency edge. In regard to the 2 μm waveband, which has been touted as a potential window for optical communications, the active Si-SiN multilayer platform, silicon switching as well as hybrid III-V/silicon photonic tunable lasers operating from 1881-1947, 1955-1992 nm has been demonstrated for the first time. In addition, at the application-rich wavelength region near 1.65 μm , a sub-kHz linewidth, hybrid III-V/silicon photonic tunable laser with a range of 1647-1690 nm is reported.

Thesis Supervisor: ***Wang Hong***

Title: **Associate Professor of Electrical Engineering**

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Abbreviations

Abbreviation	Meaning
AOM	Acoustic Optic Modulator
ASE	Amplified Spontaneous Emission
AWG	Arrayed-Waveguide Gratings
BOE	Buffered Oxide Etch
BOX	Buried Oxide
BTB	Back-To-Back
BW	Bandwidth
CMP	Chemical-Mechanical Polishing
DBR	Distributed Bragg Reflector
DC	Duty Cycle
DCA	Digital Communication Analyzer
DE(MUX)	(De)Multiplexer
DFB	Distributed Feedback
DSP	Digital Signal Processing
DUT	Device-Under-Test
DUV	Deep Ultra-Violet
EBL	Electron Beam Lithography
ECL	External Cavity Laser
EDFA	Erbium-Doped Fiber Amplifier
EO	Electro-Optic
FCA	Free-Carrier Absorption
FDTD	Finite-Difference Time-Domain
FMF	Few-Modes Fiber
F-P	Fabry-Perot
FPC	Fiber Polarization Controller
FSR	Free-Spectral Range
FWHM	Full-Half Width Maximum
HC-PBGF	Hollow Core-Photonic Bandgap Fiber
HITRAN	High-Resolution Transmission Molecular Absorption
I-O	Input-Output
IP	Internet Protocol
LCA	Lightwave Component Analyzer
LIDAR	Light Detection and Ranging
L-I-V	Light-Current-Voltage

MBE	Molecular Beam Epitaxy
MEMS	Microelectromechanical System
MIR	Mid-Infrared
MMI	Multi-Mode Interference
MO	Magneto-Optical
MOCVD	Metalorganic Chemical Vapor Deposition
MRM	Micro-Ring Modulator
MRR	Micro-Ring
MTD	Modal Transmittance Difference
MZI	Mach-Zehnder Interferometer
NCGAS	Network-Configuration Autonomous Gas Sensing
NIR	Near-Infrared
O/E/O	Optical/Electrical/Optical
OM	Optical Modulation
OPA	Optical Phased Array
PAM	Pulse Amplitude Modulation
PAT	Photon-Assisted Tunneling
PECVD	Plasma Enhanced Chemical Vapor Deposition
PIC	Photonic Integrated Circuit
Q-FACTOR	Quality-Factor
RIE	Reactive Ion Etching
RIN	Relative Intensity Noise
RT-CW	Room Temperature-Continuous Wave
SEM	Scanning Electron Microscope
SHREC	Silicon Photonic Hybrid Ring External Cavity
SMF	Single-Mode Fiber
SMSR	Side Mode Suppression Ratio
SOA	Semiconductor Optical Amplifier
SOI	Silicon-on-Insulator
SQW	Single Quantum Well
SSA	Surface State Absorption
SSC	Spot-Size Converter
TDEQ	Transmission Dispersion Eye Closure
TDFA	Thulium-Doped Fiber Amplifier
TDLAS	Tunable Diode Laser Absorption Spectroscopy
TE	Transverse Electric
TEC	Thermo-Electric Controller
TEM	Transmission Electron Micrograph

TM	Transverse Magnetic
TPA	Two-Photon Absorption
VCSEL	Vertical-Cavity Surface-Emitting Lasers
VOC	Vertical Outgassing Channel
VTE	Vernier Transmission Efficiency
WDM	Wavelength Division Multiplexing

CHAPTER 1

SILICON PHOTONICS, AN OVERVIEW

- 1.1 Beginnings: Towards energy efficient, scalable Interconnects**
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1.1 BEGINNINGS: TOWARDS ENERGY EFFICIENT, SCALABLE INTERCONNECTS

Silicon photonics, the spectacular convergence between sophisticated silicon manufacturing as well as the increased bandwidth and energy efficiency enabled by photonics, represents one of the more successful innovations over the past decades. Silicon photonics have made the leap from research labs to the marketplace. However, the opinion is that the technology is still in its earlier stages and its application-space have to encompass a broader range of applications beyond communications in order to reap the economies of scale. The abovementioned statement is cyclical; the central tenet is that the scope of silicon photonics has to first reach an “application inversion point”, increasing the production volumes. Subsequently, a greater weight of the semiconductor industry would come into play, attracting the interest of large chip-making foundries (i.e. GlobalFoundries, TSMC), driving down costs which would lead to increased demand from the marketplace, thereby, stimulating another round of cost-reduction.

This section, in its preceding paragraphs, seeks to examine the critical questions. *Why optical interconnects? What are the advantages of silicon photonics over competing optical interconnect technologies? What are the key technical challenges with regards to silicon photonics?* The work hopes to convince the reader of the potential for silicon photonics to enable pervasive applications in face of the ferocious performance and cost demand of the markets.

In 1965, Gordon Moore made the observation that the number of transistors on an integrated circuit were shrinking so fast that every year, twice as many could fit on a single chip. Subsequently, in 1975, the pace was adjusted to a doubling every 2 year (Moore's Law). The canonical Moore's law has served as a beacon that drives the electronics industry. With Intel leading the charge, the chip industry has kept Moore's prediction alive before hitting the inflexion point at the 10 nanometers node; Intel pushed the launch date of the 10 nanometers node from 2016 to 2019 (Fig. 1-1 (a)-(b)). The chip giant also decided to increase the time between future generations. With the current technology node at 7 nm, one should expect the end of the Moore's law within the coming decade [1]-[2].

Fig. 1-1. (a) Intel's initial predicted launch date of the 10-nm process node, (b) Intel pushed backed the launch of the 10-nm process node due to prior aggressive scaling targets [2].

In addition to the decline in node miniaturization, the growth in clock frequencies has shown signs of saturation since 2004 with regards to significant thermal challenges [3]. In view of the circumstances, the only pathway towards raising computational capabilities is to increase thread and processor core-count [4].

Essentials				
Product Collection	10th Generation Intel® Core™ i7 Processors	8th Generation Intel® Core™ i7 Processors	7th Generation Intel® Core™ i7 Processors	5th Generation Intel® Core™ i7 Processors
Vertical Segment	Mobile	Mobile	Mobile	Mobile
Processor Number	i7-10710U	i7-8650U	i7-7660U	i7-5650U
Status	Launched	Launched	Launched	Launched
Launch Date	Q3'19	Q3'17	Q1'17	Q1'15
Lithography	14 nm	14 nm	14 nm	14 nm
Use Conditions				Industrial Commercial Temp, PC/Client/Tablet
Recommended Customer Price	\$443.00	\$409.00	\$415.00	\$426.00
CPU Specifications				
# of Cores	6	4	2	2
# of Threads	12	8	4	4
Processor Base Frequency	1.10 GHz	1.90 GHz	2.50 GHz	2.20 GHz
Max Turbo Frequency	4.70 GHz	4.20 GHz	4.00 GHz	3.10 GHz
Cache	12 MB Intel® Smart Cache	8 MB Intel® Smart Cache	4 MB	4 MB
Bus Speed	4 GT/s	4 GT/s	4 GT/s	5 GT/s
TDP	15 W	15 W	15 W	15 W
Configurable TDP-up Frequency	1.60 GHz	2.10 GHz		
Configurable TDP-up	25 W	25 W		
Configurable TDP-down Frequency	800 MHz	800 MHz		600 MHz
Configurable TDP-down	12.5 W	10 W	9.5 W	9.5 W

Fig. 1-2. Essentials and performances for 5th, 7th, 8th, and 10th generation i7, U-series processors [5].

As indicated in Fig. 1-2, from the 5th to the 10th generation processor, the technology node has remained unchanged. Contrary to expectations, clock frequencies have generally been reduced across the five generations. The prevailing approach towards performance gains has been enabling multi-thread, multi-core processor technologies. The increased parallelism associated from such architectures and the resultant aggregate bandwidth place ever-increasing performance requirements on copper interconnects; conditions the incumbent interconnecting technology are ever struggling to satisfy as we move from layer 1 to 4 in a four-layered model of cloud and telecommunication applications (Fig. 1-3).

Fig. 1-3. The four-layered model for cloud and telecommunication applications: chips, platforms, data center and telecommunications networks [6].

The four-layered model for cloud and telecommunications applications are shown in Fig. 1-3. While the fundamental functionalities of each network are the same in terms of communications, computing and storage, the key distinguishing factor are the differences in terms of reach [6].

Layer 4 refers to the uppermost layer. It consists of a web of networks that are managed by Telcos. The reach of layer 4 ranges from distance as much as 13000 km in the case of pan-pacific submarine cabling to, from the edge of network, to the consumer (~ 40 km) [6]. Driven by the internet explosion, discrete Indium Phosphide (InP)-based photonic components is the current technology-of-choice in the domain [7]. However, as the demand for information continues to rise exponentially, there will be growing pressure to increase the processing capabilities, bandwidth density, power efficiency as well as reduce the cost of telecommunication equipment.

The datacenter (Layer 3), with reaches of typically up to 300 m, plays an integral role with regards to the core operations of internet giants such as Facebook, Amazon and Google, which came to be primarily as a result of the explosive growth in Internet Protocol (IP) traffic [6]. Cisco predicts that the annual global IP traffic per year could reach up to 4.8 zettabytes by 2022 [8]. Due to the nature of the applications provided by these internet content providers, it is predicted that 75 % of the data traffic would stay internal to the datacenter [9]. For instance, with regards to Facebook, a single user request to one the servers would generate a 1000-fold increase in traffic within the datacenter [10]. As such, efficiencies of the datacenters would directly affect the bottom line of these companies. Resource fragmentation is one of the key issues associated with traditional datacenters (Fig. 1-4 (a)). To this effect, disaggregation of the

server (Fig. 1-4 (b)) has been proposed, such that resources can be individually upgraded and optimized. In order to adaptively provision the computing resources, an energy-efficient, high-bandwidth, low latency interconnecting technology must be developed [11].

Fig. 1-4. (a) Traditional server racks [11]. (b) Disaggregated server racks, where similar resources (i.e. SSD, CPU, GPU) are pooled together [11].

With distances of up to several meters, the layer 2 (Fig. 1-3) comprises of the interconnection between networking equipment (i.e. boards, rack units) [6]. Recent industry trends, in response to the growing I/O requirements, have pondered a potential shift to optical-based backplane from the prevailing electrical-based solutions such as the VPX switched serial fabric-based architectures. The latter technology makes the issues of scalability as well as increasing the level of fault tolerance complex and costly, given that a fully populated VPX blade can consist up to 192 differential pairs in a mesh architecture. Key amongst the current difficulties is the requirement for the copper traces to be referenced to the ground plane. This would imply that individual planes would be needed for the slow/high speed routing and power layers, resulting in future backplanes requiring up to 40 layers in order to comply with terabit-scale routing requirements. Critical to the continuity of the electrical-based platform would necessitate increasing the scale of interconnection or links speeds. Increasing the number of copper traces is hardly a long-term solution, given that it would lead to an increased complexity with regards to the backplanes, potentially leading to increased cost and reduced reliability. In addition, fundamental limitations of copper-based electrical links render further developments challenging, hence the interest in optical-based solutions [12].

The silicon chip occupies layer 1 (Fig. 1-3) in the four-layered model [6]. As mentioned earlier in this section, the parallelism resulting from current multi-thread, multi-core technologies results in more I/O intensive architectures [4]. Furthermore, current clock frequencies have also implied that modern computing systems are I/O bound; interconnecting technology has become a bottleneck towards higher data rates [13].

As we move along layer 4 to 1, it has become clear that the common denominator for all layers is the need for the development for an interconnecting technology with a large bandwidth, scalable in production and energy efficient. Electrical interconnections (RC and LC lines) suffers from significant signal distortion at high modulation frequencies in terms of RC time delay and skin effect. The fundamental limit to data rates supported by electrical-based interconnecting technology can be surmised by (1.1) [14],

$$B \sim B_0 \frac{A}{L^2} \text{ b/s} \quad (1.1)$$

where A is the sum of cross-sectional area with regards to the wiring and dielectrics, L refers to the length of the wire and the value of B_0 typically ranges from 10^{15} to 10^{18} b/s [14]. While dimensional scaling benefits transistor technology in terms of integration densities and speed, it is apparent from (1.1) that reducing A to increase densities will only serve to reduce fundamental data rates. In addition, as the reach of the interconnecting technology increases from layer 1 to 4 (Fig. 1-3), the fundamental data rates will drop. Nevertheless, this does not imply that there is a reduced urgency for innovation at layer 1; modern CPUs are I/O bound [13].

The immunity of optical interconnections to skin effect and RC time delay has great potential to limit the scope of copper wiring with respect to VLSI [15]. Optics mitigates most of the issues that plague electrical interconnections. Instances include signal and clock distortion, voltage isolation, impedance matching and wave reflection phenomena [14]. Furthermore, while there is a strong mismatch in size between silicon-based optics and electronics, the industry is trending towards 2.5-D integration in a multi-chip module or 3-D integration utilizing silicon vias [11]. However, the implementation of photonic-based solutions has not been as pervasive as one would have envisioned. InP, the existing technology, allows for the monolithic integration of all optical functions, in spite of, the caveat lies in the lack of scalability and cost. To the best of our knowledge, the maximum size for InP wafers to date is 100 mm (Fig. 1-5) at a price of 4.55 USD/cm², in comparison, the silicon-on-insulator (SOI) platform used in silicon photonics are much larger and less costly with typical sizes of 300 mm, at 1.30 USD/cm² [16]. Moreover, it is also pertinent to highlight that silicon photonics benefits from excellent yields as a result of mature CMOS processing. The same, perhaps, could not be said for the InP-based platform, which, while demonstrated favorable results, has some room for improvement; i.e. aluminum containing InP lasers are prone to failure [17].

Fig. 1-5. 100 mm 2 μm -thick InP-based epitaxial structures successfully transferred to a 100 mm SOI substrate. Optimal vertical outgassing channel (VOC) of $9 \times 9 \mu\text{m}^2$ squares and 50 μm spacing is applied [18].

The silicon photonic platform, backed by the economies of trillions of dollars of investment into silicon manufacturing, poses an attractive proposition towards the realization of energy efficient, cost competitive, high bandwidth and integration densities interconnecting technology. Low-loss Si waveguides, the fundamental basis for silicon photonics has indicated propagation losses as low as 0.027 [19] and 0.45 [20] dB/cm for the strip and rib designs respectively highlighting the strength of the platform as in terms of energy efficiency. By implementing an optimum ratio of clothoid bends in a 90° bend, bending losses as low as 0.002 dB has been achieved when the radius is only 4 μm , potentially allowing unprecedented integration densities to be achieved in a photonic platform [21].

Fig. 1-6. Schematic of a 90° waveguide bend, composing of clothoid and standard bends [21].

Despite the abovementioned advantage of silicon photonics, there are still several technical hurdles that the technology must overcome. This thesis posits a positive outlook towards these problems in view of the encouraging work that has been done far. In the proceedings, we will briefly discuss the difficulties in silicon photonics and the impressive solutions that have been demonstrated.

The silicon photonics platform obeys Lorentz reciprocity. However, unidirectional flow of light enabled by isolators and by extension, circulators, are required to enable stable laser operation as well in increased scale of integration with regards to photonic integrated circuits. To date, there are three approaches towards the breaking of Lorentz reciprocity [22]. Nonlinear optical isolators are mostly based on the optical Kerr-effect, to achieve symmetry-breaking between co- and counterpropagating light. However, Kerr-induced optical non-reciprocity is shown analytically to be reciprocal for a class of small-amplitude additional waves as such, the capability of such isolators to suppress unknown back reflections might be called into question [23]. Optical isolation can also be achieved via the electro-optical effect, where time-reversal symmetry is broken with temporal-domain modulation. Nevertheless, these devices require sophisticated design, long interaction lengths and a high RF power supply to achieve effective isolation [24]. Integration of silicon photonics with magneto-optical (MO) materials may be the most feasible approach towards the realization towards achieving high-fidelity, compact, on-chip optical isolation in silicon photonics [24]. On-chip laser modes are aligned in the TE-polarization, however, attaining TE-mode optical isolation is a traditionally difficult problem. Attempts are made in resolving this issue, instances include, integrating a polarization rotator with a TM isolator, in which, while excellent suppression has been attained, it comes at a cost of complex fabrication and laborious design [25]. Of late, breakthroughs have been attained in realizing TE mode isolators (Fig. 1-7 (a)) by depositing MO garnet thin films on the sidewalls of Si interferometer waveguides (Fig. 1-7 (b)), demonstrating an excellent extinction ratio of 30 dB [26].

Fig. 1-7. (a) Micrograph of TE-mode isolator [26]. (b) Cross-sectional scanning electron microscope (SEM) image of MO-integrated TE-mode Si waveguide [26].

Key to optical communications, is the ability to perform optical modulation. Through the application of a signal (i.e. electrical), characteristics (i.e. phase) of the lightwave would change. The electrical field effects that are used primarily in semiconductor materials are the Pockels, Kerr and Franz-Keldysh effects. The Pockels effect, in response to a specific orientation of the applied electric field, produces a change in the real refractive index of the material (Δn). This effect, which has been used extensively in lithium niobite (LiNbO_3)-based modulators, however, is not present in Si due to its centrosymmetric lattice structure [27].

The Kerr optical effect, on the other hand, is a third-order electrical field effect in which the change in Δn is proportional to the square of the applied electric field:

$$\Delta n = S_{33} n_0 \frac{E^2}{2} \quad (1.2)$$

where n_0 is the unperturbed electric field, E is the applied electric field and S_{33} is the Kerr coefficient. Unfortunately, the value of S_{33} is low and it has been indicated that the applied electric field will have to approach the breakdown field of Si (10^6 V/cm) before a minute Δn (10^{-4}) has been induced [27].

Dissimilar to the Pockels and Kerr effects, the Franz-Keldysh effect brings about a change in the imaginary refractive index ($\Delta\alpha$) in addition to Δn . The application of an electric field distorts the energy bands which results in a change in $\Delta\alpha$ for wavelengths close to the bandgap value of the material. It should be noted that similar to the Kerr effect, the Franz-Keldysh is weak in Si and the prospects of achieving optical modulation is remote [27].

While the three abovementioned electric field effects are not favorable to the silicon photonic platform, fortunately, this technological hurdle has been extensively overcome with the plasma dispersion effect. By varying the hole and electron carrier concentrations in a P-N or P-I-N junction, changes in Δn and $\Delta\alpha$ can be obtained [28]. Building on the pioneering work of Professor Graham Reed, Richard Soref, Michal Lipson, Dr Brian Bennett and Intel, the bandwidth of silicon photonic-based modulators has increased from the megahertz to the multigigahertz regime [28]-[31]. By optimizing the junction shape in a microring (MRR) (Fig. 1-8 (a)), Intel have demonstrated modulation rate up to 128 Gb/s pulse-amplitude modulation (PAM4) (Fig. 1-8 (b)) in 2019 by optimizing the P-N junction shape with the optical mode [32]. The Chinese University of Hong Kong and University of California, Santa Barbara followed a few month later, reporting 160 Gb/s PAM4 (Fig. 1-9) [33], indicating a positive outlook towards

silicon-based optical modulation technology.

Fig. 1-8. (a) Designed P-N junction to ensure maximum mode-overlap with optical mode [32]. (b) 128 Gb/s, PAM 4 transmission. Left column is captured directly from the digital communication analyzer (DCA), right column shows post-processed eye-diagrams via TDECQ analysis software of the DCA (specified settings: IEEE 802.3) [32].

Fig. 1-9. 160 Gb/s, PAM-4 transmission for different lengths; back-to-back (BTB), 500 m, 1 km [33].

Due to the bandgap value of Si at 1.12 eV, the material is not capable of bandgap detection above 1.1 μm . As it stands, germanium (Ge) and indium gallium arsenide (InGaAs)-based photodetectors dominate the market. It, however, may be argued that Ge could be a better material for photodetection in view of its bandgap value (~ 0.8 eV), which corresponds closely to the telecommunications wavebands. In addition, Ge is CMOS-compatible and has a closer lattice constant to silicon, potentially enabling better integration and improved yields [34]. Specifically, waveguide-integrated photodetectors are imperative as the plane of detection is the same as that of the laser source and waveguides. High performance Ge photodiodes have been reported, demonstrating more than 70 GHz bandwidth with an internal responsivity of more than 1 A/W [35]. The wavelength-of-detection pertaining to Ge-based technologies could be extended towards the mid-infrared (MIR) via the GeSn-alloy, but however, to the best of our knowledge, the leakage currents of these photodetectors are generally higher than that of the Ge detection schemes [36].

Despite the inherent difficulties of using Si as a material for bandgap photodetection at wavelengths longer than 1.1 μm , all-Si photodetectors have the advantage of monolithic integration, thereby simplifying fabrication processes. In 2018, Intel reported a 50 Gb/s all-Si waveguide photodetector operating near the O-band by utilizing two-photon absorption (TPA), surface state absorption (SSA) and photon-assisted tunneling (PAT). The detector has a responsivity of 0.6 A/W and dark current of 850 nA when reverse bias voltage is 5.84 V [37]. Ackert et al. extended the wavelength of detection in the avalanche mode at 1.96 μm (Fig. 1-10 (a)), demonstrating a bit rate of 20 Gb/s (Fig. 1-10 (b)) through the concept of defect-mediated absorption [36].

Fig. 1-10. SEM image of the photodetector [36]. (b) 20 Gb/s operation at reverse bias voltage of 15 V [36].

Silicon has an indirect bandgap, implying that the values of the conduction band minimum and valence band maximum do not occur at the same value of crystal momentum. As photons have negligible momentum, the radiative recombination process needs to be mediated by absorbing or emitting a phonon. The abovementioned process is second-order and has a long lifetime (~ 1 s). Subsequently, this suggests that non-radiative recombination process is dominant in Si; low radiative efficiency [38].

Besides carrier inversion, simulated Raman scattering can be used to realize high performance lasers [39]. Through the concept of reducing nonlinear losses contributed by two-photon absorption (TPA) induced free-carrier absorption (FCA), Rong et al. demonstrated continuous lasing at the first-order Stokes wavelength via an optical pump at 1550 nm. By designing a ring-resonator cavity (Fig. 1-11 (a)), Rong et al. achieved single-mode lasing with a side-mode suppression ratio of 80 dB (Fig. 1-11 (b)), the maximum demonstrated output power is 23 mW (Fig. 1-11 (c)) with a linewidth of 80 kHz (Fig. 1-11 (d)) [40]-[41]. Rong et al. extended upon their previous work and demonstrated the cascaded Raman laser, where lasing up to the second-order Stokes wavelength is demonstrated; the prospects of facilitating lasing at the third-order and beyond remains an exciting prospect [42]. In order to realize practical Raman-based light sources, perhaps, it is imperative to reduce laser threshold levels such that simple, low-cost, edge emitters could be used as pump sources. Takahashi et al. did precisely that, whereby using a heterostructure nanocavity in a photonic crystal slab (Fig. 1-12 (a)), threshold pump levels of $1 \mu\text{W}$ have been achieved (Fig. 1-12 (b)) [43].

Fig. 1-11. (a) Top-down schematic of silicon ring laser cavity, P-I-N structure is formed along the waveguides [40]-[41]. (b) Silicon Raman laser spectrum [40]. (c) Laser output power as a function of coupled input pump power [40]. (d) Measured linewidth of the silicon Raman laser [41].

Fig. 1-12. (a) SEM image of the core region of the laser [43]. (b) Laser output power as a function of coupled input pump power; threshold as low as 1 μW is demonstrated [43].

Functioning as the interface between the electrical and the optical domains, the realization of an on-chip, electrically pump coherent light source is indispensable to the realization of compact, high bandwidth silicon photonic optical links. The conceptualization of a CMOS-compatible monolithic group-IV laser has been touted as the “holy grail” of silicon photonics. The direct bandgap of germanium is close to the C-band at 0.8 eV, furthermore, it is only 0.136 eV higher than that of the indirect bandgap. As such, there has been considerable interest in the material. To date, there are three approaches, namely, heavy doping [44], tensile-strain [45] and alloying with the tin (Sn) material [46]. In 2012, Camacho-Aguilera et al. demonstrated electrical-pumped pulsed lasing at 288 K via heavy doping ($4 \times 10^{19} \text{ cm}^{-3}$) of Ge. Laser power emission up 1 mW has been characterized [44]. However, building on this work has been challenging. Nevertheless, the silicon photonics community remains optimistic for the resolution of a practical, electrically pumped Ge laser in the long run.

Fig. 1-13. (a) Ge laser spectrum above threshold current [44]. (b) L-I of Ge laser; threshold current density is 280 kA/cm^2 [44].

In the meantime, the III-V/Si hybrid/heterogenous platform as pioneered by Fang et al. (Fig. 1-14) [47], is the most feasible approach in realizing practical, coherent light sources on Si. Silicon photonics offers low propagation loss and high integration densities while III-V materials contributes high gain values and the flexibility for bandgap engineering via changes in material composition. The hybrid and heterogenous approach to integration, each, with their own strengths, represents the most common approach in literature. A more detailed elaboration will be given in two following (sections 1.3.4.2, 1.3.2.3) of this chapter.

Fig. 1-14. (a) Cross-sectional schematic of laser structure [47]. (b) Laser spectra slightly above (70 mA) and above threshold current (100 mA); threshold current is 65 mA [47].

1.2 STATE OF ART & TRENDS: INDUSTRY AND ACADEMIA

While the conception of silicon photonics was motivated by the demand for large-bandwidth, scalable interconnects based on CMOS-manufacturability, it has been observed that the technology has moved beyond communication applications in view of its potential to enable pervasive applications. This growing interest can be attributed to the increased maturation of silicon photonics, as key technical challenges with regards to the technology have been adequately overcome.

Silicon photonics is unrivalled in its potential to bring about low-cost optical solutions. Silicon has many properties that is conducive to fiber optics. The band gap of silicon (1.1 eV) is such that the material is transparent to the two communication bands (1.31, 1.55 μm). The electron-hole concept used in transistor technology can be translated to silicon photonics for the modulation of light passing through silicon waveguides via electro-optic effect. Even the most pressing issue, the coupling of light onto the platform, has been satisfactorily resolved with III/V-Si hybrid/heterogenous platform and grating/edge couplers. Silicon photonics has shown to be capable of performing all the key optical functions (Fig. 1-14, 1-15) at a reasonably competitive performance level. Standard CMOS processing techniques can be used to fabricate waveguide structures on the SOI platform. In consideration to the typical wavelength bands used for optical communications, the feature size of waveguides is on the order of 0.5-1 μm . Silicon photonic devices typically require archaic processing ((90 nm type capabilities) compared to advanced microelectronic chips (16 nm type capabilities). In order words, we may already possess most of the processing technologies required to develop silicon-based photonic devices for the upcoming decade at least.

Fig. 1-15. Typical process stack representing a silicon photonics platform with grating couplers, germanium photodetectors, waveguides, modulators and MOSFETS, on a SOI wafer. Note that most of the advanced work in silicon photonics today does not utilize monolithic integration with transistors, but instead, leverages 3 or 2.5-D integration [48].

However, the cost of acquiring silicon photonic-compatible processing capabilities might still prove to be prohibitive for modestly funded start-ups and academic groups. Fortunately, the multi-project wafer run, inherited from the electronics industry allows multiple users to share the cost of a single run. The reduced cost of prototyping encourages exploration. Once the silicon chips have fulfilled the desired specifications, commercialization can proceed rapidly as the cost of a run is mostly attributed to the fabrication of the photomask.

In response to the foundational knowledge and manufacturing know-how established in silicon photonics, academic groups and start-ups have taken the lead in demonstrating novel applications on the silicon photonic platform. In the proceedings of this section, in the current silicon photonic application-space, we identify three novel technologies that may have the potential to advance the state-of-art: fully optical neural networks, optical phased arrays and spectroscopic sensing.

The development of artificial neural networks is motivated by the need for computers to learn, analyze and combine large data-sets without the need for specific instructions. Deep learning is proving to be a disruptive technology, with the ability to enhance medical informatics [49], national intelligence [50], smart manufacturing [51] and more. In spite of, current computing hardware, optimized for von Neumann computing schemes, are under-optimal with regards to artificial neural networks. Significant efforts have been spent in developing novel approaches to hardware architecture; hybrid optical-electronic, and fully optical neural networks [52]-[60].

In comparison, to microelectronic and hybrid optical-electronic implementations, fully optical networks offer inherent advantages in three areas. Firstly, artificial neural networks are based on intensive fixed matrix multiplication. As such, linear transformations can be performed in low-latency optical networks, limited by the group index of the propagating optical mode. In addition, optical systems reduce the system requirement on nonlinearities. In fact, the implicit nonlinearities can be exploited to realize nonlinear transformations in optical neural networks. Lastly, the optical network, once trained, will be passive. Subsequent computation will not require additional input of energy. In a nutshell, fully optical networks offer the potential of lower latency and high energy efficiency.

Despite the abovementioned strengths of an all optical network, such systems were limited by bulky optics, which forms its constituents. In 2017, breakthrough came via Shen and Harris et al., where via silicon photonics, a programmable nanophotonic processing consisting of 56 Mach-Zehnder interferometers (MZI) demonstrated the ability for vowel recognition. Such a system, in principle, could offer orders of magnitude improvement in terms of speed and energy efficiency [61]. Shen and Harris build upon their groundbreaking work by founding Lightelligence and Lightmatter respectively. 2019 proved to be an eventful year for both start-ups. Lightelligence demonstrated a prototype of an accelerator chip that is five order of magnitudes faster [63] than [61]. Lightmatter, on the hand, is on track to deliver the first photonics-based artificial intelligence product [64].

Fig. 1-16. Optical micrograph image of the optical interference unit; red and blue indicates matrix multiplication and attenuation respectively [61]. Inset illustrates the spatial layout of the MZI [62].

Phased arrays operating at radio frequencies are imperative to enabling a wide range of applications. Examples include radar, communications and broadcasting. However, the length of radio frequencies results in systems that are bulky and expensive to scale. In comparison, the silicon photonic platform, which supports much shorter wavelengths, provides an elegant solid-state solution to the issue of scalability. In addition, due to the inherent nature of the optical phased array as a Fourier system, the phase noise at the near-field averages out in the far-field via interference of optical projection from each element; the tolerance in phase errors becomes higher as the size of the optical phased arrays increases. In 2013, Sun et al., became the first in the world to demonstrate large scale integration of optical phased arrays. By integrating an array of 64×64 antennas, 4096 elements are integrated within a silicon photonic chip with a footprint of smaller than $576 \times 576 \mu\text{m}^2$, subsequently, sophisticated radiation patterns are generated in the far-field. Furthermore, through active phase control, it has been shown that dynamic beam steering and shaping could be realized [65].

Fig. 1-17. (a) Near-field distribution of the 64×64 optical phased array; inset indicates a magnified view of 8×8 elements [65]. (b) Far-field distribution of the 64×64 optical phased array [65].

Fig. 1-18. (a) 3-D schematic of a 8×8 optical phased array [65]. (b)-(f) Instances of dynamic far-field patterns through the application of different combinations of voltage values applied to the elements; simulated and measurement results are illustrated [65].

[65] brought the research community to attention, the feasibility and advantages of optical phased arrays. Hutchison et al., through the implementation of non-uniform emitter spacing in a two-axis large-scale emitter array, resolved the intrinsic trade-off between resolution and steering range, demonstrating 500 resolvable spots, 80° measurement-limited steering range and divergence angle of 0.14° [66]. In order to simplify the complex and power consuming phase controls in optical phased arrays, Ito et al. introduced a shallow-etched grating into a lattice-shifted photonic crystal waveguide as the double periodicity to increase upward emission efficiency. In addition, a customized prism lens is used to control the direction of steering while maintaining the collimation condition. A beam divergence angle of 0.15° , measured in a range of $40^\circ \times 4.4^\circ$ and 4256 resolvable spots was reported without precise adjustment of the lens [67].

The rapid rate of industrialization which started about two centuries ago, has raised the standards of living globally. However, as a consequence, this has led to severe environmental problems. Key amongst the issues are the release of polluting gases such as SO_x , NO_x and CO_2 . To date, there are three main approaches towards the characterization of air pollution levels: chemical, mass spectrometry, optical spectroscopy [68]. Electrochemical sensors [69]-[71] are primarily used to detect oxygen and toxic gases. Essentially, electrochemical cells are fuel cells consisting of noble metal electrodes in an electrolyte [72]. In the presence of a gas, a current proportional to the concentration will be generated. Despite its apparent popularity in the gas sensing market, the electrochemical principle poses many limitations in the form of narrow temperature range, limited shelf life and weak selectivity [73]. Mass spectrometry, on the other hand, is an extremely sensitive and specific analytical technique, capable of providing extremely low limits of detection. However, these instruments are bulky and expensive, which limits the extent of adoption in industry. Furthermore, mass spectrometers require high inversion in standards with regards to quantitative analysis, long validation times and complex algorithms and skilled personnel to process heavy data sets [74]. Optical spectroscopy, as compared to the methods suggested above, is usually more straightforward and can achieve a high sensitivity. Instantaneous response time allows one to perform in-situ monitoring. Amongst all the sensing schemes, tunable laser spectroscopy seems to be the most leading edge [75]-[77].

In recent years, there have been a significant push in the development of optical sensors operating in the infrared band [78]-[84]. As each gas has its specific absorption signature in the infrared band, selectivity can be achieved easily with tunable laser spectroscopy. The state-of-art systems based on tunable laser spectroscopy operating in the infrared range have achieved ppm resolution for some of the common gases [85]-[88].

Despite its advantages, spectrometers remain a bulky and expensive commodity, limiting its industrial viability. Implementations such as network-configuration autonomous gas sensing (NCAGS) becomes difficult to implement due to size and cost considerations. By leveraging on silicon photonics, the issue of scalability, cost and size can be easily overcome. Wang et al. reported the characterization of CO using a III-V/Si wavelength tunable Vernier laser, demonstrating good agreement with the high-resolution transmission molecular absorption (HITRAN) database, indicating the viability of the approach for trace gas spectroscopy [89].

This review of the current trends with regards to silicon photonics is by no means a comprehensive overview of the field. Silicon photonics is the subject of many exciting new directions, instances include quantum key distribution [90], compact optical clocks [91] and nonvolatile photonic memories [92].

1.3 CHALLENGES AND OPPORTUNITIES

The development of integrated optics is spurred by the need for an interconnecting technology that is compact, energy efficient, scalable and can support high data rates. To that end, the focus over the years have been placed on 3 wavebands: 850, 1310 and 1550 nm.

Multimode vertical-cavity surface-emitting lasers (VCSELs) directly modulated at 850 nm, operating at multi-mode fiber represents the dominant technology in short reach links: on the order of smaller than 300 m in modern data centers. Currently, multimode VCSELs represents the lowest cost solution in distances under 300 m. The self-hermicity, high-tolerance alignment with multimode fiber, use of plastic coupling optics and larger GaAs wafers in comparison to InP wafers reduces the cost of multimode VCSEL technology. However, as bandwidth requirement increases, there is an argument for data centers to include single-mode fibers for future proofing [93].

The prevailing technology at distances on the order to 10 km is the directly modulated InP distributed feedback (DFB) lasers operating at 1310 nm. To date, InP-based DFB lasers are used as the coherent source in conjunction with an optical isolator in silicon photonic-based transceivers in a hermetic Si package. Besides the hermetic package for the light source, the transceiver package consists of a silicon photonic integrated circuit (modulator and photodetector), driver, transimpedance amplifier and coupling optics, resulting in a more complex assemble in comparison to the directly modulated InP-based transceivers. The increased cost arising from a more elaborate packaging can be further justified when the extent of integration is increased. It has been predicted that silicon photonics-based transceivers will capture a significant market share when the data center moves into the four-channel single mode market in the near future [93].

Away from the tremendous competition of the directly modulated VCSELs and InP-based DFB lasers at shorter distances, the metro and long-reach links are an interesting market segment for silicon photonics. Optical coherent detection, which lost interest back in due to the invention of the erbium-doped fiber amplifier (EDFA), has experienced a revival in the present decade. This is due to the fact that coherent detection captures the full optical field, both magnitude and phase of both polarizations. With the availability of digital signal processing (DSP) techniques as well as advances in complementary metal-oxide semiconductor (CMOS) electronics, coherent detection have moved from single quadrature and polarization to dual quadrature and polarization, regularly demonstrating detection rates of up to 100 Gb/s. Current metro and long-reach links utilizes the intradyne coherent transmission; coherent receivers are compatible with the additional degrees of freedom offered by wavelength/ polarization division multiplexing as the phase and amplitude information of the optical mode is captured and processed by DSP techniques. While the lack of a native laser in silicon photonics is generally accepted as a significant disadvantage of the platform, in metro to long-haul applications, it might be better to separate the III-V laser/gain section away from the silicon photonics and DSP, which are subjected to high operating temperature [94]. In 2014, Doerr et al. demonstrated such a silicon photonics transceiver (Fig. 1-19), reporting data rates of up to 120 Gb/s (Fig. 1-20) with a power consumption of only 45 W [95].

Fig. 1-19. Layout of the silicon photonics coherent transceiver in terms of block diagrams; PS = phase shifter, PD = photodiode, VOA = variable optical attenuator, PBSR = polarization beam splitter and rotator [95].

Fig. 1-20. (a) Experimental setup of coherent transceiver [95]. (b) Eye diagram of 120 Gb/s DP-QPSK, demonstrated by the coherent transceiver [95]. (c) Real time measured constellation plots [95].

1.3.1 Transparency window of the Silicon-on-Insulator platform

The high-quality SOI platform (Fig. 1-21), traditionally used for the low-power CMOS electronics forms the backbone of silicon photonics. The single crystal silicon layers are firstly grown in a boule and sliced into wafers. Subsequently, the surface of these layers is oxidized, forming the native oxide (SiO_2). One wafer will be bombarded by hydrogen atoms at the depth specific to the desired thickness of the silicon device layer. The two oxide layers are bonded together in a vacuum atmosphere and cracked along the hydrogen implantation line. Lastly, the silicon device layer which has been cracked will be polished to reduce surface scattering losses [94].

Fig. 1-21. General structure of a typical SOI platform [96].

Silicon photonics can be generally regarded as optoelectronic devices fabricated from group IV materials. While the focus of GeSn materials has been mainly on photodetection [36], the prospects of Ge have moved towards a broader range of functionalities, such as compact waveguiding [97] and optical modulation [98] due to its higher index contrast in comparison to silicon. However, the scope of this work is focused on silicon fabricated devices due to their robustness in terms of material quality, thereby having the highest possibility of fulfilling the initial promise of silicon photonics: scalability and integration.

Silicon is transparent from 1.1 to 8.5 μm [99], in spite of, if we were to consider the mid-infrared absorption of SiO_2 , the longer transparency edge of the SOI platform reduces to approximately 3.9 μm [100]. Nevertheless, this still implies that there is great spectral real estate to be exploited on the SOI platform given that the typical device layers are 220, 340 and 400 nm thick; longer wavelengths into the mid-infrared can be supported via the thicker silicon device layers.

While the majority of silicon photonic devices have been based on the 1.31 and 1.55 μm waveband, recent trends suggest an extension towards longer wavelengths to take advantage of the spectrum-specific applications [101]. Demonstration of high-performance devices near 3.9 μm would provide the experimental validation on the viability of the SOI platform from 1.1 to 3.9 μm . Furthermore, many substances have significant absorption lines near 3.9 μm , examples include CH_2O , HCL , HBr and $\text{C}_6\text{H}_{12}\text{O}_6$ [102]. In response to the above, efforts have been undertaken to demonstrate the proof-of-concept. Thus far, strip waveguides with propagation loss of 1.28 dB/cm [103], bending losses of 0.02 dB/90° [104], MZIs with an extinction ratios (ER) of 34 dB and free-spectral range (FSR) of 10 nm [105], multi-mode interference (MMI) splitters demonstrating low insertion losses of 0.151 dB [103], racetrack resonators with Q-factors of up to 8200 [106] and thermo-optic MZI modulators [107] are some of the foundational work that has been reported. Moving on, by realizing devices with performance levels that could rival the established work already performed at the 1.31 and 1.55 wavebands, the broadband nature of the SOI platform can be verified and further motivate the adoption of silicon photonics as a solution with regards to applications specific to its transparency window.

1.3.2 “Capacity Crunch” at C-band

As implied in 1.1, the capability of a computational architecture is largely dependent upon 2 main factors, gate and interconnection-delay. In late 2018, GlobalFoundries, one of the world’s three largest advanced chipmakers (TSMC, Samsung, GlobalFoundries), ceased further developments at the 7-nm node [108], signaling the end to 50 over years of gate-scaling. Nevertheless, the limiting factor of current multi-core systems lies with interconnect fidelity, rather than transistor size. Silicon photonics has emerged as a scalable and large-bandwidth approach to solve the interconnect conundrum.

Similarly, the optical industry also faces its own set of problems, namely, that of information scaling. Over the past decades, exuberant innovation in the telecommunications industry have led to the development of low-loss single-mode fiber (SMF) [1], erbium-doped fiber amplifiers (EDFAs) [2], wavelength division multiplexing (WDM) techniques [3], and more recently, digital coherent transmission [4]; pushing the record transmission capacity within a factor of 2 of the nonlinear Shannon limit [5]. While mode-division multiplexing in few-modes fiber (FMF) can increase the spectral efficiency of the 1.55 μm band [6], high modal dispersion in

FMF renders the approach challenging for practical applications [7,8]. The common consensus is that there may not be much headroom left before nonlinear effects sets in with regards to the single-mode fiber (SMF) as indicated in Fig. 1-22 [109]; the growth in IP traffic has persisted at 40 % per annum since the turn of the century [110]. There is a pressing need for the development of a high-capacity physical layer technology to address the ever-growing demand for information in the long run.

Fig. 1-22. Record data transmission capacity of fiber transmission systems scaled numerically to be indicative of a ~ 1000 km system, as a function of time (years) in addition to a prediction of SMF capacity required to fulfill the 40 % annual increment in internet traffic [109].

In view of the issues above, the implementation of silicon photonics at the $2\ \mu\text{m}$ waveband becomes an attractive prospect. Breakthroughs in the hollow core-photonic-bandgap fiber (HC-PBGF) [111]-[114] and thulium-doped fiber amplifier (TDFA) [115]-[116] have highlighted the prominence of the $2\ \mu\text{m}$ waveband, specifically near $1.9\ \mu\text{m}$ for future long-haul optical communications. By propagating 99.8 % of light in air, HC-PBGFs can achieve low latency and large capacity transmission (low nonlinearity) [111]. Because of reduced infrared ‘multiphonon’ absorption via lower modal overlap with glass [112], it has been predicted that near $1.9\ \mu\text{m}$, HC-PBGFs will display loss levels comparable to that of the SMFs at the $1.55\ \mu\text{m}$ waveband [113]-[114].

Fig. 1-23. Black solid lines refer to net attenuation loss. Blue and red dashed lines refer to bulk and surface contributions respectively of a 19-cell HC-PBGF, with regards to the actual and plausible attenuation values at $\lambda = 1620$ nm; fraction of light propagating in air are 99.5, 99.8 %. Through extrapolation of the plausible fiber, the minimum attenuation loss is 0.13 dB/km when $\lambda = 1900$ nm [113].

Conveniently, the low-loss window of the HC-PBGFs ($\sim 1.9 \mu\text{m}$) coincides closely with the demonstrated operation bandwidth of the TDFA [115]-[116]. By tuning the broad emission spectra of the $^3F_4 - ^3F_6$ transition in silica fiber, amplification near $1.9 \mu\text{m}$ is demonstrated; through the in-band pumping of laser diodes operating at $\lambda = 1.55 \mu\text{m}$, gain up to 36 dB and noise figures as low as 4.5 dB is reported (Fig. 1-24). The diode-pumped TDFA is capable of delivering more than 20 dB small-signal gain with noise figures lower than 7 dB over a 200 nm bandwidth.

Fig. 1-24. Small-signal (seed power = -20 dBm), noise figures and saturated gain (seed power = 0 dBm), noise figures as a function of wavelength; gain fiber is 4 m-long [116].

To date, instances of viability of the wavelength region in terms of potential optical communications include the error-free 100 Gbit/s WDM transmission over HC-PBGF [117] as well as dense WDM transmission by means of arrayed waveguide grating [118]. Moreover, developments into the wavelength region near 1.9 μm can lead to the culmination of several other key technologies (i.e. trace-gas spectroscopy (N_2O , CO_2 , H_2O) [119], light detection and ranging (LIDAR) [120], optical logic and signal processing [121], implementation of the strong optical Kerr effect on silicon [122] and quantum-enhanced optical systems [123]).

Recent trend suggests an extension of silicon photonics from the O and C-bands towards the 2 μm waveband to enable a wide range of applications [121], [124]. As of now, most optical functions have been realized. Cao et al. demonstrated the MZI and MRR-based modulators, exploiting the plasma dispersion effect in silicon. At $\lambda = 1.95 \mu\text{m}$, the MZI-based modulator attained an experimental-bandwidth limited data rate of 20 Gbit/s, with an extinction ratio of 5.8 dB. In addition, the MRR-based modulator operating in the hybrid carrier depletion and injection mode is shown to indicate data rates of 3 Gbit/s and power consumption of 2.38 pJ/bit [29]. Ackert et al., via the low dose implantation of silicon divacancy, extended the wavelength of waveguide photodetection from 1.55 μm towards the 2 μm waveband reporting a responsivity of 300 mA/W. By operating in the avalanche mode, bit rate of up to 20 Gbit/s is obtained [36]. However, it should be noted that the waveguide photodetector requires bias voltage as high as 27 V, thereby limiting its current utility. Yin et al. demonstrated an alternate pathway towards waveguide photodetection at the 2 μm through hybrid integration with black phosphorous by developing an imprint-based deposition of black phosphorous such that the absorption of the propagating TE_0 is increased; black phosphorus with bandgap ranging from 0.3 – 1 eV, is a viable material system for photodetection up to approximately 4 μm . Via simulations, it was shown that stronger light absorption can be achieved by increasing the thickness of the black phosphorous, thereby, reducing device length and increasing bandwidth. However, a thicker black phosphorous thin film will increase the higher-mode mismatch, reflection loss at the passive to active interface of the waveguide detector. From a fabrication perspective, a thicker black phosphorous thin film has lower mechanical stability and hence the imprinting process will be challenging. By optimizing the thickness of the deposited black phosphorous thin films subject to the factors mentioned above, a high responsivity of 306.7 mA/W at bias voltage of 0.4 V is reported. High-speed operation was attained with a 3-dB bandwidth of 1.33 GHz; the device is shown to support data rates of up to 4.0 Gbit/s [125]. Optical filters are a crucial element in photonic integrated circuits. Amongst the present

architectures (i.e. MRRs [126], arrayed-waveguide gratings (AWG) [127], waveguide Bragg gratings [128]), waveguide Bragg gratings-based filters have intrinsic advantage in terms of FSR-free filtering. However, if we consider traditional waveguide-gating filters, there are only two ports, namely, input/reflection and through; a circulator will be needed to isolate the reflected light towards the input port, increasing the complexity of implementation. Liu et al., by integrating silicon multimode waveguide gratings with adiabatic dual-coupler taper-based mode (de)multiplexers, realized a four-port FSR-free add-drop optical filter, bypassing the need for isolation with regards to reflected light. The reported optical filter has a 0.5-dB bandwidth as wide as 26 nm, with a maximum measured sidelobe suppression ratio of 27 dB. Wavelength tunability was demonstrated, utilizing the thermo-optic effect [129]. Furthermore, this work, in its respective chapters, will add to the current range of optical functionalities at the 2 μm waveband in terms of multilayer platform integration (**Chapter 4**), optical switching (**Chapter 5**), mode division multiplexing and optical modulation based on the plasma dispersion effect (**Chapter 6**), wavelength-tunable electrically pumped lasing (**Chapter 7**).

1.3.3 Exploiting the application-rich 1.65 μm waveband

Over the present decade, the consumption of coal has declined sharply in favor of natural gas as a source of energy to cope with the growing global appetite for energy. This change can be mainly attributed to two factors: advent of hydraulic fracturing technique that enables the extraction of natural gas from unconventional sources and the fact that natural gas emits half as much carbon dioxide in comparison to coal [130].

The disadvantage of natural gas, however, lies in its propensity to leak; approximately 9 million tons of natural gas is leaked into the atmosphere during extraction, transport and storage accounting for United States alone. Methane constitutes 95 % of natural gas. Precise and comprehensive monitoring of methane is pertinent due to several reasons. Firstly, methane is highly explosive; leaks have resulted in fatal explosions all around the world (i.e. San Bruno, California). Methane is also highly-insulating, being able to trap up to 86 times more heat than carbon dioxide over a 20 years period; a 2 % natural gas leak can diminish the environmental benefits of natural gas over coal. Leak detection could also benefit the bottom lines of companies [130].

Tunable diode laser absorption spectroscopy (TDLAS) represents the state-of-art with regards to trace-gas monitoring. By exploiting the rovibrational transitions of gases, the TDLAS technique has been recognized to be cutting-edge with regards to sensitivity, as well as species selectivity. In spite of, widespread adoption has not occurred due to the high prices of these laser spectrometers. Key to the realization of next-generation methane monitoring systems lies in the development of low-cost, scalable, high performance photonic integrated circuits operating near the 1.65 μm wavelength region; methane has significant absorption fingerprints at the 1.65 μm wavelength region [83], [131].

As the title of this section suggests, the 1.65 μm wavelength region is rich in applications and not restricted to the spectroscopy of methane. Despite the encouraging developments in the 2 μm waveband in terms of communication applications, one should not expect to see a 2 μm network in the short term as the fiber drawing techniques of the HC-PBGF are immature and expensive. The 1.65 μm wavelength region, on the other hand, falls within the relatively low-loss window of the SMF [132]. Present communication bandwidth can be increased without having to replace existing fiber infrastructure. The potential of the 1.65 μm wavelength region as a window of communications, specifically filling the gap in telecommunications between the extend L-band EDFA and the state-of-art TDFAs (**section 1.3.2**) has been recognized in view of the development of fiber amplifiers operating in the region [132]-[133]; bismuth-doped fiber amplifier with 23 dB small signal gain and noise figures lower 14 dB has been reported [133] (Fig. 1-25).

Fig. 1-25. Small-signal (seed power = -20 dBm), noise figures and noise figures as a function of wavelength; gain fiber is 50 m-long [133].

Besides methane spectroscopy and communications, the 1.65 μm wavelength will drive numerous key technologies. Crotti et al. demonstrated that laser radiation at 1.65 μm provides enhanced penetration depth and incision quality [134]. In consideration of tissue scattering and absorption effects, it is also found that the optimum wavelength window for deep-tissue imaging corresponds lies in the $\lambda = 1600 - 1700$ nm region [135]-[137]. Due to the pervasiveness of the wavelength region in terms of its applications, this section, in no respect, offers a comprehensive overview of the field, but seeks to emphasize and coax the importance for further developments.

1.3.4 The light source conundrum

In many respects, silicon photonics appears to be an ideal technology for commercially feasible photonic integration. However, the lack of a native, electrically-pumped lasing action in silicon photonics hinders its competitiveness as a photonic platform in spite of its obvious strengths with regards to large-scale integration and low-cost, driven by a CMOS-compatible manufacturing framework. Approaches to “Lighting up Silicon”, as mentioned colloquially amongst silicon photonic workers has been mainly split into 2 camps: locating the laser source off-chip and fabricating an on/off chip coupling interface on the silicon photonic chip, integrating (hybrid/heterogenous) a III-V-based gain section with a silicon photonic-based laser cavity to form a hybrid Si laser. In the following sub-sections, an overview on each section will be provided.

1.3.4.1 Fiber-to-chip interfaces

Efficient fiber-to-chip coupling is a traditionally difficult problem in silicon photonics. This is due to silicon photonic components being typically an order of magnitude smaller than its fiber counterparts, resulting in large dimensional differences between the mode fields of the two. This has led to a great deal of discourse in the silicon photonics community over the years. Fiber-to-chip interfaces can be principally classified into two categories: in-plane and out-of-plane couplers. The latter has a larger alignment tolerance, is compatible with wafer-testing and high-volume fabrication, but has higher coupling losses, smaller bandwidth and is also polarization dependent in comparison to the in-plane coupling approaches [138].

With regards to in-plane coupling, the optical mode is coupled into the silicon photonic chip laterally via a lensed fiber; typical coupling losses are around 1 dB. As the silicon photonic coupling interfaces used in this approach are wavelength-independent, broadband operation can be achieved. The most commonly used edge-coupler consists of an inverse taper section where the width of the waveguide is linearly reduced to a tip (Fig. 1-26); width of tip is typically determined by the resolution of the fabrication process (~ 100 nm). As the optical mode propagates along the length of the taper, it becomes less confined, subsequently, the size of the optical mode increases (effective refractive index reduces) enabling a better overlap with the fiber mode [139]. However, this approach is contrary to the drive for dense on-chip integration as tapers longer than $100\text{ }\mu\text{m}$ are required for the adiabatic conversion from the waveguide mode to the taper.

Fig. 1-26. 3-D schematic of InGaAsP waveguide-based inverse taper edge coupler [139].

In order to reduce the footprint of inverse taper edge couplers, Almeida et al., by using a parabolic-shaped transitions, demonstrated a $40\text{ }\mu\text{m}$ -long adiabatic transition of a single-mode waveguide ($0.47 \times 0.27\text{ }\mu\text{m}^2$) to a tip, 100 nm wide. At the wavelength of $\lambda = 1.55\text{ }\mu\text{m}$, the measured TE and TM coupling losses are 3.3 and 6.0 dB respectively [140]. The higher TM coupling losses can be attributed to that fact that this design expands the optical mode in the in-plane direction but does not address the out-of-plane direction. To address this issue, one will have to control the size of the optical mode in the out-of-plane direction. This however, from a fabrication perspective, is highly challenging and require complex techniques such as gray-scale masks and gray-scale ultraviolet lithography; not necessarily compatible with standard CMOS process flows [138]. Another option which has a more viable mass-fabrication potential will be the deposition of claddings with refractive indices that are closer to that of the silicon waveguide core; Si_3N_4 [138], $\text{SiO}_x\text{N}_y/\text{SION}$ [141] and SiO_x [142]. This would lessen the index contrast between the silicon waveguide and its cladding material, resulting in a reduction to the extent of confinement with regards to the propagating mode.

Moving away from the inversed taper topology, Hatori et al. proposed the trident edge couplers (Fig. 1-26) that eliminates the need for dedicated fabrication flows as mentioned in the previous paragraph. Through the appropriate implementation of the gaps between the two lateral waveguides as well as the tip widths, the optical mode can be tuned. At the wavelength of $\lambda = 1.55 \mu\text{m}$, the measured TE and TM coupling losses are 0.92 and 0.94 dB respectively [143]-[144].

In addition to the inverse taper and trident-based edge couplers which has been elaborated above, metamaterial and vertical end-fire-based edge couplers are amongst the designs that have been explored [138]. However, in view of the low-coupling losses, simplicity in fabrication as well as the flexibility for optical mode tailoring, trident edge couplers may be the most promising technology with regards to commercially viable fiber-chip edge coupling interfaces.

Fig. 1-27. Schematic of the trident edge coupler; SEM images of the coupling region are shown at the inset, design parameters of the trident edge coupler operating at $\lambda = 1.55 \mu\text{m}$ indicated [143]-[144].

Thus far, the vertical coupling of light via diffractive gratings have been one of the most researched sub-sections in silicon photonics. The key performance metrics of a diffractive grating are directionality, reflectivity as well as overall coupling efficiency.

The directionality of a grating coupler can be defined as the ratio of optical power that is diffracted upwards, towards the fiber and downwards, towards the substrate. It can be improved via the implementation of mirrors underneath the gratings. This would direct the part of light that was travelling downwards, towards the substrate, upwards. As such, coupling efficiencies will increase. Such mirrors can be implemented with distributed bragg reflectors (DBR) [145] or a metallic mirror [146].

Reflectivity refers to the F-P oscillations that is typically observed in the power-wavelength spectrum of a diffractive grating. This is an intrinsic artefact amongst diffractive gratings caused by the non-zero reflectivity between the silicon waveguide and the grating section. However, the extent of reflectivity can be alleviated by increasing the periodicity of a photonic crystal-based grating coupler in the direction of lightwave propagation and reducing the dimensions of the nanoholes [147]. Furthermore, reflectivity can also be reduced via the linear apodization of the grating period of a diffractive grating [148].

Coupling efficiency indicates the amount of losses that is incurred when the light propagating in a silicon waveguide is coupled to the fundamental mode of an optical fiber via a diffractive gratings, or vice versa. The apodization technique is a powerful approach to increase coupling efficiencies via improved mode overlap. The three common approaches to diffractive grating apodization includes mode-targeting apodization, numerical optimization and linear chirping [138].

Despite the wealth of demonstration with regards to highly efficient diffractive gratings, 1-D grating couplers are still widely used due to its fabrication simplicity as well as the availability of design tools. In the proceedings of this section, the fundamental operating principle of a 1-D grating coupler will be elaborated.

Fig. 1-28. (a) Cross-sectional depiction of a 1-D grating coupler [138]. (b) Top-view depiction of a 1-D grating coupler [138].

The cross-sectional depiction of a 1-D grating coupler is shown in Fig. 1-28 (a) where L_E and L_O refers to the lengths of the etched and non-etched sections in a grating period (Λ) respectively, e is etch depth, P_{wg} , P_{up} , P_{down} and P_{sub} , are the optical power propagating in the waveguide, diffracted towards the optical fiber, directed towards the substrate and in the substrate respectively. The top-view depiction is illustrated in Fig. 1-28 (b), showing a rectangular-shaped device with typical widths of $12 \mu\text{m}$. The period (Λ) of an elementary unit in a 1-D grating coupler can be defined as (1.3).

$$\Lambda = L_E + L_O \quad (1.3)$$

The fill factor is expressed as the ratio between the L_O and Λ (1.4).

$$\text{FF} = \frac{L_O}{\Lambda} \quad (1.4)$$

To an approximation of the first order, the effective refractive index of the grating section can be defined as (1.5) where n_O and n_e are the effective refractive indices of the optical mode in the non-etched and etched sections.

$$n_{eff.} = \text{FF} \cdot n_O + (1 - \text{FF}) \cdot n_e \quad (1.5)$$

The principle of a diffractive grating can be described through the Bragg condition, which relates the wavevectors of the incident and diffracted optical modes. With regards to Fig. 1-28 (a), one can express the Bragg condition as (1.6), where m is the diffraction order, $k_{m,z}$ the magnitude of the m diffracted order in the z -axis, β is the propagation constant of the optical mode in the waveguide and K is the wavevector in the Z -direction.

$$k_{m,z} = \beta - mK, K = \frac{2\pi}{\Lambda} \quad (1.6)$$

If the refractive index of the top and bottom medium is n_1 and n_2 respectively, the wavevector of the m^{th} -diffracted order can be expressed by (1.7)-(1.8) and the waveguide propagation constant (1.9), where the n_{eff} refers to the effective refractive of the waveguide mode.

$$|k_m| = \frac{2\pi}{\lambda} \cdot n_1, \text{ in top medium} \quad (1.7)$$

$$|k_m| = \frac{2\pi}{\lambda} \cdot n_2, \text{ in bottom medium} \quad (1.8)$$

$$\beta = \frac{2\pi}{\lambda} \cdot n_{eff}. \quad (1.9)$$

Most commonly, 1-D grating couplers are designed according to the condition when $\Lambda > \lambda/n_{eff}$. As illustrated in Fig. 1-29, the Bragg condition can be demonstrated using the wavevector diagram. In this case, we consider the first diffraction order ($m = 1$). By subtracting m times of the grating vector K (light blue, solid) from the propagation constant, β (light green, solid) in the z -direction, followed tracing the vertical line (black, dashed) from the endpoint of the resultant vector perpendicularly to the interface of k_1 and k_2 (navy blue and orange respectively, solid) the angle of diffraction (θ, θ') can be determined; the second diffraction ($m = 2$) is suppressed in this case. Should the vertical line (black, dashed) crosses k_1 and/or k_2 , the solution of the diffracted beam will be physical; the vector starts at the origin and ends at the intersection point as abovementioned. The solid and dashed red arrows refers to the upwards and downwards diffracted beams.

Fig. 1-29. Wavevector diagram of a 1-D grating coupler when $\Lambda > \lambda/n_{eff}$.

By reformulating the Bragg condition when $m = 1$, the Bragg condition can be expressed as (1.10), indicating that the diffraction angles of the designated wavelength can be tuned by adjusting Λ , e , and FF.

$$n_{eff} - n_1 \cdot \sin\theta = \frac{\lambda}{\Lambda} \quad (1.10)$$

1.3.4.2 III-V/ Si heterogenous lasers

Pioneered by Intel and University of California, Santa Barbara [47], III-V/ silicon heterogenous lasers represents one of the key breakthroughs in silicon photonics. Via the bonding of materials on a wafer level scale, heterogenous integration enables a viable solution towards scaling and high-volume production, unprecedented so far in silicon photonics. By locating the III-V gain section on top of the photonic integrated circuit, electrically-pumped compact lasers can be realized on the silicon photonics platform. To date, there are 3 general approaches with regards to III-V/ silicon heterogenous integration: adhesive bonding, molecular wafer bonding.

The adhesive bonding material typically used for the heterogenous integration between III-V and silicon is the divinylsiloxane-bisbenzocyclobutene (DVS-BCB). This due to the high bonding strength of the material as well as its resilience to the subsequent III-V fabrication processes. The abovementioned adhesive bonding technology is an area which has been developed extensively by IMEC [149]-[150]. General process flows include the spin coating of DVS-BCB, followed by die attachment and curing in a nitrogen plasma at elevated temperatures. An imperative advantage of the adhesive bonding strategy is that the stringent requirements on the bonding surfaces in terms of contaminations and smoothness is greatly alleviated. This method is however, not without its caveats. DVS-BCB has a poor thermal conductivity, which will impact laser performance; laser performance could diminish as a result of heat saturation. Moreover, the requirement for thin DVS-BCB bonding layers (< 100 nm) to enable efficient III-V/ silicon efficient evanescent coupling will serve to reduce process yields. In 2017 and 2018, Wang et al. reported the heterogenous III-V/ silicon DFB [151] and Vernier-based wavelength-tunable lasers respectively [89], utilizing a DVS-BCB bonding layer 50 nm-thick. The DFB laser array covered a wavelength region of $\lambda = 2.28 - 2.43$ μm , with a side-mode suppression ratio of up to 40 dB. However, the laser output power is found to be highly sensitive to operating temperatures; maximum demonstrated output power is lower than 1 mW at the temperature of 20°C [151] (Fig. 1-30 (a)). The Vernier-based wavelength-tunable lasers were reported to have a tuning range and side-mode suppression ratio of more than 40 nm near 2.35 μm and 35 dB respectively. Similarly to [151], thermal saturation was observed amongst the tunable lasers; the highest demonstrated operating temperature is 10°C , with an output power of lower than 1.5 mW [89] (Fig. 1-30 (b)).

Fig. 1-30. (a) Light-current-voltage (L-I-V) characteristics of the heterogenous III-V/ silicon DFB laser [151]. (b) Light-current (L-I) characteristics of the heterogenous III-V/ silicon Vernier-based wavelength-tunable lasers [89].

The first demonstrated electrically-pumped III-V/ silicon laser [47] was heterogeneously integrated via the plasma-activated low-temperature molecular bonding [152]. As this process is traditionally processed without an oxide interface, generated gaseous byproducts (i.e. H_2 , H_2O) could be trapped within the bonding interface resulting in interfacial voids, impacting bonding quality [153]. The VOC technique was developed to prevent gas trapping at the bonding interface by etching through-holes to the buried oxide (BOX) layer, resulting in the absorption of gas species by the BOX layer [18]. The formation of the VOC is compatible with the waveguide fabrication process, as such, there will be no restrictions imposed on the device design. Nonetheless, it is pertinent to take note that the fabrication of outgas channels such as the VOC, will affect the pattern density of the silicon layer, thereby, the bonding strength could be reduced [153]. Thus far, III-V/ silicon lasers heterogeneously integrated via molecular bonding has demonstrated excellent performance. Prime examples include [154], where the DBR laser (Fig. 1-31 (a)) demonstrated a linewidth (Fig. 1-31 (c)-(d)) and maximum output power of 1 kHz and 37 mW (Fig. 1-31 (e)) respectively. By integrating a low-loss MRR to the DBR laser (Fig. 1-31 (b)), the linewidth is further reduced to 0.5 kHz (Fig. 1-31 (b)-(c)) as effective cavity length is increased and DBR sidelobes reduced; maximum measured output power is 4.8 mW (Fig. 1-31 (f)). The state-of-the-art performance reported in [154] can be attributed to a mature O_2 plasma-activated direct bonding procedure as well as low waveguide propagation loss (0.16 dB/cm) and narrow bandwidth (~ 2.9 GHz) Bragg gratings with an extended physical length.

Fig. 1-31. (a) 3-D schematic of the III-V/silicon DBR laser [154], (b) 3-D schematic of the III-V/silicon MRR-integrated DBR laser heterogeneously integrated through O₂ plasma-activated molecular bonding procedure [154]. Frequency noise spectra in (c) logarithmic scale [154], (d) linear scale [154], indicating minimum white-noise limited frequency noise of 350 and 170 Hz^2/Hz for the III-V/silicon DBR and MRR integrated DBR lasers respectively. The corresponding linewidth of the III-V/silicon DBR and MRR integrated DBR lasers are 1100 and 500 Hz respectively. (e) L-I-V of the III-V/silicon DBR laser [154], (f) L-I of the III-V/silicon MRR-integrated DBR laser [154] with and without active tuning of phase control section.

1.3.4.3 III-V/ Si monolithic lasers

Monolithic integration of III-V and silicon photonics promises to provide the complete suite of optical functions (i.e. electrically-pumped lasing, photodetection, waveguiding, optical modulation), albeit at low-cost and high integration densities. Over the years, this concept has remained a pipe dream due to several profound challenges: large lattice mismatch, significant differences in thermal expansion coefficient as well as distinction in polarity between silicon and III-V materials [155].

To date, as a byproduct of the recent investments made by the electronics industry in the development of high-mobility channel materials, encouraging progress have been made towards overcoming the polarity mismatch between silicon and III-V material. However, there is still, no clear path that could serve to address issues associated with discrepancy in the lattice constants and thermal expansion coefficients of the two material systems; laser yields are reduced due to profound threading dislocation generated during epitaxial growth which would only serve to worsen as a result of asymmetrical material expansion during operation [155].

The adoption of the quantum dot over quantum well structures in III-V gain materials, as it seems, is a powerful approach that would increase the resiliency of laser performance against threading dislocations, thereby, increasing lifetimes and scalability. The radius of influence with regards to a line defect is restricted to the quantum dots in its vicinity. Furthermore, quantum dots structures can function as efficient defect filters that bend threading dislocation downwards, increasing the quality of the gain layers as well as potentially reducing the required thickness of the buffer layers. The demonstration of quantum dot-based lasers grown on (001) silicon substrate [156] pushes the state-of-art with regards to the quantum dot-approach on in-plane (001) silicon surfaces. While it is challenging to extend, the emission of quantum dots to the C-band, Shi et al. circumvented the problem through the growth of InP, quantum well-based laser diodes on nano-patterned V-grooved (001) silicon substrate via metalorganic chemical vapor deposition (MOCVD), demonstrating electrically-pumped lasers operating under continuous-wave operation up to temperatures of 65 °C [157].

As abovementioned, given the large difference in lattice constants of silicon and III-V materials, thick buffer layers on the order of microns-thick are utilized, effectively isolating the III-V active region from the silicon waveguide; inhibiting evanescent coupling between the two photonic platforms. While to the best of our knowledge, there are no reports of III-V/ silicon monolithic lasers that can facilitate evanescent coupling to the silicon photonic platform, the demonstration by Wang et al., suggests the possibility [158] (Fig. 1-32 (a)). Through the fabrication methodology as detailed in [158] [Fig. 1-32 (b)], the thickness from the bottom of the silicon V-groove to the InP top surface is only 515 nm (Fig. 1-32 (c)). Furthermore, threading dislocations and anti-phase boundaries are suppressed to a 20 nm-thick defective nucleation layer that is insulated from device performance. As shown in Fig. 1-32 (d), the transmission electron micrograph (TEM) image along the length of the InP waveguide indicates good crystal quality. By integrating the laser with a DFB reflector, single mode lasing with side-mode suppression of 20 dB was attained under room-temperature pulsed-operation (Fig. 1-32 (e)); when the pump power is under laser threshold, a noisy and broadband spontaneous emission is observed. Laser operation was confirmed in Fig. 1-32 (f), as indicated by the clamping of background spontaneous emission level. The observed laser full-half width maximum (FWHM) broadening with increases in pump intensity was attributed to wavelength chip, which occurs due to modulation of carrier densities by pulsed pumping. This “buffer-less” technique was brought forward to enable the growth of high-quality InP heterostructures which would enable laser emission at the O-band. The threshold pumping density of the lasers were reduced up to a factor of 10, facilitated by carrier confinement in the InP/ InGaAs/ InP heterostructure during optical pumping.

Fig. 1-32. (a) 3-D schematic of the InP DFB lasers, monolithically integrated on silicon; InP, SiO₂ and Si indicated [158]. (b) Monolithic integration process flow; TMAH refers to tetramethylammonium hydroxide solution [158]. (c) SEM (false color) of the InP-on-Si waveguide cross section [158]. (d) TEM of the InP-on-Si waveguide along its length [158]. (e) Room-temperature laser emission spectra below (blue) and above threshold (red) [158]. (f) Room-temperature laser output power and FWHM as a function of the pump laser power (pulsed operation) [158].

1.3.4.4 III-V/ Si hybrid lasers

Amongst the most commonly implemented methods of photonic integration between III-V and silicon photonic platform is edge coupling via flip-chip bonding; notice that all the abovementioned integration techniques make use of evanescent coupling between III-V and silicon photonics. While the monolithic and heterogenous approaches, in principle, provides the greatest potential for the large-scale, low-cost integration of high performance light sources in silicon photonics, it is important to, on hindsight, recognize that these methods requires current foundries to facilitate complex fabrications process steps that might be challenging to accommodate [159]; beside the complex adhesive/molecular bonding steps, one would also have to contend with the co-fabrication of incompatible material platforms which would require separate, optimized processes. Hybrid integration between III-V and silicon photonics, on the other hand, represents the most mature technology in the photonic integration space by leaving integration as a back-end step. One of the most viable approach with regards to hybrid integration is to edge couple the III-V gain section to the silicon photonic chip through flip-chip bonding technique; the III-V gain section is bonded directly to the silicon substrate, which acts as an effective, much required heat sink [159]. This method has been adequately demonstrated, examples includes the work by Fujitsu laboratories [160], where a low coupling loss of 1.55 dB between the III-V gain section and silicon photonics is accomplished (Fig. 1-33 (a)). The DBR laser in question (Fig. 1-33 (b)) is measured to show a low threshold current of 9.4 mA with a laser output power as high as 15 mW (Fig. 1-33 (c)). In addition, the laser is also proved to be capable to be operating at temperatures of up to 60 °C with laser output power of higher than 10 mW (Fig. 1-33 (c)). NEC corporation, utilizing the flip-chip bonding technique, demonstrated a III-V/silicon hybrid laser-based module (Fig. 1-34 (a)) with a fiber-coupled output power in excess of 100 mW and linewidth of narrower than 15 kHz (Fig. 1-34 (b)). Apart from the low coupling loss between the III-V gain section, these excellent properties can be attributed to low silicon waveguide propagation loss as well as the integration of the hybrid laser with a booster gain section (Fig. 1-34 (c)) [161].

Fig. 1-33. (a) 3-D schematic of the flip-chip bonding approach [160]. (b) Micrograph image of the III-V/silicon hybrid DBR laser [160]. (c) L-I-V of the III-V/silicon hybrid DBR laser at temperatures of 20, 30, 40, 50, 60 °C [160].

Fig. 1-34. (a) III-V/silicon hybrid laser butterfly-packaged module [161]. (b) Laser module fiber-coupled output power and linewidth as a function of injection current to the booster gain section; the injection current to the gain section is 100 mA [161]. (c) 3-D schematic of the III-V/silicon hybrid laser, incorporating the booster gain section to increase laser output power [161].

While the flip-chip bonding approach has good scalability, it makes use of passive alignment technology. In other words, the quality of integration in terms of coupling loss between III-V and silicon photonics depends critically on the fabricated dimensional accuracy of the prefabricated III-V and silicon photonic chip mounting section. As such, determination of laser viability can be only carried out after the entire laser has been fabricated. Active alignment technique, by injecting current through the III-V gain section and monitoring the quality of edge coupling via a monitoring port (i.e. on-chip photodetector, inverse taper-based on/off chip edge coupler, diffractive grating-based on/off chip coupler) followed by securing the alignment position through a curing agent, could serve to provide a solution to the above problem. This manner of integration between III-V and silicon photonics, as adopted by this work [162], LioniX International [163], IMEC [164], University of Tohoku [165], University of Delaware [166], Cornell University [167] and a few more, has facilitated Si hybrid lasers with excellent performance.

More intimately, when comparing the architecture of edge-coupled hybrid III-V/ silicon lasers against the monolithically and heterogeneously integrated III-V/ silicon lasers, there may be several decisive advantages. Hybrid integration is achieved by edge coupling the III-V gain section to the passive silicon photonic-based external laser cavity. Such an architecture enables for the silicon photonics and III-V gain section to be individually optimized, enabling high-power laser emission via strong mode overlap with the gain media [168] and easier thermal management. III-V gain section is prone to thermal degradation, locating the III-V component at the edge of the hot VLSI substrate and on a thermally conductive mounting section, reduces the complexity of thermal management [168]-[169]. Furthermore, with regards to the monolithically and heterogeneously integrated III-V/ silicon lasers, low-thermal conductance materials such as DVS-BCB and SiO₂ forms the interface between the III-V and silicon photonics platform which might potentially lead to complications in thermal dissipation during laser operation.

1.4 MOTIVATION

Silicon photonics is one of the most successful innovations over the past decades, fueled by mature silicon processing, sophisticated photonic integrated circuits can now be manufactured at low-cost and large volumes. Thus far, the primary emphasis of developments in the field have geared towards communications at the O and C-band. However, the silicon-on-insulator (SOI) platform is transparent from 1.1 to 3.9 μm , implying that there is great spectral real estate to be exploited on the SOI platform given that the silicon device layers typically range from 200 to 400 nm. Recent trends suggest an extension of silicon photonics from the traditional wavebands to enable a wide range of applications, examples, while not exhaustive, includes fiber communications at the 2 and 1.65 μm wavebands as well as optical spectroscopy of methane at the latter.

This work is motivated by several factors. Firstly, the possibility of realizing devices with high performance near the longer transparency edge ($\sim 3.9 \mu\text{m}$) on the SOI platform that matches that at the incumbent. Many gases have significant absorption lines in the wavelength region, instances include CH_2O , HCL and HBR . Furthermore, successful demonstrations at this wavelength region could encourage progress in silicon photonics that exploit the full extent of transparency, of the SOI platform (**section 1.3.1**). Critically, the 2 and 1.65 μm wavebands are earmarked for further development in view of their potential to act as adjuncts to the present communication infrastructure due to the availability of low-loss fibers, as well as fiber-based optical amplifiers with favorable performance on top of a myriad of other applications (**section 1.3.2 and 1.3.3**). The objective of this thesis is to develop and demonstrate high-performance silicon photonic devices beyond the O and C-bands, indicating the viability of silicon photonics beyond the bounds of optical communications and exploiting a wider range of applications.

To this effect, passive, active and hybrid silicon photonic devices operating in the above-

mentioned wavelength regions are developed. Arbitrary power splitters displaying broadband, low-loss operation from 3.66 to 3.89 μm (230 nm) are fabricated; device insertion loss as low as 0.11 dB is measured (**Chapter 3**). The devices indicate record operation bandwidth and insertion loss in the novel wavelength region of 3.66 to 3.89 μm . With regards to the 2 μm waveband, the first SiN-SOI multilayer platform (**Chapter 4**), $1 \times N$ silicon selector switch (**Chapter 5**), mode division multiplexing and optical modulation based on plasma dispersion effect (**Chapter 6**) and III-V/silicon wavelength tunable laser diodes (**Chapter 7**) are demonstrated. The operation range of the tunable lasers are new in a silicon photonic framework, covering a wavelength region of 1.881 to 1.947 μm , 1.955 to 1.991 μm . Laser output power as high as 28 mW is characterized. In order to exploit the application-rich waveband of 1.65 μm , III-V/silicon wavelength tunable laser diodes are also developed, indicating a novel tunable range of 1.647 to 1.690 μm with a maximum characterized output power of 31.03 mW (**Chapter 7**). The laser is ultra-coherent, demonstrating one of the lowest laser linewidth reported in literature; laser linewidth is sub-kHz.

CHAPTER 2

INTEGRATED OPTICS: FUNDAMENTAL CONCEPTS

- 2.1 Waveguide description and design**
- 2.2 MMI-coupler design**
- 2.3 Design of resonant devices**
 - 2.3.1. Mach-Zehnder interferometer**
 - 2.3.2. Micro-ring resonator**
- 2.4 Single-mode semiconductor laser description**
- 2.5 Conclusion**

2.1 WAVEGUIDE DESCRIPTION AND DESIGN

Waveguiding forms the backbone of integrated optics. The nomenclature of an integrated optical waveguide is regarded as a physical channel, fabricated on a chip, that guides electromagnetic waves in the optical spectrum. As of now, there are three primary integrated optical platforms: conventional lithium niobate, III-V, as well as silicon photonics platforms. The lithium niobate platform, with a large second-order nonlinear susceptibility, piezoelectric response and broadband transparency window, have enabled modulators and periodically polled frequency converters that have served as the workhorse of the optoelectronics industry. However, the conventional lithium niobate platform may be coming to the end of its cycle due to its limited integration potential; the lithium niobate-based waveguides fabricated by the ion diffusion process are weakly confining, resulting in large device footprint and high modulation voltages [170]-[171]. While techniques such as ion milling [172], ion beam-enhanced etching [173] and focused ion beams [174] have produced devices that could circumvent the abovementioned problems, these fabrication process flows are not sufficiently mature and feasible enough from a manufacturing scalability standpoint. On the other hand, the III-V platform has remained as one of the major contender in optical technologies in view of the comprehensive portfolio of functionalities that it entails; electrically-pumped lasing, modulation, amplification and detection. However, the caveat in the technology as compared to silicon photonics, lies in the smaller and more expensive wafers, along with a less-established device manufacturing in comparison to that of silicon [175]. Stemming from low-power, high performance, reliability and cost-effective electronics, the high-quality SOI is the platform of choice for silicon photonics [176]. The triumph of silicon photonics has been its ability to integrate multiple optical functions (i.e. optical modulation, wavelength/space division multiplexing) into a compact form factor, albeit, at low costs and large yields [177]. In spite of, as mentioned in **Chapter 1**, we would like to emphasize that silicon photonics, similarly to the III-V platform, does have its shortcomings, primarily in the lack of an

electrically-pumped lasing functionality. In spite of, III-V and silicon photonics, over the years have become the major photonic platform technologies as industry leaders such as Intel [178] and Finisar [93] have kept faith in overcoming the techno-economic hurdles facing each respective technology in the middle to long-term.

In this section, a theoretical description of waveguiding in an electromagnetic framework will be provided, albeit with some assumptions that simplify the mathematics. This would provide an approximate, yet useful description with regards to the primary phenomena exploited in this thesis [179]. Following, in similar fashion to 2.2 and 2.3, waveguide design methodology will be provided.

Firstly, the Maxwell's equations are defined (2.1)-(2.4).

$$\nabla \cdot D = \rho \quad (2.1)$$

$$\nabla \cdot B = 0 \quad (2.2)$$

$$\nabla \times E = -\frac{\partial B}{\partial t} \quad (2.3)$$

$$\nabla \times H = J + \frac{\partial D}{\partial t} \quad (2.4)$$

Where D (C/m²), B (T), E (V/m), H (A/m), J (A/m²) refers to electric flux density, magnetic flux density, electric field, magnetic field and current density respectively. We can relate D and E , B and H via (2.5)-(2.6) respectively.

$$D = \epsilon_m E \quad (2.5)$$

$$B = \mu_m H \quad (2.6)$$

$$J = \sigma E \quad (2.7)$$

ϵ_m and μ_m are the permittivity and permeability of the medium that the lightwave is propagating in. The current density can be defined at (2.7) with the conductivity expressed as σ .

By applying the del operator (∇) on (2.3) and substitute B from (2.6), (2.8) is obtained.

$$\nabla \times \nabla \times E = -\mu_m \frac{\partial}{\partial t} (\nabla \times H) \quad (2.8)$$

$$\nabla \times \nabla \times E = -\mu_m \left(\frac{\partial J}{\partial t} + \frac{\partial^2 D}{\partial t^2} \right) \quad (2.9)$$

Following, the $\nabla \times \mathbf{H}$ is substituted by (2.4), attaining (2.9).

Subsequently, by replacing $\mathbf{D}$ and $\mathbf{J}$ with (2.5) and (2.7) respectively, (2.10) is derived.

$$\nabla \times \nabla \times \mathbf{E} = -\mu_m \left(\sigma \frac{\partial \mathbf{E}}{\partial t} + \epsilon_m \frac{\partial^2 \mathbf{E}}{\partial t^2} \right) \quad (2.10)$$

$$\nabla^2 \mathbf{E} = \mu_m \epsilon_m \frac{\partial^2 \mathbf{E}}{\partial t^2} \quad (2.11)$$

And by applying the vector identity $(\nabla \times \nabla \times \mathbf{E} = \nabla(\nabla \cdot \mathbf{E}) - \nabla^2 \mathbf{E})$ on the left side of (2.10) and making the assumptions that $\sigma = 0$, $\nabla \cdot \mathbf{E} = 0$ and $\rho = 0$, the wave equation (2.11) is shown.

Where the Laplacian operator is given by (2.12).

$$\nabla^2 = \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \right) \quad (2.12)$$

Let us first express the electric field of the lightwave propagating in a waveguide in terms of its cartesian coordinates (2.13); the defined coordinates are illustrated in Fig. 2-1.

$$\mathbf{E} = E_x \mathbf{i} + E_y \mathbf{j} + E_z \mathbf{k} \quad (2.13)$$

By considering the 3-dimensional coordinates (x, y, z) in (2.13), the left side of (2.11) can be expressed as (2.14).

$$\begin{aligned} \nabla^2 \mathbf{E} = & \left(\frac{\partial^2 E_x}{\partial x^2} + \frac{\partial^2 E_x}{\partial y^2} + \frac{\partial^2 E_x}{\partial z^2} \right) \mathbf{i} + \left(\frac{\partial^2 E_y}{\partial x^2} + \frac{\partial^2 E_y}{\partial y^2} + \frac{\partial^2 E_y}{\partial z^2} \right) \mathbf{j} \\ & + \left(\frac{\partial^2 E_z}{\partial x^2} + \frac{\partial^2 E_z}{\partial y^2} + \frac{\partial^2 E_z}{\partial z^2} \right) \mathbf{k} \end{aligned} \quad (2.14)$$

We assume that the lightwave is propagating in the TE polarization. In this regard, electric field only exists in the x-direction. As such, terms containing E_y and E_z will be set to zero. To simplify further, one can assume that the waveguide is infinite in the x-direction, subsequently

Fig. 2-1. Propagation of lightwave in a waveguide. Definition of propagation constant of the lightwave in the y (k_{yi}) and z (β)-direction; the refractive indices of upper (u), lower (l) cladding and waveguide core (c) are n_3 , n_2 , n_1 respectively. x, y, z coordinates are indicated.

$\partial^2 E_x / \partial x^2$ will also be zero as the field is uniform in the x-direction. (2.14) can be reduced to (2.15).

$$\nabla^2 E = \left(\frac{\partial^2 E_x}{\partial y^2} + \frac{\partial^2 E_x}{\partial z^2} \right) i \quad (2.15)$$

With (2.15), the wave equation at (2.11) can be rewritten as below (2.16).

$$\frac{\partial^2 E_x}{\partial y^2} + \frac{\partial^2 E_x}{\partial z^2} = \mu_m \epsilon_m \frac{\partial^2 E}{\partial t^2} \quad (2.16)$$

As the lightwave is defined to be in the x-direction, the electric field can be written in the following form (2.17).

$$E_x = E_x(y) e^{-j\beta z} e^{j\omega t} \quad (2.17)$$

(2.17) implies that the lightwave is propagating in the z-direction with the propagation constant β and a sinusoidal time dependence, with its electric-field polarized in the x-direction. The variation of electric field in the y-direction is not yet known.

By differentiating (2.17) twice, with respect to z and t, (2.18) and (2.19) are obtained respectively.

$$\frac{\partial^2 E_x}{\partial z^2} = -\beta^2 E_x \quad (2.18)$$

$$\frac{\partial^2 E_x}{\partial t^2} = -\omega^2 E_x \quad (2.19)$$

By substituting (2.18) and (2.19) into (2.16), as well as using following relations (2.20)-(2.23), we can redefine (2.16) as (2.24).

$$k_0 = \frac{2\pi}{\lambda_0} = \frac{\omega}{c} \quad (2.20)$$

$$\frac{1}{v^2} = \frac{\omega}{c} \mu_m \epsilon_m \quad (2.21)$$

$$c = nv \quad (2.22)$$

$$k_{yi}^2 = k_0^2 - \beta^2 \quad (2.23)$$

$$\frac{\partial^2 E_x}{\partial y^2} + k_{yi}^2 E_x = 0 \quad (2.24)$$

In (2.23) and (2.24), the notation of n and k are changed to n_i and k_{yi} to include a description of upper (u), lower (l) claddings as well as waveguide core (c) where $i = 3, 2, 1$ respectively.

The solutions of (2.24), in the upper, lower claddings and waveguide core (Fig. 2-1), in view of the generalized solution (2.17) and the boundary conditions that the electric field and its derivative are continuous at the boundaries, can be expressed by (2.25)-(2.27) respectively.

$$E_x(y) = E_u \exp\left(-k_{yu}\left(y - \frac{h}{2}\right)\right) \text{ when } y \geq \frac{h}{2} \quad (2.25)$$

$$E_x(y) = E_l \exp\left(k_{yl}\left(y + \frac{h}{2}\right)\right) \text{ when } y \leq -\frac{h}{2} \quad (2.26)$$

$$E_x(y) = E_c \exp(-jk_{yc}y) \text{ when } -\frac{h}{2} \leq y \leq \frac{h}{2} \quad (2.27)$$

In order to fulfill the boundary conditions of continuity at the upper/lower cladding-waveguide core interface, (2.25), (2.27) and (2.26), (2.27) are equated at $h/2$ and $-h/2$ respectively (2.28) - (2.29)).

$$E_u = E_c \exp\left(-jk_{yc}\frac{h}{2}\right) = E_c \cos\left(k_{yc}\frac{h}{2} + \varphi\right) \quad (2.28)$$

$$E_l = E_c \exp\left(jk_{yc}\frac{h}{2}\right) = E_c \cos\left(-k_{yc}\frac{h}{2} + \varphi\right) \quad (2.29)$$

The same is applied with regards to the derivative of (2.25)-(2.27) to obtain (2.30)-(2.31).

$$E_u = \frac{k_{yc}}{k_{yu}} E_c \sin\left(k_{yc}\frac{h}{2} + \varphi\right) \quad (2.30)$$

$$E_l = \frac{k_{yc}}{k_{yu}} E_c \sin\left(k_{yc}\frac{h}{2} - \varphi\right) \quad (2.31)$$

(2.28), (2.30) and (2.29), (2.31) are equated together to (2.32) and (2.33) respectively.

$$\tan^{-1}\left(\frac{k_{yu}}{k_{yc}}\right) = k_{yc}\frac{h}{2} + \varphi + m\pi \quad (2.32)$$

$$\tan^{-1}\left(\frac{k_{yl}}{k_{yc}}\right) = k_{yc}\frac{h}{2} - \varphi + m\pi \quad (2.33)$$

Upon the addition of (2.32) and (2.33), (2.34) is attained, where $m\pi$ remains due as tangent functions are periodic in π instead of 2π .

$$\tan^{-1}\left(\frac{k_{yu}}{k_{yc}}\right) + \tan^{-1}\left(\frac{k_{yl}}{k_{yc}}\right) = k_{yc}h + m\pi \quad (2.34)$$

By substituting for the propagation constants in (2.34) and after a series of laborious derivations,

an eigenvalue equation can be obtained; assuming that $n_2 = n_3$ is made as the waveguides in this work are symmetrical.

Fig. 2-2. Graphical solution to (2.34) for θ_1 in a symmetrical waveguide [179].

The eigenvalue equation can be conveniently solved graphically [179]. As an example, if it is assumed that $m = 0$, $h = 0.3 \mu\text{m}$, $\lambda_0 = 1.3 \mu\text{m}$ and $n_1 = 1.5$, $n_2 = n_3 = 1.4$, one can plot as shown in Fig. 2-2, find the interception point to determine θ_1 . Indicated in Fig. 2-2, the value of θ_1 will always be greater than the critical angles at the cladding interfaces ($\phi_u = \phi_l$), the solutions for the optical modes in a symmetrical waveguide will always be physical.

Now that the solutions for the electric field in the upper, lower claddings and waveguide core have been obtained, the effective index of the optical mode, propagating in the waveguide can be defined as (2.35).

$$n_{eff.} = n_1 \sin \theta_1 \quad (2.35)$$

One of the key advantage of the electromagnetic model over the optical ray model lies in its ability to visualize the optical modes. In the follow instance, an asymmetrical waveguide is

$$\begin{aligned} & k_0 n_1 h \cos \theta_1 - m\pi \\ &= \tan^{-1} \left(\frac{\left(\sin^2 \theta_1 - \frac{n_2^2}{n_1^2} \right)^{0.5}}{\cos \theta_1} \right) \\ &+ \tan^{-1} \left(\frac{\left(\sin^2 \theta_1 - \frac{n_2^2}{n_1^2} \right)^{0.5}}{\cos \theta_1} \right) \end{aligned} \quad (2.36)$$

used where the eigenvalue equation in the TE polarization can be defined as (2.36), attained via a similar approach as (2.34). The parameters used in this demonstration are $h = 1.0 \mu\text{m}$, $\lambda_0 = 1.3 \mu\text{m}$ and $n_1 = 3.5$, $n_2 = 1.5$, $n_3 = 1.0$.

By solving for (2.36) for θ_1 in a similar fashion to Fig. 2-2, the electric field distribution of the fundamental ($m = 0$) is illustrated in Fig. 2-3.

Fig. 2-3. Electric field distribution of the fundamental mode in an asymmetrical waveguide ($m = 0$) by solving (2.36) for θ_1 [179].

Moving on from the phenomenological description of waveguiding, the design procedure of waveguides will be provided. As an example, a 220 nm SOI platform is used with a 1 μm -thick

Fig. 2-4. Cross-section of a waveguide fabricated on the 220 nm SOI platform. The SiO_2 cladding and BOX are 1 and 2 μm thick respectively.

SiO₂ cladding at $\lambda = 1.55 \mu\text{m}$. The cross-section of the waveguide is illustrated in Fig. 2-4.

The waveguide was designed using the Eigenmode Solver in Lumerical Mode Solutions; cross-sectional depiction of the waveguide in the tool is illustrated in Fig. 2.4. Fig. 2-5 (a)-(g) indicates the parameters used in the simulation.

Fig. 2-5. Cross-sectional depiction of Fig. 2.4 in the Eigenmode Solver (Lumerical Mode Solutions); annotations are made to show the correspondence between Fig. 2.4 and 2.5. The simulation window used is designated to be $2 \times 2 \mu\text{m}^2$, in consideration of the evanescent fields of the optical mode as well as simulation times.

Fig. 2-6. Parameters of the Eigenmode Solver model (Lumerical Mode Solutions), used in waveguide design in the (a) General, (b) Geometry, (c) Mesh settings, (d) Boundary conditions, (e) Material, (f) Impedance, (g) Advanced options tabs.

With the simulation model, as described in Fig. 2-6, the effective indices of the optical modes, can be studied on the 220 nm SOI platform by performing a sweep of the waveguide width ($w = 0 - 1.47 \mu\text{m}$) (Fig. 2-7); the first four optical modes are computed for changes in the width of the waveguide. The results of the simulation are illustrated in Fig. 2.8.

Fig. 2-7. Eigenmode solver (Lumerical Mode Solutions) waveguide width parameter sweep ($w = 0 - 1.47 \mu\text{m}$);

Fig. 2-8. (a) Effective indices of the first four optical modes as a function of $w = 0 - 1.47 \mu\text{m}$ on the 220 nm SOI platform, $\lambda = 1.55 \mu\text{m}$; TE00 & TM00, TM00 & TE01, TM00 & TE02 hybrid points and single, multi-mode regimes indicated. (b) Optical modes of TE00 & TM00 at the TE00 & TM00 hybrid point. (b) Optical modes of TM00 & TE01 at the TM00 & TE01 hybrid point. (c) Optical modes of TM00 & TE02 at the TM00 & TE02 hybrid point.

As indicated in Fig. 2.8 (a), the waveguide remains in the single-mode regime when $w < 0.5 \mu\text{m}$. In other words, only TM00 and TE01 can be supported within the waveguide. When $w > 0.2 \mu\text{m}$, the effective index of TE00 crosses over that of TM00 and becomes higher. This is referred to the TE00 & TM00 hybrid point. With regards to the multi-mode regime, 2 hybrid points are found when the width of the waveguide is computed up to $1.47 \mu\text{m}$. At $w = 1.07 < w < 0.67 \mu\text{m}$, $w > 1.07 \mu\text{m}$, the effective indices of TE01 and TE02 crosses TM00 to a greater value respectively. Certainly, the waveguide will be able to support a larger amount of optical modes as the width of the waveguide increases, but in this example, for sake of discussion, only the first four optical modes are illustrated. The waveguide design methodology as described in this section can be extended to other photonic platforms (i.e. 400 nm SOI, SiN-Si multilayer platform, germanium-on-insulator (GEOI)).

2.2 MMI-COUPLER DESIGN

Power distribution is one of the fundamental functionalities in silicon photonics. To this effect, the concept of utilizing the self-imaging phenomena in an optical multimode interference waveguide to construct optical splitters/combiners have remained widespread [162], [180]-[182]. Self-imaging phenomena can be obtained when the optical mode propagating in a single-mode waveguide, is introduced to a heavily multi-mode waveguide. The input field will be coupled to all the optical modes that are supported by the multi-mode waveguide, with various amplitude coefficients. Through inter-mode interference in the multi-mode waveguide, the original mode-fields can be replicated at certain lengths of the multi-mode waveguide. Via the discretion of the electrical field distribution in multi-mode waveguide, one will be able to determine the length of the multi-mode waveguide that is required to obtain the desired number of copies of the original mode-fields; power splitting is achieved as a result [183].

The persistent implementation of such devices can be traced to several reasons. Firstly, in comparison to power splitters based on Y-branches as well as evanescent coupling, MMI couplers have a superior fabrication tolerance [183]. This would directly translate into higher device yields, especially when such couplers are used as an elementary component in large and complex silicon photonic circuits. Attributed to the growing number and sophistication of photonic simulation software (i.e. Lumerical, Synopsys) in the market, silicon photonic workers can now model MMI-couplers accurately. In addition to the above, MMI-couplers are fairly compact and has good operation bandwidth [162]. This section will introduce MMI-couplers from a design viewpoint. In the following, the design of a 1×2 and 2×2 MMI couplers, both optimized to operate at $\lambda = 1.9 \mu\text{m}$ on the 220 nm SOI platform. Device performance in terms of simulated insertion loss and operation bandwidth will be illustrated.

The 1×2 and 2×2 MMI couplers are designed using the Eigenmode Expansion Solver in Lumerical Mode Solutions. Firstly, with regards to the 1×2 MMI coupler, the width of the multi-mode waveguide is fixed to be at $6 \mu\text{m}$. Output tapers, $1.1 \mu\text{m}$ -wide and $10 \mu\text{m}$ -long are used to tap the optical modes from the multi-mode waveguides to single-mode waveguides, $0.6 \mu\text{m}$ wide; the length of the taper is sufficiently long enough to enable low loss conversion from a waveguide width of 1.1 to $0.6 \mu\text{m}$ at $\lambda = 1.9 \mu\text{m}$. With regards to the 1×2 MMI coupler, the distance between the center of the 2 output tapers should be kept at one half, the width of the MMI coupler. The top-view depiction of the 1×2 MMI coupler in the tool, with the without the simulation window, mesh and monitor are shown in Fig. 2.9 (a)-(b) respectively. Fig. 2.10 (a)-(f) illustrates the parameters used in the simulation model.

Fig. 2-9. Top-view depiction of the 1×2 MMI coupler in the Eigenmode Expansion Solver (Lumerical Mode Solutions); port 1 and 2 represents the input and output from one of the 2 output waveguides respectively. (a) with simulation window, mesh and monitor, (b) with MMI-features annotated and without simulation window, mesh and monitor.

Edit EME solver

You are in ANALYSIS mode. Switch to LAYOUT mode to make changes:

name: EME

General EME setup Transverse mesh settings Boundary conditions Material Advanced options

cell geometry

x min (μm) [-20] number of cell groups [5]

energy conservation [make passive] number of modes for all cell groups [20] ☒ allow custom eigensolver settings

cell group definition

	group spans (μm)	cells	subcell method	modes	custom	cell range
1	10	1	none	10	default	[1]
2	10	10	CVC5	10	default	[2 ... 11]
3	32	1	none	50	default	[12]
4	10	10	CVC5	10	default	[13 ... 22]
5	10	1	none	10	default	[23]

☒ display cells Clear settings for cell group 1 Custom settings for cell group 1

y (μm) [0] y min (μm) [-4]
y span (μm) [8] y max (μm) [4]
z (μm) [0.11] z min (μm) [-1.25]
z span (μm) [2.72] z max (μm) [1.47]

periodicity

number of periodic groups [1]

periodic group definition

	start cell group	end cell group	periods
1	1	1	1

cell group sequence

row 1: invalid periodic group

Cancel

Edit EME solver

You are in ANALYSIS mode. Switch to LAYOUT mode to make changes:

name: EME

General EME setup Transverse mesh settings Boundary conditions Material Advanced options

Mesh definition

define x mesh by [maximum mesh step]
define y mesh by [number of mesh cells]
define z mesh by [number of mesh cells]

Actual number of mesh cells used

actual mesh cells x
actual mesh cells y [262]
actual mesh cells z [200]

Minimum mesh step settings

min mesh step (μm) [1e-06]

Maximum mesh step settings

dx (μm)
dy (μm)
dz (μm)

Number of mesh cells without override regions

mesh cells x
mesh cells y [200]
mesh cells z [200]

Mesh grading

grading factor [1.41421]

Cancel

Fig. 2-10. Parameters of the Eigenmode Expansion Solver model (Lumerical Mode Solutions), used in the design of the 1×2 MMI coupler at the (a) general, (b) EME setup, (c) Transverse mesh settings, (d) Boundary conditions, (e) Material, (f) Advanced option tabs.

Fig. 2-11. Eigenmode Expansion Solver (Lumerical Mode Solutions) 1×2 MMI coupler length sweep (coupler length = 1 – 50 μm) at a resolution of 0.1 μm .

As all the parameters of the 1×2 MMI coupler have been previously defined with exception of the length of the 1×2 MMI coupler. In Fig. 2-11, the length of the 1×2 MMI coupler is optimized; the length of the 1×2 MMI coupler is referred as group span 3 in the simulation model. The length of the MMI coupler is swept from 1 to 50 μm at a interval of 0.1 μm . The simulated transmittance of the 1×2 MMI coupler as a function of coupler length is shown in Fig. 2-12 (a). The value of minimum insertion loss is 0.54 dB when the coupler length is 23.9 μm ; the top-view electric field distribution of the optimized 1×2 MMI coupler is shown in Fig. 2-12 (b).

Fig. 2-12. (a) 1×2 MMI transmittance as a function of coupler length. (b) Top-view electric field distribution of the 1×2 MMI at the optimized coupler length of $23.9 \mu\text{m}$; the x and y-coordinates corresponds to the position and size of the 1×2 MMI coupler in the simulation model.

The taper, waveguide dimensions as well as MMI coupler width of the 2×2 MMI coupler are set identically to the previously demonstrated 1×2 MMI coupler. The 2×2 MMI coupler is designated according to Fig. 2-13 in the simulation model. With regards to the input side of the MMI coupler on the left of Fig. 2.13, only one taper is implemented instead of 2. This is because the 2×2 MMI coupler is symmetrical along its length. The parameters used in the simulation model is depicted in Fig. 2-14 (a)-(f).

Fig. 2-13. Top view description of the 2×2 MMI coupler in the Eigenmode Expansion Solver (Lumerical Mode Solutions); port 1, 2, 3 represents the input and the output from the 2 output waveguides (a) with simulation window, mesh and monitor, (b) with MMI-features annotated and without simulation window, mesh and monitor.

Edit EME solver

You are in ANALYSIS mode. Switch to LAYOUT mode to make changes:

name: EME

(a)

General EME setup Transverse mesh settings Boundary conditions Material Advanced options

algorithm: finite-difference

background index: 1.444

simulation temperature (K): 300

solver type: 3D: X Prop

set frequency/wavelength

wavelength (μm): 1.9

Cancel

Edit EME solver

You are in ANALYSIS mode. Switch to LAYOUT mode to make changes:

name: EME

(b)

General EME setup Transverse mesh settings Boundary conditions Material Advanced options

cell geometry

x min (μm): -20

number of cell groups: 5

energy conservation: make passive

number of modes for all cell groups: 20

☒ allow custom eigensolver settings

cell group definition

	group spans (μm)	cells	subcell method	modes	custom	cell range
1	10	1	none	10	default	[1]
2	10	10	CVCS	10	default	[2 ... 11]
3	32	1	none	50	default	[12]
4	10	10	CVCS	10	default	[13 ... 22]
5	10	1	none	10	default	[23]

☒ display cells

Clear settings for cell group 1 Custom settings for cell group 1

y (μm): 0 y min (μm): -4

y span (μm): 8 y max (μm): 4

z (μm): 0.11 z min (μm): -1.25

z span (μm): 2.72 z max (μm): 1.47

periodicity

number of periodic groups: 1

periodic group definition

	start cell group	end cell group	periods
1	1	1	1

cell group sequence

row 1: invalid periodic group

Cancel

Edit EME solver (c)

You are in ANALYSIS mode. Switch to LAYOUT mode to make changes: Switch To Layout Mode

name: EME

General EME setup Transverse mesh settings Boundary conditions Material Advanced options

Mesh definition

define x mesh by: maximum mesh step
define y mesh by: number of mesh cells
define z mesh by: number of mesh cells

Actual number of mesh cells used

actual mesh cells x:
actual mesh cells y: 262
actual mesh cells z: 200

Minimum mesh step settings

min mesh step (μm): 1e-06

Maximum mesh step settings

dx (μm):
dy (μm):
dz (μm):

Number of mesh cells without override regions

mesh cells x:
mesh cells y: 200
mesh cells z: 200

Mesh grading

grading factor: 1.41421

Cancel

Edit EME solver (d)

You are in ANALYSIS mode. Switch to LAYOUT mode to make changes: Switch To Layout Mode

name: EME

General EME setup Transverse mesh settings Boundary conditions Material Advanced options

Boundary conditions

x min bc:
x max bc:
y min bc: Metal
y max bc: Metal
z min bc: Metal
z max bc: Metal

☐ allow symmetry on all boundaries

Cancel

Fig. 2-14. Parameters of the Eigenmode Expansion Solver model (Lumerical Mode Solutions), used in the design of the 1×2 MMI coupler at the (a) general, (b) EME setup, (c) Transverse mesh settings, (d) boundary conditions, (e) Material, (f) Advanced option tabs.

In a similar fashion to the 1×2 MMI coupler, the length of the 2×2 MMI coupler is swept from 1 to 50 μm at a resolution of 0.1 μm (Fig. 2-15). The transmittance at the 2 output ports in Fig. 2-13 is indicated in Fig. 2-16 (a); the transmittance at output port 2 and 3 are T_{12} and T_{13} respectively.

Fig. 2-15. Eigenmode Expansion Solver (Lumerical Mode Solutions) 2×2 MMI coupler length sweep (coupler length = 1 – 50 μm) at a resolution of 0.1 μm .

Fig. 2-16. (a) T_{12} , T_{13} as a function of coupler length. (b) Top-view electric field distribution of the 2×2 MMI at the optimized coupler length of 32.8 μm ; the x and y-coordinates corresponds to the position and size of the 2×2 MMI coupler in the simulation model.

Considering Fig. 2.16 (a), the value of coupler length which corresponds to the highest value of transmittance where $T_{12} = T_{13}$ is 32.8 μm . By considering the summation of T_{12} and T_{13} , the insertion loss of the 2×2 MMI coupler when the coupler length is 32.8 μm is 0.68 dB; the electric field distribution from the top-view of the 2×2 MMI when coupler length is 32.8 μm is illustrated in Fig. 2-16 (b).

The simulated wavelength-dependence of the optimized 1×2 and 2×2 MMI couplers are indicated in Fig. 2-17.

Fig. 2-17. Simulated wavelength dependence of the optimized 1×2 and 2×2 MMI coupler.

2.3 DESIGN OF RESONANT DEVICES

Resonant devices are an integral part of silicon photonics. These devices are key enablers in functionalities such as optical modulation [29], [184], sensing [185]-[186] and wavelength division multiplexing [187]-[188].

Mach-Zehnder interferometers and microring resonators are pervasive in the implementation of silicon photonics devices. Pertaining to linear optics, the common denominator with regards to these structures is wavelength dependence; resonances formed in the wavelength spectra are related to device design parameters as well as operating environments; the latter forms the basis behind silicon photonic refractive sensors. While electric field effects are not significant in silicon, high speed control of wavelength resonance can be achieved via the plasma dispersion effect (**section 1.1**). Furthermore, due to the high thermo-optic effect of silicon [179], resonance tuning can also be attained on a passive silicon photonic platform via the mounting of thermo-optic phase shifters. Thermo-optic effect is significantly slower than the plasma dispersion effect, thereby, not suitable for high speed operation. Nevertheless, passive thermo-optic devices require lesser lithographic layers resulting in lower manufacturing costs in addition to potentially higher device yields.

The following subsections will provide a description on the operating principle that will enable the design of MZIs and MRRs.

2.3.1 Mach-Zehnder interferometer

Fig. 2-18. Top-view schematic of a Mach-Zehnder interferometer.

The top view schematic of an MZI is shown in Fig. 2.18. The structure comprises of two waveguides of different lengths (L_1 , L_2), connected via splitters/combiners at both ends. At the other end of the splitters/combiners, single waveguides are connected to form the input and output port. In the following description, it is assumed that the waveguide is single-mode, thereby, the total field intensity within the waveguide is considered. The field distribution inside the waveguide is neglected.

The intensity of the lightwave at the input is defined as I_i with an electric field of E_i . From the output of the splitter, the electric field at the top and bottom branches are defined as (2.37) and (2.38) respectively.

$$E_1 = \frac{E_i}{2^{0.5}} \quad (2.37)$$

$$E_2 = \frac{E_i}{2^{0.5}} \quad (2.38)$$

The propagation constant of the waveguides, with lengths of $L_1 = L_2 + \Delta L$ and L_2 is written in (2.39) and (2.40) respectively.

$$\beta_1 = \frac{2\pi n_1}{\lambda} \quad (2.39)$$

$$\beta_2 = \frac{2\pi n_2}{\lambda} \quad (2.40)$$

$$E_{o1} = \frac{E_i}{2^{0.5}} e^{-i\beta_1 L_1 - \frac{\alpha_1}{2} L_1} \quad (2.41)$$

$$E_{o2} = \frac{E_i}{2^{0.5}} e^{-i\beta_2 L_2 - \frac{\alpha_2}{2} L_2} \quad (2.42)$$

The electric field at the end of the top and bottom waveguides can be described by (2.41) and (2.42) where α_1 and α_2 refers to the loss coefficients at the top and bottom waveguides respectively. One can define the electric field and subsequently the intensity at the output of the MZI after the combiner as (2.43) and (2.44) respectively.

$$E_o = \frac{E_i}{2} (e^{-i\beta_1 L_1 - \frac{\alpha_1}{2} L_1} + e^{-i\beta_2 L_2 - \frac{\alpha_2}{2} L_2}) \quad (2.43)$$

$$I_o = \frac{I_i}{2} |e^{-i\beta_1 L_1 - \frac{\alpha_1}{2} L_1} + e^{-i\beta_2 L_2 - \frac{\alpha_2}{2} L_2}|^2 \quad (2.44)$$

If the losses were to be negligible, (2.44) can be simplified to (2.45).

$$I_o = \frac{I_i}{2} (1 + \cos(\beta_1 L_1 + \beta_2 L_2)) \quad (2.45)$$

Where via (2.44), the output of an MZI is understood to be a sinusoidal function of wavelength ($\beta = 2\pi n_{\text{effective}}/\lambda$). The free spectral range (FSR) of the function can be computed via (2.46); the group index (n_g) is expressed in (2.47).

$$FSR = \frac{\lambda^2}{n_g} \quad (2.46)$$

$$n_g(\lambda) = n_{\text{eff}}(\lambda) - \lambda \frac{dn_{\text{eff}}}{d\lambda} \quad (2.47)$$

Through the thermo-optic/plasma dispersion effect, the effective index of the optical mode at the Mach-Zehnder arms can be altered, thereby, changing the propagation constant, resulting in resonant shifts. An experimental example of the wavelength spectra is shown below in Fig. 2.19, where a Mach-Zehnder modulator is subjected to bias voltages of 0, -4 and -8 V [189].

Fig. 2-19. Wavelength spectra of a Mach-Zehnder modulator with bias voltage of 0, -4 and -8 V [189].

2.3.2 Micro-ring resonator

Fig. 2-20. Top-view schematic MRR in the (a) all-pass, (b) add-drop configuration.

Assuming fundamental mode operation with an MRR radius of r . The interaction between the electric fields propagating at the annotated positions of the resonator (E_{i1} , E_{t1} , E_{i2} , E_{t2}) in an all-pass configuration (Fig. 2-20(a)) can be expressed via the following matrix relation (2.48).

$$\begin{pmatrix} E_{t1} \\ E_{t2} \end{pmatrix} = \begin{pmatrix} t & \kappa \\ -\kappa^* & t^* \end{pmatrix} \begin{pmatrix} E_{i1} \\ E_{i2} \end{pmatrix} \quad (2.48)$$

Complex magnitude of the electric fields (E) are normalized; squaring the magnitudes gives rise to the modal power. Coupling and transmission coefficient are indicated by κ and t respectively, where $*$ implies conjugation. In consideration of reciprocity, the resonator is symmetric. Thereby, κ and t are related via (2.49).

$$1 = |\kappa|^2 + |t|^2 \quad (2.49)$$

To simplify the mathematics, E_{i1} is set to be equals to 1. As such, we can express a round trip in the MRR as (2.50).

$$E_{i2} = \alpha \cdot e^{j\theta} E_{t2} \quad (2.50)$$

$$\theta = \frac{\omega L}{c} = \frac{\kappa c_0 L}{c} = k \cdot n_{eff} \cdot 2\pi r = \frac{2\pi \cdot n_{eff} \cdot 2\pi r}{\lambda} = 4\pi^2 n_{eff} \cdot \frac{r}{\lambda} \quad (2.51)$$

α refers to the attenuation constant of the resonator. ω , L , c , c_0 implies the angular frequency,

ring circumference and propagation speed of the lightwave in the resonator and free-space respectively. Via (2.48) and (2.50) E_{t1} , E_{i2} and E_{t2} can be expressed as (2.52), (2.53) and (2.54) respectively.

$$E_{t1} = \frac{-\alpha + t \cdot e^{-j\theta}}{-\alpha t^* + e^{-j\theta}} \quad (2.52)$$

$$E_{i1} = \frac{-\alpha \kappa^*}{-\alpha t^* + e^{-j\theta}} \quad (2.53)$$

$$E_{t2} = \frac{-\kappa^*}{1 - \alpha t^* e^{j\theta}} \quad (2.54)$$

The power (P) circulating in the add drop structure can be expressed simply via the relation $P = |E|^2$. Corresponding to the resonant condition of the MRR, dips in the wavelength spectrum will be formed (Fig. 2-21) [48].

By considering the MRR in an add-drop configuration (Fig. 2-20(b)) and assuming that E_{i1} is equals to 1. The electric field at the through (E_{t1}) and drop (E_{t2}) ports can be expressed as (2.55) and (2.56) respectively, where $\alpha_{1/2} = \alpha^{0.5}$ and $\theta_{1/2} = \theta/2$ [190]. An experimental illustration of the through and drop ports is shown in Fig. 2-22 [191].

$$E_{t1} = \frac{t_1 - t_2^* \alpha e^{j\theta}}{1 - \alpha t_1^* t_2^* e^{j\theta}} \quad (2.55)$$

$$E_{t2} = \frac{-\kappa_1^* \kappa_2^* \alpha_{1/2} e^{j\theta_{1/2}}}{1 - \alpha t_1^* t_2^* e^{j\theta}} \quad (2.56)$$

Fig. 2-21. Wavelength spectra of a MRR in an all-pass configuration [48].

Fig. 2-22. Wavelength spectra of a MRR in an add-drop configuration; through and drop ports indicated [191].

2.4 SINGLE-MODE SEMICONDUCTOR LASER DESCRIPTION

The inception of the LASER (Light Amplification by Stimulated Emission of Radiation) is a watershed moment technologically. Soon after the demonstration of microwave amplification by simulated emission and the ruby laser, semiconductor lasers are first reported in 1962. Currently, semiconductor lasers form the fundamental basis for pervasive applications. Instances, while not limited, include coherent communications, cold atomic physics research, high resolution metrology and spectroscopy. In comparison to its counterparts (i.e. solid state, gas lasers), semiconductor lasers offer several advantages owing to the its intrinsic lasing mechanism; laser emission in semiconductor lasers is enabled by the carrier (electrons and holes) transition between the conduction and valence bands. Firstly, semiconductor lasers can be pumped using current injection with decent electro-optic efficiency. Solid state and gas lasers require optical pumping and high voltage electric discharge respectively, resulting in complex implementation. Semiconductor lasers are compact and lightweight, bearing good compatibility with fiber-optic networks and high-density optical storage systems. Furthermore, by altering the band structure of semiconductor material, a coverage of laser emission ranging from the ultraviolet to the mid-infrared can be achieved [192].

This section seeks to provide a brief description of single-mode, semiconductor lasers in terms of laser resonance condition. Should one desire a detailed treatise on this topic, there are a wealth of excellently written monographs in the area [192]-[193].

Fig. 2-23. Schematic of a Fabry-Perot cavity laser.

As illustrated in Fig. 2-23, a laser is generally comprised of three components: optical cavity, gain section and mirrors that enable optical feedback. The concept of optical gain can be simply elaborated as below. Through a photon travelling in the laser cavity, a second photon with identical phase and wavelength will be generated via simulated emission, thereby, the intensity of the monochromatic wave is doubled. If the number of photons in the laser cavity is scaled up, the resultant quantity of photons by simulated emission will be significant. However, this amplification process competes with photon absorption by the generation of an electron-hole pair. Simulated emission overwhelms simulated absorption under the condition that there are more electrons in the conduction band than the valence band; laser must be pumped to carrier inversion to obtain net amplification.

The following discussion will utilize the simplistic Fabry-Perot cavity laser (Fig. 2-23). Optical feedback and subsequently resonance are achieved by two reflective facets with reflectivity of R_1 and R_2 . As such, the emission of laser at the facets can be defined as $T_1 = 1 - R_1$ and $T_2 = 1 - R_2$. The propagation loss coefficient of the waveguide, due to imperfections, is α per unit length. The lightwave propagating in the waveguide is amplified by a coefficient of ΓG , where G is material optical gain and Γ is the confinement of the optical mode in the active region. The photon round-trip gain can be written as (2.57).

$$\text{Round-trip gain} = R_1 R_2 e^{(\Gamma G - \alpha)2L} = e^{(\Gamma G - \alpha - \alpha_{\text{mirr.}})2L} \quad (2.57)$$

Where L refers to the length of the Fabry-Perot cavity. The mirror loss ($\alpha_{\text{mirr.}}$) from the two facets can be expressed as (2.58).

$$\alpha_{\text{mirr.}} = \frac{1}{2L} \ln \left(\frac{1}{R_1 R_2} \right) \quad (2.58)$$

$$\Gamma G_{\text{th.}} = \alpha_{\text{tot}} = \alpha + \alpha_{\text{mirr.}} \quad (2.59)$$

For lasing to occur the product of optical confinement and modal gain (ΓG) must be equals to the total losses ($\alpha_{\text{tot.}}$) in a round trip; the modal gain at this condition is referred as threshold modal gain ($\Gamma G_{\text{th.}}$) and G_{th} is the threshold material gain.

In addition to the gain condition expressed in (2.57), the phase condition (2.60) must be satisfied.

$$2L \frac{2\pi}{\lambda} n_{eff.} + \angle r_1 + \angle r_2 = 2\pi M \quad (2.60)$$

Where M , $n_{eff.}$ and $\angle r_i$ refers to an integer, effective index of the optical mode and the phase contribution from the facet. The free-spectral range (FSR) of the lasing modes pertaining to the Fabry-Perot cavity laser is defined as (2.59); n_g is the group index of the optical mode (2.47) [194].

$$FSR = \frac{\lambda^2}{2Ln_g} \quad (2.61)$$

Considering that the semiconductor Fabry-Perot cavity laser can be electrically pumped, for injection current levels (I) corresponding to the threshold modal gain (I_{th}), the output power of the laser above I_{th} can be expressed as (2.62) via the laser rate equations [193].

$$P_0 = \eta_d \frac{h\nu}{q} (I - I_{th}), (I > I_{th}) \quad (2.62)$$

Where η_d , h and ν refer to the differential quantum efficiency, Planck constant and laser frequency. An example of a Fabry-Perot cavity laser Power-Current (L-I) characteristics below and above I_{th} is shown in Fig. 2-24 (a); the laser output power generally increases with injection current and the spontaneous power saturates at the level corresponding to the threshold. The evolution of the laser emission spectra is shown in Fig. 2-24 (b). The strength of the lasing modes can be attributed to the relative gain of the material at the specific wavelength, certainly, non-lasing modes are a result of (2.57) and (2.60) not being fulfilled [157].

Fig. 2-24. (a) L-I laser of the Fabry-Perot cavity laser grown on Si and InP; wall-plug efficiency is illustrated [30]. (b) lasing evolution spectra of the Fabry-Perot cavity laser grown on Si [157].

Fig. 2-25. The fundamental mechanism behind single-mode laser.

The concept with regards to the resonance condition ((2.57), (2.60)) in the Fabry-Perot cavity laser can be extended to single-mode lasers by including a wavelength-selective reflector as part of the laser cavity. In **Chapter 7**, the fabricated III-V waveguide is tilted and anti-reflection coatings are applied on both ends such that it becomes an optical amplifier. In this architecture, the III-V waveguide and the wavelength-selective reflector becomes a single laser cavity and there is essentially only a single wavelength that is resonant. The wavelength-selective functionality is enabled by the MRRs. As illustrated in Fig. 2-25, by reducing the losses at a specific longitudinal mode (λ_1) while keeping the rest high in the laser cavity, the laser will be “forced” to lase at a single longitudinal mode (λ_1) with a side mode suppression ratio (SMSR) of a certain value via mode competition; the remaining longitudinal modes do not satisfy (2.57). Lasing via wavelength selective cavity loss control is the approach that is used in the realization of distributed feedback/ Bragg reflector (DFB, DBR) lasers [154]. To this effect, the realization of the above via the III-V/silicon hybrid/heterogenous platforms has gained significant interest of late. By virtue of the high integrability and low-loss silicon photonics platform, one can reduce the ratio of optical mode oscillating in the III-V as well as increase the effective cavity length of the laser cavity. The result is a reduction in quantum noise via lowering the extent of spontaneous emission in the laser cavity [195]. Laser linewidth on the order of kHz can be achieved (**Chapter 7**), bringing about significant improvement from monolithic semiconductor lasers; the linewidth of a commercial DFB laser at 7.5 MHz (Lorentz fit) was measured using the self-heterodyne technique with a 35 Km fiber offset and an acoustic-optic modulator operating at 80 MHz (Fig. 2-26). Furthermore, by exploiting the tight bending radius of silicon photonic MRRs, high performance widely tunable lasers can be realized (**Chapter 7**).

Fig. 2-26. Measured linewidth of the 1.65 μm DFB commercial laser using the self-heterodyne technique; 35 Km fiber offset and an acoustic-optic modulator operating at 80 MHz is used. (a) Screenshot from the electrical spectrum analyzer. (b) Lorentz-fit of the measured spectrum, indicating a linewidth of 7.5 MHz.

2.5 CONCLUSION

This chapter provides a fundamental description of the devices that will be presented in this work. Waveguides form the underlying basis in **Chapters 3, 4, 5, 6** and **7**. MMI couplers are utilized as interferometric regions in the elementary switching cell (**Chapter 5**) as well as full-reflectors in the III-V/Si hybrid wavelength tunable laser diodes (**Chapter 7**). The Si optical switch presented in **Chapter 5** is based on the MZI switch engine. In **Chapter 7**, compact silicon MRRs are exploited to realize wavelength selective reflectors with large FSRs, leading to wavelength tunable lasers with large tuning range. Finally, an elaboration of the single-mode laser resonance condition and the rationale behind the hybrid integration and III-V is provided.

This work builds on the foundational silicon photonics and III-V fabrication work achieved in Silicon Centre of Excellence, School of Electrical and Electronic Engineering, Nanyang Technological University over the years. As such, to prevent repetition, one can refer to [196] and [197] for a detailed narrative with regards to silicon photonics and III-V fabrication respectively.

CHAPTER 3

ULTRA-BROADBAND, LOW-LOSS, COMPACT ARBITRARY POWER SPLITTER OPERATING AT THE LONGER TRANSPARENCY EDGE OF SOI

- 3.1 Introduction
- 3.2 Device design
- 3.3 Device fabrication and characterization
- 3.4 Conclusion

3.1 INTRODUCTION

This chapter focuses on the development of arbitrary power splitters operating at the MIR. Arbitrary power splitters are a ubiquitous component of photonic integrated circuits. Specifically, broadband arbitrary power splitters with low insertion loss will be critical with increased levels of integration. System designers can utilize such components to enable broadband systems, realizing highly-parallel processing, leading to gains in operational efficiency. Instances of such systems include optical phased arrays (OPA) [198] and on-chip sensing circuits. With regards to optical sensing, input light will be split into two paths. One path will be used for sensing while the other will be used as a reference; subtracting environmental noise from the experimental results. It is important to note that for spectroscopic gas-sensing, broadband operation will be a key requirement. Power splitters have been researched extensively over the years. Besides the standard MMI design, arbitrary power splitting has been demonstrated through alterations in the multimode waveguide [199]-[202]. Directional couplers [203]-[204] can also achieve the above via the tuning of rib waveguide dispersion or phase control through asymmetrical waveguides. The listed examples are however not exhaustive. Devices based on interference or evanescent-coupling tend to be wavelength selective. Narrow bandwidth appears to be an implicit feature of the abovementioned approaches. Of all the design schemes proposed in the literature, adiabatic taper-based power splitters [205]-[207] seems to provide the most promising performance in terms of insertion loss, bandwidth, fabrication complexity and footprint.

By making use of adiabatic mode evolution, this chapter demonstrate low loss, broadband, compact arbitrary power splitters at the longer transparency edge of the silicon-on-insulator platform ($\sim 3.8 \mu\text{m}$) by fabricating asymmetrically spaced tapers on the 400 nm SOI platform (Fig. 3-1). Firstly, Lumerical 3D-FDTD simulation indicates arbitrary power splitting with an operation bandwidth of larger than 230 nm across the $3.8 \mu\text{m}$ waveband. The concept is proven

by fabricating splitters with ratios of 50:50, 60:40 and 70:30. To the best of our knowledge, the arbitrary power splitters demonstrate low insertion loss (0.11-0.6 dB) across the largest operation bandwidth of 230 nm (limited by the tunable range of our laser) in silicon photonics.

3.2 DEVICE DESIGN

In this chapter, we experimentally demonstrate broadband, low loss, arbitrary power splitters based on the adiabatic mode evolution on the 400 nm SOI platform. To ensure that only the fundamental TE mode is supported in the strip waveguide, simulations were performed using the finite difference eigenmode solver; the width of the single mode strip waveguide is designated to be $1.3\ \mu\text{m}$. Fig. 3-1 depicts the three-dimensional schematic of the proposed TE-mode arbitrary power splitter. A fundamental TE-mode input strip waveguide is tapered down and inserted into 2 output tapers with the same length. With regards to the input TE-mode, it will be squeezed out as it travels along the input taper since it will not be supported as the taper width reduces from w_1 to w_2 (Fig. 3-2 (c)). By varying the coupling gap on one side of the taper, arbitrary splitting ratios can be achieved. As shown in the Fig. 3-2 (a), the travelling mode will be enhanced and concentrated in the gaps between the tapered waveguides due to electric field discontinuities. Following, the lossless eigenmodes will be coupled into the two inverse output tapers. The mode evolution process along the length of the taper is shown in Fig. 3-2 (b); the top view of the proposed power splitter is shown in Fig. 3-2 (c).

Fig. 3-1. 3D Schematic of Proposed Power Splitter.

Fig. 3-2. (a) Electric field distribution of TE mode along the device. (b) Cross-sectional view of mode evolution along the taper length. (c) Top view of proposed device; the coordinates in the direction of light propagation.

To obtain low loss and large bandwidth adiabatic mode evolution, it is imperative to ensure that only the fundamental TE-mode is excited along the length of the taper. A 3D-FDTD simulation of the 3-dB coupler (symmetrical gap) was first carried out to determine the optimal taper length at wavelength of $3.8 \mu\text{m}$. The coupling gaps (Variable and Fixed Coupling Gap) and tip width are initially assumed to be 100 nm and 60 nm , respectively. From Fig. 3-3 (a), we can see that when the taper length exceeds $12 \mu\text{m}$, the simulated insertion loss becomes almost negligible. To examine the effect that tip width and coupling gaps have on simulated insertion loss and bandwidth, we performed a 3D-FDTD simulation on a 3-dB coupler with a taper length of $12 \mu\text{m}$. When the tip width is varied from 30 to 120 nm with both coupling gaps fixed at 100 nm , according to Fig. 3-3 (b), the optimal tip width is shown to be 90 nm . However, gains in efficacy is shown to be extremely marginal when tip widths are varied from 30 to 120 nm . Device performance has a high degree of tolerance to tip width, which is extremely important for repeatability between devices. Following, we examine the optimal gap for the 3-dB coupler. From Fig. 3-3 (c), when the gap is decreased from 250 to 100 nm , the simulated insertion loss decreases. We did not consider gaps smaller than 100 nm to ensure compatibility with commercial CMOS process lines.

Fig. 3-3. (a) Variation of simulated Insertion Loss against taper length. (b) Variation of simulated insertion loss against tip width. (c) Variation of simulated insertion loss against gap for the 3-dB coupler.

Following the above design optimization, the taper length, coupling gaps and tip width are selected to be 12 μm, 100 nm and 100 nm respectively. We performed mode analysis (eigenmode solver) at the positions $x = 2, 4, 6, 8, 10 \mu m$ along the length of the coupling region and found that higher mode excitation only occurs from $x = 10 \mu m$ onwards. The TE00 and TE01 modes at positions $x = 10, 10.5, 11, 11.5 \mu m$ (Fig. 3-2 (c)) are shown in Fig. 3-4 (a)-(h). The effective refractive indices of TE00 and TE01 at the abovementioned taper positions are computed in Fig. 3-4 (i). Indicated in Fig. 3-4 (j), as light propagates along the length of the taper, from positions $x = 10$ to 12 μm, the difference between the effective refractive index of TE00 and TE01 decreases. This implies that coupling loss from TE00 to TE01 becomes easier as light propagation approaches the end of the taper. However, as TE01 is not supported throughout the entire coupling region, higher order modes are expected to be better suppressed.

Fig. 3-4. (a)-(h) Cross section of TE00 and TE01 modes along the length of the taper. (i) Effective Refractive index of TE00 and TE01 along the length of the taper. (j) Difference in Effective Refractive Index along the length of the taper.

Fig. 3-5 (a) shows that arbitrary power splitting can be achieved by increasing the variable coupling gap on one side of the power splitter. However, when the variable coupling gap is increased, the simulated insertion loss increases. The effective refractive index analysis was carried out for arbitrary splitting ratios (60:40, 70:30, 80:20, 90:10). As the splitting ratio is varied from 60:40 to 90:10, the difference between the effective refractive index of TE00 and TE01 decreases (Fig. 3-5 (b)). Coupling loss from TE00 to TE01 becomes more viable. It is however likely that coupling loss from TE00 to TE01 does not represent the main source of device insertion loss. Rather, as Wang. et al [205] have stated, TE polarization is sensitive to sidewall roughness during the mode transition process in the coupling region. Simulation indicates that all arbitrary splitting ratios have a bandwidth of greater than 230 nm (3.66-3.89 μm). Following the above design optimization, the taper length and tip width are selected to be 12 μm and 100 nm respectively. To demonstrate arbitrary splitting ratios, we select coupling gaps as shown in Table 3-1.

Fig. 3-5. (a) Different variable gaps corresponding to various arbitrary power splitting ratios and simulated insertion loss. (b) Difference in Effective Refractive Index along the length of the taper; arbitrary power ratios of 60:40, 70:30, 80:20 and 90:10.

TABLE 3- 1.

SELECTED COUPLING GAPS FOR SPLITTING RATIOS OF 50:50, 60:40 AND 70:30.

Gap (nm)	Splitting Ratios
(Fixed Coupling Gap, Variable Coupling Gap)	
100, 100	50:50
100, 130	60:40
100, 200	70:30

3.3 DEVICE FABRICATION AND CHARACTERIZATION

The fabrication process flow is shown in Fig. 3-6. 300 nm of ZEP-520A is spin-coated followed by a soft-bake process on a 400 nm SOI platform. Electron Beam Lithography (EBL) was used to pattern the photoresist. Following, ZED-N50 was used to develop the sample. A single 400 nm etch step using Reactive Ion Etching (RIE) was then carried out to define the waveguides and the grating couplers. O₂ plasma etch was utilized to remove any remaining ZEP-520A. Finally, a 2 μm thick SiO₂ passivation layer is deposited using Plasma Enhanced Chemical Vapor Deposition (PECVD). The device footprint is estimated to be smaller than 12 × 2.9 μm². The power splitters are fabricated according to the optimized parameters obtained earlier. Arbitrary power splitters are fabricated according to the coupling gaps indicated in Table 3-1 (mentioned earlier). To demonstrate the consistency of the power splitting ratio, each power splitter is cascaded over 4 stages as shown in the micrograph image of Fig. 3-7 (a). The insertion loss is obtained with the following approach.

$$IL \text{ (dB)} = \frac{10 \log_{10} \left(\frac{x_1 + x_2 + x_3 + x_4 + x_5}{x_0} \right)}{4} \quad (3.1)$$

Where $x_1, 2, 3, 4, 5$ corresponds to the power from each of the 5 outputs. x_0 refers to the output from the reference waveguide. A factor of 1/4 is used in consideration of the 4 stages. The insertion loss consists of splitter insertion loss and waveguide propagation loss. Grating coupler insertion loss is removed via (3.1) from the insertion loss characterization.

Fig. 3-6. Schematic process flow of the proposed power splitter.

Fig. 3-7. (a) Micrograph image of 4 cascaded stages of power splitter. (b) SEM image of grating coupler and waveguide. (c) SEM image of coupling region with coupling gaps of 100, 100 nm. (d) SEM image of coupling region with coupling gaps of 100, 200 nm.

SEM images of the grating coupler, waveguide, arbitrary power splitter with coupling gaps of (100 nm, 100 nm) and (100 nm, 200 nm) are shown in Fig. 3-7 (b)-(d), respectively. The coupling gaps and taper lengths are measured to be consistent with the intended design parameters. However, the fabricated width of the tip width was found to be 45 nm. Nevertheless, according to Figure 3- 3 (b), the value of tip width has a large degree of fabrication tolerance from 30 to 120 nm. The measurement setup is shown in Fig. 3-8. The light source is a linearly polarized continuous wave tunable laser. A half-wave plate is placed immediately after the

chopper for fine polarization control. Light is launched into the ZrF₄ mid-infrared fiber and focused via the ZnSe lens. Light is then coupled into the device through grating couplers. The grating couplers used in this application have a period of 2440 nm, duty cycle (DC) = 0.5, and an etch depth of 400 nm. Light from the output grating coupler is then coupled to the fiber and directed towards the detector, which is connected to the lock-in amplifier.

Fig. 3-8. Schematic of the experimental measurement set-up.

Fig. 3-9 (a)-(c) shows the experimentally measured spectra for devices with variable gaps of 100, 130, 200 nm respectively in the 4-stage testing structure (Fig. 3-7 (a)). A wavelength sweep is performed from 3.66-3.89 μm and it is observed that the spectrum is relatively flat over the maximum tunable range of our laser. The minor fluctuations can be regarded as experimental noise as we can see that the specific line shape is present in each of the 4 ports. The broadband insertion loss for each beam splitter is shown in Fig. 3-10(a)-(c); the maximum and minimum values of device insertion loss is indicated in Table 3-2.

Fig. 3-9. Experimentally measured spectra at port 1,2,3 and 4 for power splitters with gaps of (a) 100, (b) 130 and (c) 200nm.

Fig. 3-10. Experimentally measured device broadband insertion loss (3.66-3.89 μm) with gaps of (a) 100, (b) 130 and (c) 200nm.

Fig. 3-11. (a)-(c) Linear fit for power splitters with gap of 100, 130, 200 nm across 4 output ports. (d) Splitting ratios of the single-stage power splitter.

TABLE 3- 2.

MINIMUM AND MAXIMUM LEVELS OF INSERTION LOSS FOR ARBITRARY POWER SPLITTERS WITH DIFFERENT SPLITTING RATIOS.

Gap (nm)			
(Fixed Coupling Gap, Variable Coupling Gap)	Splitting Ratios	IL _{min.}	IL _{max.}
100, 100	50:50	0.11	0.46
100, 130	60:40	0.14	0.48
100, 200	70:30	0.22	0.6

For accurate characterization of the splitting ratios, 4-stage and single stage testing structures are utilized. Firstly, for the 4-stage testing structure (Fig. 3-7 (a)), the measured output power at each port was linearly fitted at 3.8 μm . According to Fig. 3-11(a)-(c), we have managed to obtain splitting ratios of -3.10 dB (~50:50), -1.96 dB (~60:40) and -1.37 dB (~70:30) for power splitters with variable gaps of 100, 130 and 200 nm respectively. The ratios between the 2 output ports (Fig. 3-1) of the single-stage testing structures across 3.66-3.89 μm are indicated in Fig. 3-11 (d). The splitting ratios obtained from the single-stage testing structures validates the results from Fig. 3-11 (a)-(c). The coupling gaps fabricated to obtain splitting ratios of 50:50, 60:40 and 70:30 are shown to agree closely with the simulated results in Fig. 3-5 (a). Table 3-3 provides a brief comparison of the work in this chapter with some arbitrary power splitters

in the literature.

TABLE 3-3.

MINIMUM AND MAXIMUM LEVELS OF INSERTION LOSS FOR ARBITRARY POWER SPLITTERS WITH DIFFERENT SPLITTING RATIOS.

Mechanism	Wavelength	Insertion loss	Splitting Ratios obtained	Bandwidth
Asymmetric MMI [200]	~ 1.55 μm	~ 0.3 dB	50:50, 60:40, 70:30, 80:20, 90:10	60 nm
“QR” code MMI [201]	~ 1.55 μm	~ 1.0 dB	50:50, 67:33, 75:25	30 nm
Angled sub-wavelength grating MMI [202]	~ 1.55 μm	Not stated	50:50, 60:40, 80:20, 90:10	100 nm
Rib waveguide dispersion directional coupler [203]	~ 3.8 μm	~ 0.6 dB	50:50* 100:0	85 nm* 230 nm
Asymmetric-waveguide based phase control [204]	~ 1.55 μm	< 1 dB	50:50, 60:40, 70:30, 80:20, 90:10	75 – 100 nm
<i>This work</i>				
<i>Adiabatic Mode</i>	~ 3.8 μm	0.11 – 0.6 dB	0.6	230 nm
<i>Evolution</i>				

As indicated in Table 3-3, in comparison to various operating mechanisms, the adiabatic mode evolution exploited in this work enables wavelength-independent operation; MMI and directional couplers are wavelength-dependent. Furthermore, the devices operate at the longer transparency window of the SOI platform which has been scarcely explored; to the best of our knowledge the other available work is [203]. The devices are measured to have record bandwidth and insertion loss, indicating its potential in high performance, broadband optical systems.

3.4 CONCLUSION

In conclusion, through the design and optimization of anti-symmetrical adiabatic evolution-based power splitters, we have experimentally demonstrated splitting ratios of 50:50, 60:40 and 70:30 in this chapter. Broadband operation and low broadband insertion loss have been obtained from 3.66-3.89 μm (230 nm), at the longer transparency edge of the SOI platform. The tip width, being the smallest feature in the device, has a large degree of fabrication tolerance, paving the possibility for this device to be fabricated in commercial CMOS process lines. The fabrication of the device is simple, only requiring a single etch step. Broadband operation (230 nm), low broadband insertion loss (0.11-0.6 dB), CMOS compatibility, compact footprint and ease of fabrication makes this device a strong candidate to serve as a fundamental component in commercial scale MIR integrated optics. Through the adiabatic mode evolution mechanism, arbitrary power splitters with the largest operation bandwidth (~ 230 nm) has been demonstrated in the relatively uncharted wavelength region of 3.66 to 3.89 μm .

CHAPTER 4

SiN-SOI MULTILAYER PLATFORM FOR PROSPECTIVE APPLICATIONS AT 2 μ M

- 4.1 Introduction**
- 4.2 SiN waveguide propagation loss and bend loss condition**
- 4.3 Highly efficient 3-dB SiN power splitter**
- 4.4 Si-SiN adiabatic interlayer coupler**
- 4.5 Conclusion**

4.1 INTRODUCTION

This chapter narrates the development of a multilayer photonic platform at the 1.9 μm wavelength region. Multilayer platforms consisting of different materials, enables the optimal allocation of optical functionalities to the material layer that is the most well suited. In view of the wide range of applications at the 1.9 μm wavelength region (**section 1.3.2**), much work has been done in silicon photonics [208]-[212]. However, multilayer platforms in a CMOS-compatible framework have not been reported. The high index-contrast ($\Delta n_{\text{Si-SiO}_2} \approx 2$) of the SOI platform, as well as electron/hole mobility of the Si allows passive (i.e. tight bending radius, efficient grating couplers) [213]-[214] and active (high-speed electro-refractive induced modulation) [215]-[216] optical functions respectively. However, high-index contrast gives rise to increased thermal and fabrication intolerance. This could serve to impact device yields, stability and performance [217]-[218]. SiN, a commonly used material in CMOS foundries for masking, strain-engineering and passivation could aid the mentioned deficits in Si passive functionalities with its moderate index-contrast ($\Delta n_{\text{SiN-SiO}_2} \approx 0.5$) and lower thermo-optic effect [218]. In addition, SiN can be easily deposited on other material platforms via plasma-enhanced chemical vapor deposition (PECVD) in a CMOS-compatible process ($T < 400^\circ\text{C}$) enabling increased integration flexibility. Such low temperatures are compatible with the back end of line. The proposed Si-SiN platform in this chapter can exploit the active functionalities of the Si layer, while leaving the waveguiding to the low-loss SiN layer. In this chapter, for the first time, the Si-SiN platform is extended from the near-infrared (NIR) [218]-[220] to the 1.9 μm wavelength region. The scope of this chapter is concerned with the implementation of SiN passives at the 1.9 μm wavelength region as well as the coupling approach between the Si-SiN device layers. Low-loss interlayer couplers are pertinent in such a platform to ensure that the penalties incurred from interlayer transition does not offset the benefits reaped from material optimization. First of all, SiN waveguides are designed using the finite difference eigenmode approach. Propagation loss of 2.32 dB/cm is reported. Proceeding, the minimum bending loss

of the SiN waveguides are explored. A broadband, low-loss 3-dB power splitter implemented on the SiN device layer with a measured operating bandwidth of 55 nm ($\lambda = 1935 - 1990$ nm) and insertion loss as low as 0.05 dB is presented. Most critically, low interlayer transition is demonstrated between the Si and SiN device layers, indicating the viability of the multilayer platform.

4.2 SiN WAVEGUIDE PROPAGATION LOSS AND BEND LOSS CONDITION

The 3-D schematic of the Si-SiN platform is illustrated in Fig. 4-1, together with the coordinates. The Si device layer is utilized for the realization of I/O grating couplers on the 220 nm Silicon-on-Insulator (SOI) platform. The conventional TE-mode grating coupler ($\Lambda = 930$ nm, $DC=0.55$, Etch Depth = 70 nm) has a measured coupling loss of ~ 6 dB. Such an I/O implementation will allow for alignment-tolerant fiber-coupling at the wafer-level and subsequent transition to the lower-loss SiN device layer via the interlayer coupler. The propagation loss of the single-mode TE Si waveguide (Cross-section = $0.6 \times 0.22 \mu\text{m}^2$) is experimentally determined to be 3 dB/cm. Firstly, deep ultra-violet (DUV) immersion lithography and reactive ion etching (RIE) is used to define the Si layer. PECVD is used for blanket deposition of SiO_2 followed by chemical mechanical polishing to the desired thickness ($h_{\text{SiO}_2} = 300$ nm). Following, the PECVD is used again for the deposition of the SiN device layer ($h_{\text{SiN}} = 400$ nm). Similarly, to the Si device layer, the SiN device layer is defined using DUV immersion lithography and RIE. Lastly, 1 μm -thick SiO_2 cladding is deposited using PECVD.

Fig. 4-1. 3-D schematic of the SiN-SOI platform at the 1.9 μm wavelength region (directional coordinates indicated); including Si TE grating couplers, waveguide, Si-SiN adiabatic interlayer coupler and SiN waveguide. Inset illustrates the X-Z plane of the Si-SiN adiabatic interlayer coupler.

Fig. 4-2 shows the calculated effective indices of the first four eigenmodes (TE₀₀, TM₀₀, TE₀₁, TM₀₁) as a function of waveguide width (W) in a 400 nm thick SiN device layer; electric-field distribution of TE₀₀, TM₀₀, TE₀₁, TM₀₁ together with the corresponding values of W are shown in the inset. Refractive indices applied for the Si, SiN and SiO₂ layers are 3.444, 1.962 and 1.444 respectively. The single-mode condition is satisfied for $W \leq 1.5 \mu\text{m}$; the wavelength used for computation is 1970 nm. The TM₀₀/TE₀₁ hybrid point occurs when $W \geq 2.4 \mu\text{m}$.

Fig. 4-2. Theoretical effective indices for TE₀₀, TM₀₀, TE₀₁ and TM₀₁ as a function of waveguide width.

Fig. 4-3. Experimental setup for device characterization.

The experimental setup is shown in Fig. 4-3. A tunable laser source is connected to the fiber-polarization controller (FPC) and coupled in and out of the device-under-test (DUT) via cleaved, single mode fibers, angled at 13° , into the photodetector. The position of the input/output fiber are optimized by X/Y/Z precision alignment stages.

The cutback approach was used to determine the propagation loss of the fabricated SiN waveguide (Cross-section = $W \times 0.4 \mu\text{m}^2$). Waveguides with lengths(L) of 0.904, 2.134, 4.032 and 6.135 cm are fabricated, and the micrograph images are shown in Fig. 4-4 (a). In Fig. 4-4 (b)-(c), we show the measured normalized transmission of waveguides with $W = 1.2, 1.4 \mu\text{m}$ and lengths as mentioned above. The measured propagation loss of the waveguides together with its associated error bars, over the maximum range ($\lambda = 1935 - 1990 \text{ nm}$) of our tunable laser (Thorlabs, customized) is shown in Fig. 4-4 (d), obtained through the linear regression with regards to 4 different waveguide lengths (Fig. 4-4 (a)-(c)). In general, it is observed that propagation loss increases at longer wavelengths. At shorter wavelengths, the waveguide propagation ($W = 1.2, 1.4 \mu\text{m}$) losses are similar, however, as the wavelength redshifts towards 1990 nm, the propagation loss when $W = 1.2 \mu\text{m}$ becomes higher in contrast to $W = 1.4 \mu\text{m}$. The minimum, maximum measured propagation loss of waveguide when $W = 1.2, 1.4 \mu\text{m}$ are 2.38, 3.64 and 2.33, 3.35 dB respectively. While we do not have a definitive explanation for the trend, we suspect that at shorter wavelengths, when optical confinement of the waveguides is higher, SiN material absorption plays a relatively significant role in propagation loss values. On the other hand, when wavelength increases, the wider waveguide ($W = 1.4 \mu\text{m}$) would be less susceptible to SiO_2 absorption and waveguide sidewall roughness in comparison to the narrower waveguide ($W = 1.2 \mu\text{m}$) due to higher confinement of the optical mode, thereby, accounting for the smaller increase in propagation loss as wavelength increases.

Fig. 4-4. (a) Micrograph images of SiN waveguides with $L = 0.904, 2.134, 4.032, 6.135$ cm. (b) Measured normalized transmission of SiN waveguides ($W = 1.2 \mu\text{m}$) with $L = 0.904, 2.135, 4.032, 6.135$ cm. (c) Measured transmission of SiN waveguides ($W = 1.4 \mu\text{m}$) with $L = 0.904, 2.135, 4.032, 6.135$ cm. (d) Measured waveguide propagation loss as a function of wavelength ($W = 1.2, 1.4 \mu\text{m}$).

Following, the effects of bending radius (R) on radiation loss is also studied. Firstly, Lumerical 3D-FDTD simulation (high mesh resolution) [48] was used to evaluate the critical value of bending R at $\lambda = 1970$ nm, beyond which radiation loss is trivial for a $1.2 \mu\text{m}$ -wide waveguide; when bending R exceeds $40 \mu\text{m}$, radiation loss becomes negligible (Fig. 4-5 (a)). A single wavelength ($\lambda = 1970$ nm) is used because we did not observe any wavelength dependence (1935-1990 nm) of waveguide bending loss with regards to R . At the inset of Fig. 4-5 (a), we show the X-Z plane electric-field distribution when $R = 5, 40 \mu\text{m}$. The bending loss when $R = 30, 40 \mu\text{m}$ is characterized with the bend-loss test structures (No. of SiN bends = 12, 24, 36, 72); micrograph images when $R = 40 \mu\text{m}$ are shown in Fig. 4-5 (b). With the wavelength of the

light source fixed at 1970 nm, the bending loss per 90° bend is measured to be 0.30 and 0.13 dB when $R = 30, 40 \mu\text{m}$ respectively (Fig. 4-5 (c)-(d)). As illustrated in Fig. 4-5 (a), there is a close match between experimental and simulated results.

Fig. 4-5. (a) Simulated SiN 90° bending loss as a function of R . The 2 data points corresponds to the measured SiN 90° bending loss when $R = 30, 40 \mu\text{m}$; inset illustrates the electric-field distribution (X-Z plane) when $R = 5, 40 \mu\text{m}$. (b) Micrograph images of 12, 24, 36, 72 SiN 90° when $R = 40 \mu\text{m}$ (c) Measured SiN 90° bending loss from 12, 24, 36, 72 SiN 90° bends when $R = 30 \mu\text{m}$. (d) Measured SiN 90° bending loss from 12, 24, 36, 72 SiN 90° bends when $R = 40 \mu\text{m}$.

4.3 HIGHLY EFFICIENT 3-dB POWER SPLITTER

The 3-D schematic of the SiN 3-dB power splitter is illustrated in Fig. 4-6; coordinates are indicated. The power splitter consists of tapering a single-mode TE waveguide (Cross-section = $1.2 \times 0.4 \mu\text{m}^2$), which will be inserted between 2 identical tapers; the 2 output tapers will expand to 2 single-mode TE waveguides, each carrying half of the initial input power ($i/2$).

Fig. 4-6. 3-D schematic of the SiN-based 3-dB power splitter (directional coordinates are indicated). Inset illustrates the X-Z plane of the power splitter.

Through the design methodology elaborated in **Chapter 3** [221], the tip width (W_{tip}), gap (G), taper length (L_{taper}) are designated to be 0.3, 0.15 and 12 μm respectively. The 3-dB splitter is compact, with a footprint of $3 \times 12 \mu\text{m}^2$. With the design parameters, the electric-field distribution in the X-Z plane is shown in Fig. 4-7 (a); the lightwave in the TE polarization travelling along the input taper will be enhanced in G and coupled into the 2 output tapers. 3D-FDTD simulation indicates negligible insertion loss and wavelength-independent operation over the maximum tunable range of our light source ($\lambda = 1935\text{-}1990 \text{ nm}$). As means to characterize the splitting ratio and broadband insertion loss, single-stage and 4-stage testing

structures are fabricated; the micrograph of the 4-stage testing structure is shown in Fig. 4-7 (b). The measured normalized transmission spectra at port T_1 , T_2 , T_3 and T_4 is shown in Fig. 4-7 (c). Broadband, wavelength-independent 3-dB power splitting, measured from the 4-stage testing structure is experimentally demonstrated from 1935 to 1990 nm in Fig. 4-7 (d). The measured ratios between the 2 output ports in a single-stage testing structure (Fig. 4-7 (e)) indicates a maximum power imbalance (Imb_{max}) of 0.05 dB, validating the splitting ratios obtained from the 4-stage testing structure (Fig. 4-7 (d)). The insertion loss of the 3-dB power splitter is obtained via the following approach.

$$IL \text{ (dB)} = \frac{10 \log_{10}((\sum_{i=1}^5 T_i)/T_0)}{4} \quad (4.1)$$

Where $T_{1,2,3,4,5}$ refers to the measured transmission from each of the output ports. T_0 refers to the output from the reference waveguide. The factor of $1/4$ is used in consideration of the 4 stages in the testing structure. Grating coupler insertion loss is factored out via (4.1). Experimentally determined broadband insertion loss is illustrated in Fig. 4-7 (f); we have characterized a minimum and maximum insertion loss of 0.05 and 0.40 dB from 1935 to 1990 nm respectively. Owing to the field enhancement in G, the insertion loss of the power splitter will be impacted by the extent of sidewall roughness with regards to the taper region [221]-[222]. Implementation of the structure on a device layer with moderate index contrast such as SiN will serve to relax processing requirements, thereby, significant reduction in device loss can be achieved as shown in this chapter.

Fig. 4-7. (a) Electric-field distribution of optimized 3-dB power splitter (X-Z plane). (b) Micrograph image of the 4-stage testing structure; output is labelled for reference. (c) Measured normalized transmission of T1, T2, T3 and T4, obtained from the 4-stage testing structure. (d) Splitting ratio measured from the 4-stage testing structure. (e) Splitting ratio measured from the single-stage testing structure. (f) Experimentally measured 3-dB power splitter broadband insertion loss.

4.4 SI-SiN ADIABATIC INTERLAYER COUPLER

In order to enable low-loss adiabatic transition from the Si to the SiN device layers, a Si-SiN push-pull taper with 300 nm SiO₂ gap between the 2 device layers is utilized (Fig. 4-1). The tip width of the Si and SiN tapers are determined to be 150 and 300 nm respectively (Fig. 4-1, inset) in consideration of process limitations. Through the eigenmode expansion method, we determine that low-loss adiabatic transition between the Si (Cross-section = $0.6 \times 0.22 \mu\text{m}^2$) and SiN (Cross-section = $1.2 \times 0.4 \mu\text{m}^2$) device layers can be achieved when the taper length (L_{i-c}) exceeds 40 μm (Fig. 4-8 (a)) at $\lambda = 1970 \text{ nm}$. Bandwidth simulation indicates that the adiabatic interlayer coupler is capable of wavelength-independent operation over the maximum tunable range of our light source. Fig. 4-8. (b)-(f) shows the mode evolution of the electric-field distribution in the X-Y plane as the lightwave propagates along a 40 μm -long Si-SiN adiabatic interlayer coupler. The electric-field distribution of the interlayer coupler ($L_{i-c} = 40 \mu\text{m}$) in the Y-Z plane is illustrated in Fig. 4-8 (g). $L_{i-c} = 20, 40, 60 \mu\text{m}$ -long test structures with 12, 24, 36 and 48 Si-SiN transitions are fabricated; micrograph images are indicated in Fig. 4-8 (h). Via the testing structures, the insertion loss per Si-SiN transition are measured to be 0.37, 0.06, 0.05 dB for $L_{i-c} = 20, 40, 60 \mu\text{m}$ respectively when $\lambda = 1970 \text{ nm}$ (Fig. 4-8 (a)). Following, the light source is swept from 1935 to 1990 nm characterize the broadband insertion loss of the Si-SiN adiabatic interlayer coupler. Fig. 4-8 (i) demonstrates low-loss operation from 1935 to 1990 nm; maximum and minimum transition loss is found to be 0.06 and 0.04 dB respectively when $L_{i-c} = 60 \mu\text{m}$. The experimental data in good agreement with modelling.

Fig. 4-8. (a) Simulated insertion loss of the Si-SiN adiabatic interlayer coupler ($\lambda = 1970 \text{ nm}$). The 3 data points corresponds to the measured insertion loss of the Si-SiN adiabatic interlayer coupler when $L_{i-c} = 20, 40, 60 \mu\text{m}$ ($\lambda = 1970 \text{ nm}$). (b)-(f) Evolution of electric-field distribution (X-Y plane) as the lightwave propagates along a 40 μm -long coupler, $X = 0, 10, 20, 30, 40 \mu\text{m}$ (refer to the coordinates indicated in Fig. 4-1) (g) Electric-field distribution of the lightwave as it propagates along a 40 μm -long coupler. (h) Micrograph images of coupler test structures with $L_{i-c} = 20, 40, 60 \mu\text{m}$ and 12, 24, 48 Si-SiN transitions. (i) Measured insertion loss as a function of wavelength.

4.5 CONCLUSION

In this chapter, the CMOS-compatible Si-SiN platform is extended to the 1.9 μm wavelength region for the first time. Broadband (1935-1990 nm), low-loss, Si-SiN interlayer coupler (Insertion Loss = 0.04 dB per Si-SiN transition) and SiN 3-dB power splitter (Insertion Loss = 0.05 dB) are shown. The waveguide propagation loss is good at 2.32 dB/cm. The limits of bending radius of the SiN waveguides are also explored. In regards to the growing interest in silicon photonics at 1.9 μm , the work in this chapter can act as a basis for future developments at the 1.9 μm wavelength region on the novel Si-SiN platform, encouraging the development of more complex devices and systems to be designed and build in the future. To such an effect, **Chapter 7** will build on the work in this chapter to demonstrate passive spatial multiplexing and waveguiding on the SiN layer, active optical modulation on the Si layer.

CHAPTER 5

1 × 8 SILICON SELECTOR SWITCH FOR PROSPECTIVE TECHNOLOGIES AT 2 μM

- 5.1 Introduction**
- 5.2 Device structure, fabrication**
- 5.3 Elementary cell characteristics**
- 5.4 Demonstrating 1 × 8 silicon selector switch**
- 5.5 Conclusion**

5.1 INTRODUCTION

This chapter elaborates on the development of a passive silicon photonic switch operating at the 1.9 μm wavelength region. This will be the last passive device that is covered in the thesis. In response to the potential of the 1.9 μm wavelength region in supporting prevalent applications (**section 1.3.2**), there has been an increased focus on the development of silicon photonic devices (i.e. hybrid lasers [162], [164], photodetectors [36], [209], Mach-Zehnder Interferometer (MZI)/ micro-ring resonators (MRR)-based modulators [211], Vernier filter [223], MZI-based single-switch unit [224]) that can be utilized in the proposed communication infrastructure. High-speed electrical switches are the incumbent technology in short-haul data center communications. However, this approach has several disadvantages. Such systems require multiple conversion of signals from the electrical to optical domain which increases the power consumption of the system. Wavelength Division Multiplexing (WDM), an imperative feature of modern optical communications is not compatible with electrical switching. Furthermore, as a result of rising demand for bandwidth, the size of electrical switches is approaching an upper limit in regard to metal and pin routing [225]. Silicon photonic-based optical switches are a scalable, low-cost solution to improving datacenter performance through enabling high-bandwidth links. It can also serve to optimize resource utilization via bandwidth steering and disaggregation. The demonstration of a silicon photonic switch operating near 1.9 μm will increase the viability of the waveband as a “communication window” in context of the encouraging further infrastructural developments arising from the TDFA and HC-PBGF. Silicon photonic switch engines demonstrated thus far are primarily based on microelectromechanical system (MEMs), MRRs and MZIs [225]. The MZI-based architecture will provide superior operation bandwidth in comparison to the MRR and MEMS actuated switches while also balancing conditions on switching speeds, footprint, low driving voltage and fabrication simplicity [225]. In this chapter, we report the $I \times N$ optical selector switch operating near the 1.9 μm wavelength region based on the thermo-optic MZI-based architecture,

experimentally demonstrating its static and dynamic characteristics in the process. As an elementary cell ($N = 2$), we report a P_π of 23 mW, 10-90% switching time of lesser than 38 μ s and a crosstalk of lower than -25 dB from 1880 to 1955 nm. The scalability of the elementary cell is proven by demonstrating the 1×8 optical switch ($N = 8$) with a crosstalk of lower than -21 dB at the wavelength range in consideration of all possible switching configurations (75 nm bandwidth, 8 paths). Insertion loss levels for both configurations are provided. To the best of our knowledge, the switch fabric demonstrated in this chapter is the first in the $1 \times N$ configuration at the 1.9 μ m wavelength region. It is also the largest and has the widest operating bandwidth.

5.2 DEVICE STRUCTURE, FABRICATION

The 3-D schematic of a $1 \times N$ ($N = 2, 8$) silicon selector switch is shown in Fig. 5-1 (a), (b) respectively. 2-D schematic of Fig. 5-1 (a), (b) are illustrated in Fig. 5-1 (c), (e) respectively; micrograph images are shown in Fig. 5-1 (d), (f). An elementary cell ($N = 2$, Fig. 5-1 (a)) consists of 2 Mach-Zehnder arms ($L = 250 \mu\text{m}$) connected by 1×2 and 2×2 MMI couplers at the ends. A thermo-optic heater is mounted on one of the arms such that the effective optical path length can be altered via the thermo-optic effect. The output states of the elementary cell can be alternated when the phase difference between the both optical paths corresponds to π . In such a switching configuration, a single input can be allocated to any one of the N possible outputs.

The $1 \times N$ silicon selector switch is fabricated on the 220 nm silicon-on-insulator platform via a standard CMOS process line (CompoundTek Pte Ltd). The single-mode waveguide ($0.6 \times 0.22 \mu\text{m}^2$) propagation loss is experimentally characterized to be 3 dB/cm at $\lambda = 1910 \text{ nm}$. With a width of $6 \mu\text{m}$, the 1×2 and 2×2 MMI coupler lengths are optimized (eigenmode expansion method) to be $24.3 \mu\text{m}$ and $32.4 \mu\text{m}$ respectively at $\lambda = 1910 \text{ nm}$. After the waveguide fabrication steps, a thermal isolation trench with dimensions of $24 \times 140 \mu\text{m}^2$ was fabricated around one of the Mach-Zehnder arm with the mounted phase shifter ($25 \mu\text{m}$ away from the waveguide). This implementation enables the thermal isolation of both Mach-Zehnder arms. Subsequently, a $1.2 \mu\text{m}$ thick SiO_2 cladding is deposited followed by 120 nm and $2 \mu\text{m}$ of TiN heater and Al routing layers respectively. The resistance of the TiN heater is 1250Ω . Fig. 5-1 (e) illustrates the cross-sectional view.

Fig. 5-1. 1×2 elementary cell (a) 3-D schematic (c) 2-D top view, (d) micrograph. 1×8 silicon selector switch (b) 3-D schematic (e) 2-D top view, (f) micrograph. Heater and ports annotated in (c), (e). (g) Cross-sectional view.

5.3 ELEMENTARY CELL CHARACTERISTICS

The experimental setup for the static characterization of the elementary cell is shown in Fig. 5-2. A fixed laser source ($\lambda = 1910$ nm) connected to the FPC/ Amplified Spontaneous Emission (ASE) source was coupled in and out of the cell via inverse tapers (tip cross-section: $0.18 \times 0.22 \mu\text{m}^2$, length = $200 \mu\text{m}$, Fig. 5-1 (a) inset) to the photodetector/ optical spectrum analyzer to determine V_π , switching transients (Fig. 5-3 (a), 5-5 (a)-(c)) and the device bandwidth, crosstalk (Fig. 5-3 (b), 5-6 (a)-(g), 5-7) respectively. The fiber to chip coupling loss is 4 dB. A DC signal was applied to the thermo-optic phase shifter to vary the relative optical phase shift between the Mach-Zehnder arms. The normalized transmittance-heater power characteristics of the elementary cell are shown in Fig. 5-3 (a); normalized to an adjacent waveguide with inverse tapers on both sides. The power (P_π), required to achieve a π optical phase shift necessary for switching between Ports a and b is 23 mW (P_a , P_b , indicated in Fig. 5-1 (a)) with an extinction ratio of larger than 32 dB.

Fig. 5-2. Experimental setup for static characterization.

Fig. 5-3. Static characterization of the elementary cell, normalized transmittance (a) as a function of heater power ($\lambda = 1910$ nm), (b) as a function of wavelength ($\lambda = 1880 - 1955$ nm).

The normalized wavelength detuning characteristics of the cell are indicated in Fig. 5-3 (b); power applied on the heaters (H) are 17.7 and 41.9 mW. The minimum and maximum insertion loss of the cell is 1.1 dB and 3.6 dB respectively, from 1880-1955 nm (75 nm demonstrated operating bandwidth). As the optimal operating wavelength of the MMI coupler is designed to be centered at $\lambda = 1910$ nm, the insertion loss at longer wavelengths will be higher in comparison to the shorter wavelengths. Crosstalk of lower than -25 dB is obtained throughout the abovementioned spectral range.

Fig. 5-4. Experimental setup for dynamic characterization.

Fig. 5-4 illustrates the setup to characterize the switching transients of the elementary cell. While the input configuration to the cell has remain unchanged (Fig. 5-2), a RF signal was applied to the thermo-optic phase shifter. The rise and fall time of the pattern generator are lower than 12 ns respectively. The output of the cell is connected to the high-speed photodetector, which is in turn linked to the oscilloscope. The dynamic switching characteristics of the cell, subjected to a 1 kHz signal, 2 V peak-to-peak voltage (V_{pp}), biased (V_{bias}) at 5.9 V is shown in Fig. 5-5 (a); the noise at the peaks are a result of experimental artefact. The 10-90% rise (Fig. 5-5 (a)) and fall time (Fig. 5-5 (b)) are 33.08 and 37.84 μ s respectively.

Fig. 5-5. (a) Switching transients of the elementary cell, subjected to 1 kHz RF signal, $V_{bias} = 5.9$ V, $V_{pp} = 2$ V, (b) rising edge, (c) falling edge measured by the oscilloscope. The noise at the peaks are a result of experimental artefact.

5.4 DEMONSTRATING 1×8 SELECTOR SWITCH

The normalized wavelength detuning characteristics of each individual port (P_1 to P_8 , indicated in Fig. 5-1 (b)) when $N = 8$ are examined from Fig. 5-6 (a)-(g). A high degree of uniformity is achieved across the 7 elementary cells as evidenced by the consistency across each port (Fig. 5-6 (a)-(h)). The minimum and maximum insertion loss levels, considering all 8 switching configurations are 3.4 and 10.1 dB, which is in line with the loss levels obtained from the elementary cell (3 stages); as abovementioned, the upper range of insertion loss can be attributed to the wavelength-dependence of the MMI, the general insertion loss levels can be mitigated via the integration with a semiconductor optical amplifier [162]. The minimum insertion loss is limited by the MMIs in the switch. By considering the crosstalk levels of P_1 - P_8 at Fig. 5-7, the lowest measured crosstalk was at 31 dB while crosstalk lower than 21 dB was obtained in the wavelength range of 1880-1955 nm respectively. In Table 5-1, we show the values of heater power applied to each individual phase shifter (labelled in Fig. 5-1 (b)) and total power consumption (H_T) that corresponds to 8 switching configurations.

Fig. 5-6. Normalized wavelength detuning characteristics of the 1×8 optical switch (a) P_1 , (b) P_2 , (c) P_3 , (d) P_4 , (e) P_5 , (f) P_6 , (g) P_7 , (g) P_8 .

Fig. 5-7. Crosstalk levels (XT) of each output configuration in 1×8 switch.

TABLE 5- 1.

HEATER POWER FOR EACH OUTPUT CONFIGURATION.

Output Port	H ₁₁	H ₂₁	H ₂₂	H ₃₁	H ₃₂	H ₃₃	H ₃₄	H _T
P ₁	18.3	0	17.5	0	0	0	18.9	
P ₂	18.3	0	17.5	0	0	0	50.5	
P ₃	18.3	0	48.7	0	0	17.2	0	
P ₄	18.3	0	48.7	0	0	51.1	0	
P ₅	51.8	18.3	0	0	17.2	0	0	
P ₆	51.8	18.3	0	0	51.4	0	0	
P ₇	51.8	48.7	0	17.3	0	0	0	
P ₈	51.8	48.7	0	49.2	0	0	0	

*Values in Table 5-1 are in mW.

While the heater values in this work are adjusted manually to ensure the highest power at the desired output port (i.e. P₇), it would not be able to determine, with accuracy, the solutions of the high-dimensional phase distribution borne from mild fabrication imperfections when the elementary cell is scaled-up. This would explain the degradation of crosstalk when the N is increased from 2 to 8. Machine-enabled methods such as the bacteria foraging algorithm [226] would facilitate greater precision, thus, reducing crosstalk and insertion loss.

5.5 CONCLUSION

This chapter reports the first $I \times N$ silicon photonic selector switch operating at the 1.9 μm wavelength region. It is also the largest switch fabric that has been demonstrated at the wavelength region thus far. As a proof of concept, the switches are demonstrated for $N = 2, 8$, indicating that such switches are indeed scalable. Larger switch fabrics could be integrated with optical amplifiers, such as the ones elaborated in **Chapter 7** to overcome higher insertion losses. Regarding an elementary cell, P_π of 23 mW, minimum insertion loss of 1.1 dB, switching speeds of faster than 38 μs and a crosstalk of lower than 25 dB has been experimentally shown. Pertaining to the $I \times 8$ switch, the maximum crosstalk is 21 dB, measured across the wavelength region. The reason for higher crosstalk from the $I \times 8$ switch in comparison to the elementary cell is caused an inability to account for the random phase errors, intrinsically introduced during the fabrication of the switch, which might be especially prevalent given the high index contrast of the SOI platform. This issue can be circumvented via controls from machine-enabled algorithms [226]. The $I \times N$ selector switch demonstrated in this chapter can be applied to routing enabling critical applications such as bandwidth steering, thereby, improving resource utilization in multi-wavelength, large-bandwidth links amongst datacenters.

CHAPTER 6

SPATIAL MULTIPLEXING + OPTICAL MODULATION ON THE SiN-SOI MULTILAYER PLATFORM AT 2 μ M

- 6.1 Introduction
- 6.2 (De)multiplexing via asymmetrical tapers: design and experimental characterization
- 6.3 (De)multiplexing + optical modulation system
 - 6.3.1. Static characterization
 - 6.3.2. Dynamic characterization
- 6.4 Conclusion

6.1 INTRODUCTION

This chapter focuses on optimal modulation, an active functionality on the silicon photonics platform that has not been explored in this thesis till now. Furthermore, we also demonstrate that besides wavelength division multiplexing (WDM), higher degrees of freedom in terms of multiplexing are possible, that will enable us to push the bandwidth of optical communication systems even further. Thus far, attempts in silicon photonics to increase bandwidth density has mainly utilized WDM of the fundamental mode (i.e. TE_{01}) [165], [227]. The exploitation of spatial modes in a single multi-mode waveguide, each as an individual channel, can allow for greater scalability in comparison to WDM, which typically requires a larger number of sub-components (i.e. resonators, waveguides, crossings) [228]-[229]. It is, however, imperative to take note that the higher-order spatial modes will have a greater degree of interaction with the waveguide sidewall in comparison to the fundamental mode. Such an effect will be pronounced with regards to high-index contrast platforms such as silicon-on-insulator (SOI) [230]. The silicon nitride-on-silicon-on-insulator multilayer platform on the other hand, enables low-loss multi-mode propagation at the silicon nitride device layer (moderate index contrast) while maintaining active functionalities at the silicon layer [230]. In this chapter, we report the mode (de)multiplexer ((*de*)*mux*) + optical modulation (*om*) system operating at the 1.9 μm wavelength region by building on our work in **Chapter 4**; 3-D schematic of the (*de*)*mux* + *om* system with transverse-electric spatial modes of up to TE_{01} (experimentally demonstrated in this chapter) and TE_{02} (for illustration) are shown in Fig. 6-1 (a)-(b) respectively. Using Fig. 6-1 (a) as a reference (coordinates indicated), the lightwave is coupled into 2 single-mode Si waveguides ($0.6 \times 0.22 \mu\text{m}^2$), at P_{11} and P_{12} , following, interlayer transition to the fundamental-mode SiN waveguide ($1.4 \times 0.4 \mu\text{m}^2$) is enabled via the Si-SiN interlayer adiabatic coupler. Lightwave at P_{12} propagates into the coupling region, where asymmetrical tapers are designed in consideration of phase matching from TE_{00} into the TE_{01} mode at the wide bus waveguide. P_{11} on the other hand, adds the propagation of the TE_{00} mode into the wide bus waveguide.

Fig. 6-1. 3-D schematic of the (de)mux + om system utilizing (a) TE_{00} , TE_{01} modes, (b) TE_{00} , TE_{01} , TE_{02} modes; for illustration. MRM contacts not illustrated. Not drawn to scale.

This approach to multiplexing lends the propagation of multiple spatial modes in a simple multimode waveguide. In order to achieve uniform modulation characteristics across the ports, the eigenmodes are demultiplexed prior to modulation by an electro-optic micro-ring modulator that is designed to operate at the $1.9\ \mu\text{m}$ wavelength region, in the fundamental mode. Further mode-scaling can be easily implemented in the approach that TE_{01} is (de)multiplexed as mentioned above; only a single modulator design is required. Passive characteristics with regards to the fundamental mode Si, SiN waveguide propagation loss and Si-SiN interlayer coupler are detailed in **Chapter 4** [230]. This chapter is organized as follows. Firstly, the optimization and experimental characterization of the (de)mux will be presented. As a proof of concept, we demonstrate multi-mode operation of TE_{00} and TE_{01} . With regards to the TE_{00} and TE_{01} mode in the wavelength region of $1.9 - 2.0\ \mu\text{m}$, crosstalk and insertion loss levels as low as 20.3 and -1.469 dB, -19.2, 1.766 dB respectively are demonstrated. Following, the micro-ring modulators (MRMs) operating at the fundamental mode are cascaded with the (de)mux demonstrating (Fig. 6-1) the DC characteristics of the (de)mux + om system in the process; record modulation efficiency as low as 0.278 V.cm is achieved at the $1.9\ \mu\text{m}$ wavelength region. Lastly, the electro-optic (EO) response of the device is measured; EO response of 15.7 GHz is achieved. To the best of our knowledge, the MRM presented in this chapter indicates the highest EO response and modulation efficiency amongst silicon photonic modulators operating at the $1.9\ \mu\text{m}$ wavelength region.

6.2 (De)multiplexing via asymmetrical tapers: design and experimental characterization

The 2-D schematic (XZ-plane) of the *(de)mux*, utilizing dual-core adiabatic tapers on a 400 nm-thick SiN device layer is shown in Fig. 6-2; coordinates and respective dimensions of the device are annotated. Such an architecture, as investigated extensively by Dai et al. [228], enables the scaling of spatial modes with relative ease. Moreover, in comparison to the *de(mux)* based on asymmetrical directional couplers, this implementation imposes less requirements on fabrication. The varying effective refractive index of the optical mode travelling on either side of the tapers will increase the probability of effective coupling, should processing variability be present. This is in contrast to the latter, where the effective refractive indices are constant; any fabrication variations in coupler dimension, specifically waveguide width, will impact device performance [231]. In this section, by building on the methodology of Dai et al. [228], we propose an approach towards device optimization, subject to several rules and boundary conditions.

Fig. 6-2. 2-D schematic (XZ-plane) of the *(de)mux*; coordinates and respective dimensions of the device are annotated. The electric-field distribution of the optimized *(de)mux* with $(W_{I-1}, W_{I-2}) = (3.5, 2.6) \mu\text{m}$ in the XZ-plane of the device is illustrated at the inset.

Fig. 6-3 (a) shows the effective refractive indices (n_{eff}) of the eigenmodes present in the SiN waveguide (TE_{00} , TE_{01} , TE_{02}) as a function of waveguide width (W), calculated by the Lumerical Eigenmode Solver; to standardize further discussions, the effective refractive index of the X^{th} -TE mode with a waveguide width of W is referred as $n_{\text{eff}}(X, W)$. With regards to the (De)mux, $W_{I-1} > W_{I-2}$, $W_{II-1} > W_{II-2}$, $W_{I-2} > W_{II-1}$, $W_{I-0} = W_{I-1}$, $W_{II-0} = W_{II-1}$, $W_{I-2} = W_{I-3}$ and $W_{II-2} = W_{II-3}$. W_{II-2} is selected to be $0.3 \mu\text{m}$ to constrain the optical modes in the wide core as well as process limitations. W_{II-1} ($1.4 \mu\text{m}$) is designated according to the single-mode condition, with a minimum propagation loss of 2.32 dB/cm [230]. The criteria for W_{I-2} and W_{II-1} is subject upon the condition that $n_{\text{eff}}(W_{I-2}, 1) < n_{\text{eff}}(W_{II-1}, 0) < n_{\text{eff}}(W_{I-2}, 0)$ where 0 and 1 refers to TE_{00} and TE_{01} modes respectively. In addition, $W_{I-2} < 2.2 \mu\text{m}$ should be avoided as it leads to significant sidewall interaction, increasing scattering loss; a comparison of the optical mode sidewall interaction when $W_{I-2} = 2.0, 2.2 \mu\text{m}$ is shown in Fig. 6-3 (b). Besides, as TE_{01} (X^{th} -TE mode) is the highest order mode in this implementation, the cut-off width ($W_{\text{Cut-off}}(TE_{02})$) for TE_{02} ($(X+1)^{\text{th}}$ -TE mode) should be considered; as shaded in blue, solutions for TE_{02} exist at $W > 2.7 \mu\text{m}$. The value for W_{I-2} should be lower than $W_{\text{Cut-off}}(TE_{02})$ to ensure effective isolation from the TE_{02} mode in the device. In a nutshell, the possible range of values of W_{I-2} ($2.2 \mu\text{m} < W_{I-2} < 2.7 \mu\text{m}$) is shaded (green) in Fig. 6-3 (a). In accordance to the above, with the parameters W_{II-1} , W_{II-2} , gap (G) and taper length (L_{taper}) fixed at 1.4 , 0.3 , 0.3 and $150 \mu\text{m}$ respectively and the initial value range of (W_{I-1}, W_{I-2}) selected to be $(3.6 \pm 0.4 \mu\text{m}, 2.4 \pm 0.4 \mu\text{m})$, we performed particle swarm optimization within the bounds of the fixed parameters; solutions for TE_{00} and TE_{01} exist within the stated W_{I-1} range. Due to the laborious nature of high-resolution FDTD, the wavelength range is set to be $\lambda = 1.98825 \pm 0.005 \mu\text{m}$; the resonant wavelength of the (de)mux + om system presented in the following section operates near $\lambda = 1.98825 \mu\text{m}$. The optimized values of (W_{I-1}, W_{I-2}) are $(3.5 \mu\text{m}, 2.6 \mu\text{m})$. The simulated insertion loss and crosstalk at $\lambda = 1.98825 \mu\text{m}$ are 0.06 and -20.73 dB respectively. The electric-field distribution of the optimized (de)mux in the XZ-plane of the device is illustrated at the inset of Fig. 6-2, indicating that effective (de)multiplexing has been demonstrated by simulation [228]-[229].

Fig. 6-3. (a) Theoretical effective indices for TE_{00} , TE_{01} and TE_{02} as a function of waveguide width. (b) Electric-field distribution of the TE_{01} optical mode (XY-plane) when $W_{1-2} = 2.0, 2.2 \mu\text{m}$; sidewall interaction is significant for $W_{1-2} < 2.2 \mu\text{m}$.

The devices in this chapter are fabricated in a standard CMOS process line. The static characteristics of the optimized (de)mux and subsequent (de)mux + om system is determined via the following experimental setup (Fig. 6-4).

Fig. 6-4. Experimental setup for static characterization.

An Amplified Spontaneous Emission (ASE) source was coupled in and out of the DUT via inverse tapers to the OSA. The insertion loss of the inverse taper (tip cross-section: $0.18 \times 0.22 \mu\text{m}^2$, length = $200 \mu\text{m}$) is 7 dB. The measured normalized transmittances ($T_{1121} = P_{11} \gg P_{21}$, $T_{1122} = P_{11} \gg P_{22}$, $T_{1222} = P_{12} \gg P_{22}$, $T_{1221} = P_{12} \gg P_{21}$) of the (de)mux when $\lambda = 1.9\text{-}2.0 \mu\text{m}$ is illustrated in Fig. 6-5; ports labelled in Fig. 6-2 (i.e. P_{11} , P_{12}). With regards to the TE_{00} and TE_{01} modes, the minimum and maximum insertion loss are measured to be 1.469 and 2.353 dB, 1.766 and 2.977 dB respectively. The crosstalk levels for TE_{00} ($X_{\text{talk}_{11}} = T_{1121} - T_{1122}$) and

$TE01$ ($X_{talk_{12}} = T_{1222} - T_{1221}$) modes are shown in the inset; $TE00$ and $TE01$ modes are measured to have a maximum and minimum crosstalk of -20.3 and -16.2 dB, -19.2 and -16.4 dB respectively.

Fig. 6-5. Measured normalized transmittances (T_{1121} , T_{1121} , T_{1121} , T_{1121}) of the $(de)_{mux}$ ($TE00$, $TE01$). The crosstalk levels ($X_{talk_{11}}(TE00)$, $X_{talk_{12}}(TE01)$) are illustrated at the inset.

6.3 (De)multiplexing + optical modulation system

6.3.1. Static characterization

The 2-D schematic (XZ-plane) of the *(de)mux + om system* is illustrated in Fig. 6-6 (a); 2 identical MRMs operating in the fundamental mode (TE_{00}) based on the carrier-depletion effect was implemented following the demultiplexing step of TE_{00} and TE_{01} optical modes. The cross-section (XY-plane) of the MRM with radius of 20 μm is indicated in Fig. 6-6 (b). As informed in **Chapter 4**, the Si device layer is 220 nm-thick. The dimensions of the rib waveguide width and slab thickness are 0.6 and 0.09 μm respectively. 2 levels of n and p-type doping was realized about the center of the Si rib waveguide; doping concentrations from left to right in Fig. 6-6 (b) are $1 \times 10^{20}(\text{n}++)$, $1 \times 10^{17}(\text{n})$, $1 \times 10^{17}(\text{p})$, and $1 \times 10^{20}(\text{p}++)$ cm^3 respectively. In order to avoid resonant photon absorption by the heavily-doped regions, the p++ and n++ doped regions are placed 1.3 μm away from the center of the rib waveguide; overlap analysis (XY-plane) at the inset of Fig. 6-6 (b) indicates that 99 % of the optical energy are contained away from the p++ and n++ doped regions.

Fig. 6-6. (a) 2-D schematic (XZ-plane) of the *(de)mux + om system*. (b) Cross-section (X-Y plane) of MRM; overlap analysis (X-Y plane) within the p and n-doped regions illustrated at the inset.

Fig. 6-7 (a) shows the transmittance spectra of the *(de)mux* + *om* system, utilizing the experimental setup in Fig. 6-4. As expected, the resonance of the MRM is superimposed on each transmittance spectra (Fig. 6-5) of the *(de)mux* with an FSR of 16.23 nm. The Q-factor and extinction ratio of the MRM resonance ($\lambda = 1.98825 \mu\text{m}$) is determined to be 3400 and 8.3 dB when no bias voltage is applied ($V_{\text{bias}} = 0 \text{ V}$). In Fig. 6-7 (b), $V_{\text{bias}} = -2, -1, 0, 0.8, 0.9 \text{ V}$ was varied via the DC probe (Fig. 6-4). Increasing the value of V_{bias} in the negative polarity increases the depletion width of the PN-junction, reducing the refractive index that the optical mode sees, resulting in a red-shift of the MRM resonance; the opposite is true when the polarity of V_{bias} is reversed. V_{π} can be expressed as (6.1).

Fig. 6-7. (a) Measured transmittance spectra of the *(de)mux* + *om* system. (b) Measured transmittance spectra for $V_{\text{bias}} = -2, -1, 0, 0.8, 0.9 \text{ V}$. (c) Measured modulation efficiency ($V_{\pi}L_{\pi}$) of the PN junction in the MRM.

$$V_{\pi}L_{\pi} = \left(\frac{1}{2} \cdot \frac{L_{\pi} \cdot \text{FSR}}{\frac{\partial \lambda}{\partial V}} \right) V \cdot \text{cm} \quad (6.1)$$

Where L_{π} corresponds to $\frac{1}{6}$ of the MRM circumference and $\frac{\partial \lambda}{\partial V} = 0.0026 \text{ V} + 0.0306 \text{ cm.V}^{-1}$ is derived from Fig. 6-7 (b). As indicated in Fig. 6-7 (c), the $V_{\pi}L_{\pi}$ is 0.278 V.cm when $V_{\text{bias}} = 0 \text{ V}$ before degrading to 0.685 V.cm when $V_{\text{bias}} = 7 \text{ V}$ due to the sublinear relation between PN junction width and increasing V_{bias} . The values of $V_{\pi}L_{\pi}$ reported in this chapter, to the best of our knowledge, represents the highest modulation efficiency reported at the $1.9 \mu\text{m}$ wavelength region.

6.3.2. Dynamic characterization

The EO response of the *(de)mux + om* system is characterized via the experimental setup illustrated in Fig. 6-8. For each value of V_{bias} , the wavelength of the laser source is tuned 3-dB down into the MRM resonance near $1.98825 \mu\text{m}$, through the fiber-polarization controller (FPC) and coupled in and out of the DUT via inverse tapers using lensed fibers. A RF input power of 5 dBm from the lightwave component analyzer (LCA) and $V_{\text{bias}} = 0, 1, 2 \text{ V}$ are applied to a bias tee, sent to the DUT via the RF probe. The output fiber is connected to the LCA and the EO response of the modulator, is measured up to 40 GHz (Fig. 6-9).

Fig. 6-8. Experimental setup for EO characterization.

Fig. 6-9 shows a measured EO response of 14.7, 15.7, 15.7 GHz when $V_{\text{bias}} = 0, 1, 2 \text{ V}$ respectively. This is due to the fact that as V_{bias} increases, junction depletion width becomes wider, leading to drop in capacitance and subsequent RC time constant. The electrical bandwidth of the PN junction in the MRM would increase as a result, accounting for the trend observed in Fig. 6-9.

Fig. 6-9. Measured EO response up to 40 GHz when $V_{\text{bias}} = 0, 1, 2 \text{ V}$.

6.4 CONCLUSION

In this chapter, we report a novel *(de)mux + om system*, fabricated on the Si-SiN multilayer platform, operating near the 1.9 μm wavelength region. This system highlights the strengths of each material layer in a Si-SiN multilayer platform which was developed in **Chapter 4**. Silicon enables high-speed optical modulation whereas SiN facilitates low-loss passive functionalities such as waveguiding and spatial multiplexing. Firstly, a *(de)mux* with a minimum and maximum crosstalk of 20.3 and 16.2 dB, 20.3 and 16.2 dB is reported from 1.9-2.0 μm in consideration both *TE00* and *TE01* optical modes respectively. Following, 2 identical MRM are implemented in conjunction with the *(de)mux*. Favorable modulation efficiency ($V_\pi L_\pi$) and EO response of 0.278 V.cm and 15.7 GHz respectively are demonstrated in the 1.9 μm wavelength region.

CHAPTER 7

SILICON PHOTONIC HYBRID RING EXTERNAL CAVITY (SHREC)/III-V WAVELENGTH TUNABLE LASER DIODES OPERATING FROM 1.647 – 1690, 1881 – 1947, 1955 – 1993 μM

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- 7.6 Demonstration of ultra-narrow linewidth, wavelength-tunable laser diodes operating from 1.647 – 1.690 μm**
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7.1 INTRODUCTION

This chapter is concerned with the demonstration of laser sources on the silicon photonic platform. Due to the indirect bandgap of silicon, unlike the III-V platform, the realization of an electrically-pumped laser is challenging. However, the CMOS-compatibility and potential for large scale integration with regards to silicon photonics have motivated researchers in the area to search for solutions. Fang et al. was the first to cross this milestone by realizing an electrically-pumped F-P lasers via a heterogeneous framework with III-V materials in 2006 [47]. Following, various laser designs such as distributed feedback (DFB) lasers have been realized [154].

Wavelength-tunable lasers will become a critical component in contemporary coherent/wavelength division multiplexing (WDM) systems [232]. A tunable laser can take the place of an array of single wavelength DFB lasers, thereby, reducing system complexity, wavelength contention and inventory cost [162]. The applications of tunable lasers are not restricted to optical communications, other applications, while not exhaustive, are identification of gas sensing via spectroscopy [119], as well as enabling the differential absorption LIDAR technique [233].

The crux in the realization of such lasers, depends on the integration of a wavelength-selective mechanism and an optical gain-section (**section 2.4**). While distributed feedback laser arrays and MEMS-enabled VCSELs has been shown to demonstrate wavelength-tuning functionality, there may be limitations in terms of DFB array coupler loss [234] and mechanical instability [235] respectively. Littman/Littrow-configured external cavity lasers (ECL) have also indicated wide spectral operating range, but however, the application-space of these class of lasers are limited typically by their bulk [236], as well as higher vulnerability to environmental vibrations [237]. The challenge is for the development of a solid state-based laser diode with a

compact footprint, good performance (i.e. tuning range, output power) that can be manufactured in a scalable, high-yield and low-cost process.

The silicon photonic platform, backed by the economies of trillions of dollars of investment into silicon manufacturing poses an attractive proposition for the realization of the abovementioned laser diode. The high-index contrast of the silicon-on-insulator (SOI) platform enables compact MRRs to be enabled without sacrificing radiation losses. As a result, Vernier filters with a large FSRs that can lead to broadly wavelength-tunable lasers can be realized (~140 nm). However, due to the indirect bandgap of silicon and germanium, the realization of an electrically-pumped group IV laser remains elusive [44]. Hybrid/heterogenous silicon photonics, integrating silicon photonic passives and III-V gain medium offers the best of both worlds [238]. Silicon photonics enables low propagation loss, high integration densities while III-V materials enables efficient optical gain and flexibility for spectral-engineering. In addition, hybrid/heterogenous III-V/silicon photonic lasers, by virtue of quantum noise reduction in the hybrid/heterogenous laser cavity, can result in ultra-narrow linewidth that could prove critical in applications such as coherent detection, optical clocking, high resolution metrology and spectroscopy [195], [239]; spontaneous emission is lowered when the ratio of the optical mode in the III-V active region is reduced [195].

In this chapter, hybrid integration is utilized in which the III-V waveguide is edged coupled to the silicon photonic hybrid ring external cavity (SHREC) (Fig. 7-1). Such an architecture enables for the SHREC and III-V waveguide to be individually optimized, enabling high-power laser emission via strong mode overlap with the gain media [240] and easier thermal management; i.e. III-V waveguide are prone to thermal degradation, locating the III-V component at the edge of the hot VLSI substrate reduces the complexity of thermal management [240]-[241].

Thus far, impressive work on SHREC wavelength-tunable laser diodes have been achieved near the C-band [165], [166], [242]-[245]; examples include wide tuning range [242], increased power and operating temperature [243], large SMSR [244] and shifting of tuning range from C- to L-band [245]. Recent trend in silicon photonics suggest an extension from the traditional wavebands of O and C to exploit potential wavelength-specific applications, as well as the inherent broadband nature of the SOI platform (**section 1.3.1**).

Firstly, this chapter provides a systematic description of the SHREC wavelength-tunable laser diode in term of its constituent components. Analysis of laser performance as a result of coupling gaps between the bus waveguide and the MRRs (Gap_{mrr}) in the Vernier-based wavelength-selective cavity is studied; Gap_{mrr} is the smallest parameter in the laser assemble. With regards to the vicinity of the 2 μm waveband, SHREC wavelength-tunable lasers operating from 1.881 – 1.947, 1.955 – 1.993 μm is demonstrated (**section 1.3.2**). Lastly, enabled by a SHREC that is designed to operate at the vicinity of 1.65 μm , a sub-kHz linewidth SHREC wavelength-tunable laser diode operating from 1.647 – 1.690 μm will be presented in (**section 1.3.3**). Via the implementation of the fiber loop, addition of the avalanche photodiode, RF amplifier as well as high output power of the laser, the laser linewidth is determined by the self-heterodyne technique to be smaller than 0.7 kHz by circulating four times, the laser output in the 35 km fiber loop. The laser linewidth obtained is amongst the lowest in the area in silicon photonics.

7.2 SHREC WAVELENGTH TUNABLE LASER DIODE

Fig. 7-1 illustrates the 3-D schematic of the SHREC wavelength-tunable laser diode together with the coordinates that will be standardized in this manuscript. The inset of Fig. 7-1 shows the micrograph images of semiconductor optical amplifier (SOA), Si slab waveguide, spot-size converter (SSC) [166] and wavelength-tunable Vernier cavity. In order to realize the hybrid laser cavity, a wavelength-tunable Vernier cavity is edged-coupled to the SOA via the Si slab waveguide and the spot-size converter (SSC); the SOA provides optical gain, whereas the Vernier cavity enables wavelength-selective feedback. The wavelength-tunable Vernier cavity comprises of 2 MRRs (mrr1, mrr2) and an MMI-based reflector; Vernier effect is facilitated by the 2 MRRs, the MMI-based reflector allows full reflectance. As indicated in Fig. 7-1, mrr1 and mrr2 has a radius of 16.8 and 18.2 μm respectively. Thermo-optic phase-shifters mounted on top of the MRRs are used to enable thermal control of lasing wavelength. Lasing output occurs at the facet of the SOA as indicated in Fig. 7-1.

Fig. 7-1. 3-D schematic of the SHREC wavelength-tunable laser diode; inset shows the micrograph images of the SOA, SiPh SSC and wavelength-tunable Vernier cavity.

The SHREC is fabricated on the 220 nm silicon-on-insulator (SOI) platform via the standard CMOS process. We characterize the propagation loss of the single-mode (TE₀₀) strip waveguide ($0.6 \times 0.22 \mu\text{m}^2$) to be 3 dB/cm. At the coupling facet of the SHREC to the III-V waveguide, a low-confinement slab ($6 \times 0.07 \mu\text{m}^2$) waveguide is designed to enable good overlap between both optical modes. A 200 μm -long SSC is used for low-loss conversion from the slab to the strip waveguide. mrr1 and mrr2 has FSRs of 8.9 nm (740 GHz) and 8.5 nm (706 GHz) respectively. After the fabrication of the waveguides, 1.2 μm of SiO₂ cladding is deposited followed by 120 nm of TiN (phase-shifter layer) and 2 μm of Al (routing layer). The footprint of the SHREC is $0.95 \times 0.3 \text{ mm}^2$.

7.2.1. Wavelength tunable Vernier filters

We can define the power transmittance spectra at the drop port of a single MRR as (7.1), where κ is the electric-field coupling coefficient between the bus waveguide and the MRR, θ is the incurred phase of the lightwave after propagating one round in the MRR, α is the waveguide loss coefficient. The theoretical power transmittance spectra of the 2 individual MRRs is presented in Fig. 7-2 (a).

$$P_{mrr1,2} = \left| \frac{-\kappa^* \kappa \sqrt{\alpha} \exp(j\sqrt{\theta_{mrr1,2}})}{1 - (\sqrt{1 - |\kappa^2|})^* (\sqrt{1 - |\kappa^2|})^* \alpha \exp(j\theta_{mrr1,2})} \right|^2 \quad (7.1)$$

Following, the Vernier spectra can be computed as a product of the power transmittance spectra of the 2 MRRs, (7.2). Fig. 7-2 (b) shows the theoretical Vernier power transmittance spectra.

$$P_{Vernier} = P_{mrr1} \times P_{mrr2} \quad (7.2)$$

By exploiting the thermo-optic effect of silicon through the phase-shifters, one will be able to control the wavelength corresponding to the lowest loss in the laser cavity via the overlap of the 2 MRR resonant peaks; single and dual shifter tuning will facilitate discrete and fine tuning of laser wavelength respectively. Consequently, the cavity longitudinal mode closest to the Vernier transmittance peak will be the lasing wavelength. Modal transmittance difference (MTD) as indicated in Fig. 7-2 (b), is the extent of transmittance difference between the main and adjacent peaks. It is the primary feature that determines the extent of mode-selectivity with regards to the SHREC, enabling lasing of the specific cavity longitudinal mode nearest to the Vernier peak via mode competition. Vernier transmittance efficiency (VTE) indicates the insertion loss at the wavelength of the Vernier peak (Fig. 7-2 (b)). In this work, the designed Vernier filter has an FSR of 140 nm (1843-1983 nm) which can be computed via (7.3). The demonstrated tuning bandwidth (1881-1947 nm) of the laser reported in this work is shaded in

green at Fig. 7-2(a)-(b).

$$FSR(Vernier) = \left| \frac{FSR(mrr1) \times FSR(mrr2)}{FSR(mrr1) - FSR(mrr2)} \right| \quad (7.3)$$

Fig. 7-2. (a) The red and blue lines indicate the theoretical power transmittance spectra of mrr1 and mrr2 respectively. (b) The grey line indicates the theoretical power transmittance of the Vernier power transmittance spectra; basic definitions of the Vernier power transmittance spectra are indicated.

Fig. 7-3. Measured and theoretical Vernier power transmittance when $H_{\text{mrr1}} = H_{\text{mrr2}} = 0 \text{ mW}$ (lower half) (a) $\text{Gap}_{\text{mrr}} = 160 \text{ nm}$, $H_{\text{mrr1}} = 15.5 \text{ mW}$, $H_{\text{mrr2}} = 0 \text{ mW}$ (upper half), (b) $\text{Gap}_{\text{mrr}} = 180 \text{ nm}$, $H_{\text{mrr1}} = 12.4 \text{ mW}$, $H_{\text{mrr2}} = 0 \text{ mW}$ (upper half), (c) $\text{Gap}_{\text{mrr}} = 200 \text{ nm}$, $H_{\text{mrr1}} = 11.1 \text{ mW}$, $H_{\text{mrr2}} = 0 \text{ mW}$ (upper half), (d) $\text{Gap}_{\text{mrr}} = 220 \text{ nm}$, $H_{\text{mrr1}} = 10.0 \text{ mW}$, $H_{\text{mrr2}} = 0 \text{ mW}$ (upper half), (e) $\text{Gap}_{\text{mrr}} = 240 \text{ nm}$, $H_{\text{mrr1}} = 8.7 \text{ mW}$, $H_{\text{mrr2}} = 0 \text{ mW}$ (upper half), (f) $\text{Gap}_{\text{mrr}} = 260 \text{ nm}$, $H_{\text{mrr1}} = 7.8 \text{ mW}$, $H_{\text{mrr2}} = 0 \text{ mW}$ (upper half).

Fig. 7-3 (a)-(f) shows the normalized measured and theoretical Vernier power transmittance spectra with respect to $\text{Gap}_{\text{mrr}} = 160, 180, 200, 220, 240, 260$ nm; experimental data are shown to resemble theoretical expectations closely. The lower-half of each individual plot corresponds the case when the power supplied to phase-shifter 1 and 2 ($H_{\text{mrr1}}, H_{\text{mrr2}}$) are 0 mW. The upper-half of Fig. 7-3(a)-(f) illustrates the resultant spectra when $H_{\text{mrr2}} = 0$ mW and $H_{\text{mrr1}} = 15.5, 12.4, 11.1, 10.0, 8.7, 7.8$ mW are applied respectively; a larger Gap_{mrr} would lead to an increased MRR Q-factor, as such, the effective MRR optical length will increase, leading to gains in phase-shifter efficiency. It can be seen that the noise floor of the detector is at approximately 21 dB, thus, measurement of the Vernier spectra beyond the detection limit is not possible. We measured the Vernier filter from 1935-1985 nm due to the maximum tunable range of our light source. Through the appropriate application of H_{mrr1} , we are able to red-shift the resonant wavelength of mrr1 by approximately 2 nm from $H_{\text{mrr1}} = 0$ mW (Fig. 7-3(a)-(f), lower-half), resulting in a Vernier transmittance peak at $\lambda \approx 1947$ nm (Fig. 7-3(a)-(f), upper-half). This corresponds to the longest demonstrated wavelength of the tunable laser in this work.

The characteristics of the Vernier filter is summarized experimentally and theoretically in Fig. 7-4 (a)-(d). There is a close match between experimental data and theoretical trends. According to Fig. 7-4 (a), when Gap_{mrr} is increased, MTD rises. VTE however, drops when Gap_{mrr} is increased (Fig. 7-4 (b)); laser cavity loss is expected to increase. Another important point of consideration is the FWHM and Q-factor of the individual MRRs. FWHM decreases and Q-factor increases when Gap_{mrr} becomes larger (Fig. 7-4 (c)-(d)). MRRs with low FWHM has a greater propensity to be misaligned by environmental thermal drifts. Furthermore, as indicated in the previous paragraph, while a higher Q-factor will lead to higher phase-shifter efficiency, it can also result in greater sensitivity to inconsistencies in environment temperature [126], [217]. The data presented below suggests that the implications of Gap_{mrr} on the Vernier filter is critical for subsequent Vernier-based laser design.

Fig. 7-4. (a) Theoretical MTD as a function of $\text{Gap}_{\text{mrr}} = 140\text{--}320$ nm, experimental MTD when $\text{Gap}_{\text{mrr}} = 160, 180, 200, 220, 240, 260$ nm. (b) Theoretical VTE as a function of $\text{Gap}_{\text{mrr}} = 140\text{--}320$ nm, experimental VTE when $\text{Gap}_{\text{mrr}} = 160, 180, 200, 220, 240, 260$ nm. (c) Theoretical FWHM as a function of $\text{Gap}_{\text{mrr}} = 140\text{--}320$ nm, experimental FWHM when $\text{Gap}_{\text{mrr}} = 160, 180, 200, 220, 240, 260$ nm. (d) Theoretical Q-factor as a function of $\text{Gap}_{\text{mrr}} = 140\text{--}320$ nm, experimental Q-factor when $\text{Gap}_{\text{mrr}} = 160, 180, 200, 220, 240, 260$ nm.

7.2.2. MMI-based reflector optimized for wavelength-tunable laser diodes operating from 1.881 – 1.947 μm

Fig. 7-5. (a) 3-D schematic of MMI coupler with associated physical parameters. (b) Measured linear fit for 1×2 MMI over 4 stages. (c) Simulated operation bandwidth of the 1×2 MMI.

The 1×2 MMI structure was used in the reflector due to its fabrication tolerance; by closing the loop at the double output end of the 1×2 MMI, a reflector can be formed (Fig. 7-1). The MMI width, length, gap between output tapers, taper length and taper width are designed to be 6, 24.2, 3.14, 20, 1.35 μm respectively as shown in Fig. 7-5 (a). In order to characterize the single trip insertion loss of the MMI-based reflector, the MMI coupler is cascaded over 4 stages. The measured normalized transmittances at $\lambda \approx 1947 \text{ nm}$ shown in Fig. 7-5 (b). The insertion loss ($\text{Loss (MMI)}_{\lambda \approx 1947 \text{ nm}}$) is experimentally characterized to be 0.538 dB. Due to the limited tuning range of our light source, we are unable to measure the operation bandwidth of the MMI over the demonstrated operation region of this work, nevertheless, we show the

simulated operation bandwidth of the MMI in Fig. 7-5 (c). The fabricated MMI has a simulated 0.25-dB ($BW_{0.25\text{dB}}$) and 0.5-dB ($BW_{0.25\text{dB}}$) bandwidth of 1859-1965 nm and 1840-1990 nm respectively; ($BW_{0.25\text{dB}}$) and ($BW_{0.25\text{dB}}$) refers to the spectral width corresponding to 0.25 and 0.5 dB below the peak transmittance value of the MMI.

As an example, the estimated round-trip insertion loss of the wavelength-tunable Vernier cavity at $\lambda \approx 1947$ nm with $\text{Gap}_{\text{mrr}} = 180$ nm is experimentally characterized to be $(\text{Loss (Cavity)})_{\lambda \approx 1947\text{nm}} = [2 \times \text{Loss (Vernier)}_{\lambda \approx 1947\text{nm}}] + [2 \times \text{Loss (MMI)}_{\lambda \approx 1947\text{nm}}] = 3.834$ dB.

7.2.3. InGaSb/AlGaAsSb SOA

In this work, the designed epitaxial structure intended for the fabrication of the SOA was grown on a (100) n-GaSb substrate using the molecular beam epitaxy (MBE); cross-section (x-y plane) of the epitaxial structure is illustrated in Fig. 7-6 (a). The designed structure is composed of a 10 nm-thick $\text{In}_{0.2}\text{Ga}_{0.8}\text{Sb}$ single quantum well (SQW) sandwiched by 270 nm-thick $\text{Al}_{0.25}\text{GaAsSb}$ barrier layers. The cladding comprises of 2000 nm-thick $\text{Al}_{0.5}\text{GaAsSb}$ layers. The barrier and cladding layers, with exception to the SQW layer, are latticed matched to the GaSb substrate; 1.26 % compressive strain is exerted on the SQW layer.

The fabrication process steps of the SOA are similar to our previous work [246]. Firstly, the ridge ($6.4 \times 1.0 \mu\text{m}^2$) was defined using UV lithography and wet chemical etching. After which, SiO_2 was deposited using the plasma-enhanced chemical vapor deposition (PECVD) for injection current confinement. Following, we defined a contact window at the center of the ridge using UV lithography and buffered oxide etch (BOE) process. Chemical-mechanical process (CMP) was carried out on the GaSb to reduce the thickness of the SOA; the resultant thickness is approximately 100 μm . A thinner SOA cross-section will facilitate cleaving, reduce series resistance, as well as allowing responsive thermal control during laser operation. Ti/Au and Ni/Ge/Au/Ni/Au are deposited using electron-beam evaporation to form the p and n side ohmic contacts respectively. Finally, the III-V waveguide is cleaved to be 2.4 mm-long. Due to the fact that Fabry-Perot (F-P) oscillations can reduce the single-mode stability of the tunable laser [243], the III-V waveguide is angled at 4.5° . The epitaxial structure of the SOA is designed to operate about 1.9 μm wavelength region. By measuring the output at the facet of the waveguide, the spontaneous emission spectra at $I_{\text{bias}} = 100, 200, 300, 400, 500$ mA is presented in Fig. 7-6 (b); the emission spectra resembles that obtained from our previous work [247], implying that reflections within the III-V has been successfully subdued.

Fig. 7-6. (a) Cross-sectional depiction of the InGaSb/AlGaAsSb SOA. (b) Measured spontaneous emission spectra of the InGaSb/AlGaAsSb SOA when $I_{\text{bias}} = 100, 200, 300, 400, 500$ mA.

7.3 HYBRID INTEGRATION

To facilitate hybrid integration between the SOA and the wavelength tunable Vernier cavity, both the Si slab waveguide and SSC are used; Si slab waveguide enables mode coupling at the III-V /silicon interface whereas the SSC converts the Si slab mode to the strip mode. The Si slab waveguide is angled at 9.8° to ensure compatibility with the III-V waveguide. In order to reduce edge-coupling losses, the facet quality was improved through polishing. Characterization of the laser was carried out by placing the SOA and SiPh chip on 2 different x/y/z precision manual alignment stages, each connected to a thermo-electric controller (TEC); near-field electric field distribution of the III-V waveguide and Si slab waveguide together with its respective sizes are indicated at the inset of Fig. 7-7 (a). The lasing output is collected from the output facet of the SOA via a lensed-fiber [165] (prevent possible reflection into the laser cavity) and connected to the optical spectrum analyzer for measuring the lasing spectra or coupled directly into the aperture of the photodetector for laser power characterization taking into account laser divergence angles (on-chip output power). The III-V waveguide-lensed fiber coupling loss is 10 dB; the coupling loss is determined by comparing the difference in the two cases when laser output is coupled directly into the aperture of the photodetector and coupled via a lensed fiber connected to the photodetector. The SOA has a fast and slow-axis divergence angles of 69.3° and 10.8° respectively. Theoretical coupling loss as a function of misalignment between III-V waveguide and Si slab waveguide in the x/y/z direction is simulated using eigenmode analysis as shown in Fig. 7-7 (a). While a low coupling loss of 1.46 dB can be achieved under optimal alignment condition where the center of both mode fields is aligned together, we find that a $0.5\ \mu\text{m}$ misalignment in the y-direction will result in a high coupling loss of 6 dB. The x and z-direction, on the other hand, are much more resilient; a $0.5\ \mu\text{m}$ misalignment would result in coupling losses of 1.58 and 1.79 dB respectively. As the silicon photonic chip is fabricated in a CMOS process line, the height of the Si slab waveguide and Si taper tip width are fixed at $0.07\ \mu\text{m}$ and $0.15\ \mu\text{m}$ respectively, leaving the SSC length as the only

parameter to optimize. In Fig. 7-7 (b), the length of the SSC [166] is optimized using the 3D-FDTD; when the length of the coupler exceeds 75 μm , low-loss conversion from the slab to strip waveguide can be achieved; the length of the SSC is fabricated to be 200 μm . The inset of Fig. 7-7 (b) shows the electric-field distribution (y-z plane) of the lightwave as it propagates along a 200 μm -long SSC.

Fig. 7-7. (a) Simulated SiPh Chip-SOA coupling as a function of misalignment (x/y/z). Inset shows the near-field electric-field distribution of the Si slab and III-V waveguide. (b) Simulated insertion loss of the SSC as a function of coupler length. Inset shows the electric-field distribution (y-z plane) of a 200 μm -long SSC.

7.4 DEMONSTRATION AND PERFORMANCE ANALYSIS OF WAVELENGTH-TUNABLE LASER DIODES OPERATING FROM 1881 – 1947 NM AS A FUNCTION OF COUPLING GAPS BETWEEN BUS WAVEGUIDE AND MRRs

The L-I curves of the tunable laser up to $I_{th} = 470$ mA when $Gap_{mrr} = 140, 180, 250, 320$ nm are illustrated in Fig. 7-8 (a); values for (slope efficiency) η_s are indicated at the inset. Room temperature continuous-wave operation is achieved for all cases. It can be seen that as Gap_{mrr} decreases from 320 nm to 140 nm, η_s reaches a peak value of 0.232 W/A at $Gap_{mrr} = 180$ nm, before dropping drastically to 0.152 W/A at $Gap_{mrr} = 140$ nm. A similar trend is observed with regards to maximum on-chip output power in Fig. 7-8 (b); maximum on-chip output power reaches a maximum at 28 mW when $Gap_{mrr} = 180$ nm, minimum of 13 mW when $Gap_{mrr} = 140$ nm. The inverse trend to η_s and maximum on-chip output power is observed with regards to I_{th} in Fig. 7-8 (b); I_{th} decreases with Gap_{mrr} and reaches a minimum value of 356 mA at $Gap_{mrr} = 180$ nm before increasing again at $Gap_{mrr} = 140$ nm.

Fig. 7-8. (a) On-chip output power against I_{bias} for $Gap_{mrr} = 140, 180, 250, 320$ nm; inset shows η_s for for $Gap_{mrr} = 140, 180, 250, 320$ nm. (b) Maximum on-chip output power and I_{th} for $Gap_{mrr} = 140, 180, 250, 320$ nm. (c) Lasing spectra corresponding to $Gap_{mrr} = 140, 180, 250, 320$ nm when $I_{bias} = 470$ mA.

Fig. 7-8 (a)-(b) point to $\text{Gap}_{\text{mrr}} = 180$ nm being the optimal value with regards to η_s , maximum on-chip output power and I_{th} . At $I_{\text{bias}} = 470$ mA, single-mode lasing with side-mode suppression ratio of 26, 35, 39, 42 dB corresponding to $\text{Gap}_{\text{mrr}} = 140, 180, 250, 320$ nm respectively was obtained (Fig. 7-8 (c)).

The improvement of η_s , maximum on-chip output power and I_{th} when Gap_{mrr} decreases from 320 to 180 nm can be attributed to the reduced laser cavity losses brought about by an increase in VTE (Fig. 7-4 (b)). However, $\text{Gap}_{\text{mrr}} = 140$ nm bucks the trend in all the above-mentioned laser performance metrics. According to Fig. 7-8 (c) when Gap_{mrr} reduces from 180 to 140 nm, there is a large drop in SMSR from 35 to 26 dB. We suggest that increased amplified spontaneous emission (ASE) due to low MTD is the reason behind the phenomena; the roll-off value of MTD occurs when $\text{Gap}_{\text{mrr}} = 140$ nm, is predicted to be 3.97 dB theoretically (Fig. 7-4 (a)). To simplify explanations, one can equate the SHREC to a wavelength-dependent mirror [165]. When Gap_{mrr} is small ($\text{Gap}_{\text{mrr}} = 140$ nm), the reflectance difference between the wavelength corresponding to the Vernier peaks and the rest of the spectrum will be low, implying a low MTD (Fig. 7-4 (a)). Consequently, unwanted reflections at the secondary peaks of the Vernier spectrum will become more significant in the laser cavity leading to the significant onset of ASE. This effect can be seen from the relative strength and number of parasitic oscillations when $\text{Gap}_{\text{mrr}} = 140$ nm in comparison to larger Gap_{mrr} . The extent of population inversion that can be achieved in the laser system is limited by depopulation losses resulting from ASE. Significant ASE oscillation can lead to quenching of amplifier gain, as well as decrease in laser efficiency [248]-[251]. Laser performance in terms of η_s , maximum on-chip output power and I_{th} is determined by the interplay between MTD and VTE of the SHREC.

Fig. 7-9 (a)-(d) shows the superimposed lasing spectra pertaining to lasers with $\text{Gap}_{\text{mrr}} = 140, 180, 250, 320$ nm respectively when $I_{\text{bias}} = 450$ mA. Tuning range of 1881-1947 nm (66 nm) was achieved. As confirmed in Fig. 7-8 (c), 7-9 (a)-(d), increases in Gap_{mrr} will lead to clear improvement in SMSR due to larger MTD (Fig. 7-4 (a)); strength and number of parasitic oscillations are significantly reduced. Through the increase of $H_{\text{mrr}1}$, the resonant peaks of MRR 1 will red-shift, subsequently, the Vernier transmittance peak will blue-shift in step sizes corresponding to $\text{FSR}_{\text{mrr}2}$ via the overlap of the 2 resonant peaks (Fig. 7-2 (a)-(b)), lasing will occur at the longitudinal mode that experience the least cavity loss through mode competition [162]. The values of $H_{\text{mrr}1}$ corresponding to each demonstrated lasing wavelength of the laser

diodes (Fig. 7-9 (a)-(d)) are illustrated in Fig. 7-9 (e). Although only H_{mrr1} is utilized in this work, tuning of H_{mrr2} can also achieve discrete tuning. The only exception is that lasing wavelength will shift towards longer wavelength in steps of FSR_{mrr1} with regards to increases in H_{mrr2} . Fig. 7-9 (e) illustrates an increase in phase-shifter efficiency when Gap_{mrr} is increased, this is in line with the trend for H_{mrr1} values observed in Fig. 7-3 (a)-(f). As mentioned earlier, the increase in phase-shifter efficiency can be attributed to longer effective optical length of the MRR due to larger Gap_{mrr} (higher Q-factor). With H_{mrr} as low as 47.2 mW, discrete tuning of lasing wavelength from 1881-1947 can be obtained. Fine tuning operation on the order of 0.8 nm is demonstrated in Fig. 7-10 (a); values of H_{mrr1} and H_{mrr2} corresponding to each wavelength is shown in Fig. 7-10 (b).

SMSR implies the amount of power that is generated in the main longitudinal mode. High SMSR is required for a wide range of applications such as high-end optical communications systems and spectroscopic sensing. In addition, high channel uniformity (extent of variability of SMSR) across the lasing channels is desirable. Low channel uniformity can introduce noise into measurement/detection, potentially impacting system performance [252]-[253]. Fig. 7-11 (a) illustrates the distribution of SMSR across the discrete tuning wavelengths obtained from Fig. 7-9 (a)-(d). While larger Gap_{mrr} can result in a higher SMSR, channel uniformity decreases. In Fig. 7-11 (b), we show population standard deviation (σ) of the SMSR as a function of Gap_{mrr} . Increases in σ as a result of larger Gap_{mrr} can be attributed to the increased tendency for MRR resonant peaks with lower FWHM and higher Q-factor (Fig. 7-4(c)) to be misaligned by environmental thermal drifts [126], [217], impacting wavelength-selective characteristics of the tunable cavity.

Fig. 7-9. Superimposed lasing spectra of tunable lasers with different Gap_{mrr} (a) $\text{Gap}_{\text{mrr}} = 140 \text{ nm}$, (b) $\text{Gap}_{\text{mrr}} = 140 \text{ nm}$, (c) $\text{Gap}_{\text{mrr}} = 140 \text{ nm}$, (d) $\text{Gap}_{\text{mrr}} = 140 \text{ nm}$. (e) $H_{\text{mrr}1}$ corresponding to each discrete wavelength within the tuning range of the laser ($\text{Gap}_{\text{mrr}} = 140, 180, 250, 320 \text{ nm}$).

Fig. 7-10. (a) Superimposed lasing spectra with ~ 0.8 nm (100 GHz) resolution tuning when $\text{Gap}_{\text{mrr}} = 180$ nm. (b) H_{mrr1} and H_{mrr2} required for lasing at corresponding wavelength.

Fig. 7-11. (a) Distribution of SMSR at each demonstrated discrete lasing wavelength when $\text{Gap}_{\text{mrr}} = 140, 180, 250, 320$ nm. (b) σ of SMSR when $\text{Gap}_{\text{mrr}} = 140, 180, 250, 320$ nm.

In response to the potential of the 1.9 μm wavelength region in enabling a wealth of applications, the prior sections in this chapter demonstrates the development of SHREC wavelength-tunable lasers with an operating range of 1881-1947 nm (66 nm). This is made possible through the integration of appropriately designed SHREC and SOA chips. η_s , maximum on-chip output power and SMSR up to 0.232 W/A, 28 mW and 42 dB respectively are achieved across the developed laser diodes. Via the increase in MRR Q-factor through Gap_{mrr} , higher phase-shifter efficiency can be obtained; discrete wavelength tuning of 1881-1947 nm can be covered by applying 47.2 mW of phase-shifter power on a mrr. The Vernier transmittance spectra of the SHREC is highly sensitive to Gap_{mrr} , the smallest feature of the laser. As such, lasing behavior would be prone to fabrication process variations. By changing Gap_{mrr} , trends in laser performance metrics are systematically studied and analyzed. The findings of this chapter thus far can be summarized as follows:

- 1) Optimal η_s , maximum on-chip output power and I_{th} can be achieved when $\text{Gap}_{\text{mrr}} = 180$ nm. Increasing Gap_{mrr} beyond 180 nm will lead to degradation of these parameters due to decreased VTE (Fig. 7-4 (b)); laser cavity loss is increased. Decreasing Gap_{mrr} from 180 nm to the roll-off value 140 nm will also diminish laser performance. We propose that the drop in efficiency is due to significant onset of ASE brought about by the low MTD of the Vernier spectra ($\text{MTD}_{\text{estimated}} = 3.97$ dB).
- 2) Phase-shifter efficiency increases as Gap_{mrr} becomes larger; increasing Gap_{mrr} will result in a higher MRR Q-factor, resulting in a longer effective MRR length.
- 3) SMSR rises with increasing Gap_{mrr} . A high MTD resulting from a large Gap_{mrr} will enhance the mode-selectivity of the SHREC.
- 4) Channel uniformity decreases with increments in Gap_{mrr} . Larger Gap_{mrr} will serve to reduce the FWHM and increase the Q-factor of the 2 MRR resonant peaks, increasing the propensity to be misaligned by environmental thermal fluctuations [126], [217].

7.5 DEMONSTRATION OF WAVELENGTH-TUNABLE LASER DIODES OPERATING FROM 1955 – 1993 NM

In order to extend the coverage of the SHREC/GaSb wavelength tunable laser diode operating at the 2 μm waveband, 2 adjustments were made to the wavelength-tunable laser diode demonstrated in the previous section: the length of the MMI-coupler is decreased to 24 μm from 24.2 μm (**section 7.2.2**) such that the optimal wavelength of the MMI-coupler is $\lambda = 1.97$ μm (center wavelength of the ASE), the Al composition in the 270 nm-thick waveguide layer of the GaSb-based SOA (**section 7.2.3**) was reduced from 0.25 to 0.2 ($\text{Al}_{0.25}\text{GaAsSb}$ to $\text{Al}_{0.2}\text{GaAsSb}$).

The fabrication process flow of the SOA is identical to that elaborated in **7.2.3**. In Fig. 7-12, the spontaneous emission spectra, coupled via a lensed fiber to the OSA corresponding to I_{bias} levels of 100, 200, 300, 400, 500 mA are presented; a clear emission window from 1.8 to 2.1 μm is measured without significant presence of gain ripples. The SOA waveguide tilted at 5 degrees, is shown to successfully suppress Fabry-Perot oscillations. Similarly, to Fig. 7-6 (b),

Fig. 7-12. Measured spontaneous emission spectra of the InGaSb/AlGaAsSb SOA when $I_{\text{bias}} = 100, 200, 300, 400, 500$ mA.

there is no significant presence of gain ripple in the measured spontaneous emission.

The L-I of the laser, as shown in Fig. 7-13, under RT-CW condition, was obtained by directly coupling the laser emission into the aperture of the power-detector. An I_{th} of 423 mA was obtained with a η_s of 70 mW/A. The maximum demonstrated on-chip output power is 6.1 mW.

Fig. 7-13. L-I of the SHREC wavelength-tunable laser diode.

In a similar fashion to the characterization of the SOA spontaneous emission, the tuning range of the wavelength-tunable laser diode was measured by coupling the laser emission to the OSA through a lensed-fiber. Fig. 7-14 (a) illustrates the superimposed lasing spectra, obtained when $I_{bias} = 500$ mA and H_{mrr1} ($R = 16.8$ μ m) is tuned; H_{mrr1} corresponding to each wavelength is indicated in Fig. 7-14 (b). The tuning range of the laser is 1955-1993 nm. As mentioned earlier, by exploiting the Vernier effect the, wavelength-dependent hybrid cavity loss can be controlled, leading to wavelength-selective lasing via mode competition.

Fig. 7-14. (a) Superimposed lasing spectra ($I_{bias} = 500$ mA), (b) corresponding heater 1 power values (H_{mrr1}) for each demonstrated lasing wavelength.

7.6 DEMONSTRATION OF ULTRA-NARROW LINEWIDTH, WAVELENGTH-TUNABLE LASER DIODES OPERATING FROM 1647 – 1690 NM

As mentioned in 1.3.3, the 1.65 μm wavelength region facilitates pervasive applications. However, there has been a lack of hybrid/heterogenous silicon photonic-based coherent light source that operates in the wavelength region in spite of the obvious advantages with regards to silicon manufacturing as well as III-V/Si integration.

Of late, one of the primary vector amongst hybrid/heterogenous silicon photonic lasers is linewidth reduction from solitary semiconductor lasers that suffers from significant quantum noise which in turn, increases the degree of spontaneous emission in the laser cavity [195]. Prior to this work, to the best of our knowledge, linewidth reduction to the sub-kHz level is demonstrated in ring-assisted DBR lasers. Key to the realization of the above result, besides quantum noise reduction via the integration of an extended silicon photonic section in the laser cavity and lowering of waveguide propagation loss, the implementation of an MRR into the DBR structure serves to further increase the cavity length and reduce DBR reflector sidelobes [154]. In this section, SHREC wavelength tunable laser diodes operating from 1647-1690 nm is demonstrated for the first time. RT-CW operation with an on-chip output power of up to 31.03 mW is measured.

With regards to the characterization of ultra-narrow laser linewidth (< 5 kHz), the laser frequency noise measurement technique is the dominant approach; quantum-limited Lorentzian linewidth can be obtained from the frequency noise spectrum [154], [195]. However, the measurement system is complex and might be challenging to implement [195]. By exploiting the relatively low fiber propagation loss near the 1.65 μm wavelength region (0.5 dB/km) and good on-chip output power of the laser, a fiber loop is integrated into the delayed

self-heterodyne technique [254]. Via a Lorentzian fit, the linewidth is estimated to be 0.7 kHz. Furthermore, the relative intensity noise (RIN) of the laser is measured.

The design approach of this laser (Fig. 7-15), operating from 1647-1690 nm is similar to the SHREC wavelength tunable lasers presented earlier. The width of the strip waveguide is 0.5 μm with a propagation loss of 0.4 dB/cm, radii of MRR1 and MRR2 are 18.3 and 17.2 μm respectively and the length of the MMI is 28.9 μm , optimized at 1670 nm. The wavelength-tunable Vernier cavity (consisting of a Vernier filter and an MMI-based reflector) is edged coupled to the indium phosphide 5-quantum well-based (InP 5QW) SOA. The gain spectrum of the SOA is designed to be centered near 1670 nm. In order to reduce the gain ripple of the ASE, the SOA is angled at 6.5° and antireflection coating are applied on both ends.

Fig. 7-15. 3-D schematic of the SHREC wavelength-tunable laser diode.

With the power coupling coefficient (κ_p) between the MRRs and the bus waveguide designated to be 0.093 ($\text{Gap}_{\text{mrr}} = 160 \text{ nm}$), the Vernier transmittance spectra, as a product (7.2) of the spectra of the 2 MRRs (7.1) in the lower half of Fig. 7-16 indicates a MTD of 10.76 dB in the upper half of Fig. 7.16. Via (7.3), the FSR of the designed Vernier filter is 130 nm. Through the thermo-optic tuning of the heaters mounted on top of the MRRs, the wavelength corresponding to the Vernier peak (lowest insertion loss) can be tuned. Thereby, the laser cavity will lase at the longitudinal mode closest to the Vernier peak.

Fig. 7-16. Theoretical power transmittance spectra of MRR1, MRR2 (lower half) and Vernier filter (upper half).

Fig. 7-17. Measured and theoretical Vernier power transmittance spectra; inset shows the Lorentzian fit of the Vernier peak.

For lack of a laser source operating within the range of the demonstrated laser the Vernier spectrum cannot be characterized from 1647–1690 nm. By applying 7.079 mW of heater power on MRR2, the Vernier spectrum with a peak at 1625.17 nm is measured from 1619–1626 nm. As shown in Fig. 7-17, a close correspondence is obtained between theoretical and measured results. The Lorentzian fit of the Vernier peak is shown at the inset with an estimated 3-dB bandwidth of 70 pm; the Q-factor of the Vernier resonance is 23000. As the characteristics of the Vernier filter in terms of MTD and 3-dB bandwidth is largely affected by the extent of confinement of the optical mode in the strip waveguide, one can expect that the values of MTD

and 3-dB bandwidth from 1647-1690 nm matches closely, to that measured in Fig. 7-17, from 1619-1626 nm; the change in optical confinement of the strip waveguide from 1619-1626 nm to 1647-1690 nm is minute.

The fabrication process steps of the InP 5QW SOA is elaborated in (section 7.2.3). The spontaneous emission spectrum when $I_{\text{bias}} = 200, 300, 400, 440$ mA (Fig. 7-18) is smooth, indicating that F-P oscillations have been extensively suppressed. Thermal saturation can be observed when I_{bias} is increased beyond 400 mA to 440 mA.

Fig. 7-18. Measured spontaneous emission spectra of the InP 5QW SOA at $I_{\text{bias}} = 200, 300, 400, 440$ mA.

Fig. 7-19. L-I-V of the SHREC wavelength tunable laser diode.

The L-I-V of the laser is shown in Fig. 7-19. The laser output power is characterized by coupling the laser emission directly into the aperture of the detector, taking into consideration the divergence angles. RT-CW operation is obtained with an I_{th} and η_s of 296 mA and 0.312 W/A respectively. The lasing evolution spectra obtained by coupling the lasing emission via the lensed fiber to the OSA is shown in Fig. 7-20. The maximum on-chip output power is 31.02 mW with a SMSR and wall-plug efficiency of 46.01 dB and 5.56 % respectively when $I_{bias} = 400$ mA. Similar to the trend observed from Fig. 7-18, thermal roll-off occurs when I_{bias} is increased beyond 400 mA as the SMSR degrades to 39.93 and 37.87 dB when $I_{bias} = 420, 440$ mA respectively.

Fig. 7-20. Lasing evolution spectra when $I_{bias} = 300, 320, 340, 360, 380, 400, 420, 440$ mA.

Fig. 7-21. (a) Superimposed discrete tuning lasing spectra when $I_{bias} = 380$ mA. (b) H_{MRR1} values corresponding

Fig. 7-22. (a) Superimposed fine tuning spectrum when $I_{bias} = 380$ mA. (b) H_{MRR1} and H_{MRR2} values corresponding to each fine tuning lasing wavelength.

The superimposed discrete tuning spectrum is illustrated in Fig. 7-21 (a). By tuning MRR1, the transmittance of MRR1 will redshift, thereby, overlapping with the transmittance of MRR2. As a result, the Vernier transmittance peak will shift towards longer wavelength at step sizes corresponding to the FSR of MRR2. A maximum tunable range of 1647-1690 nm is obtained with a SMSR of higher than 34.16 dB. The values of H_{MRR1} corresponding to each discrete lasing wavelength is shown in Fig. 7-21 (b). Through the application of H_{MRR1} and H_{MRR2} , fine tuning can be achieved. In Fig. 7-22 (a), fine tuning with a resolution of 0.5 nm is enabled. The values of H_{MRR1} and H_{MRR2} at each fine tuning lasing wavelength is indicated in Fig. 7-22 (b).

Fig. 7-23. Set-up to measure RIN.

The RIN of the laser is measured using the setup illustrated in Fig. 7-23. The laser emission, firstly, is split through a 1×2 coupler (10:90) where 10% of the laser output is fed into the OSA, where the spectrum is monitored. 90% of the laser output pass through an optical isolator, followed by a photodetector, where the direct current (DC) and alternating current (AC) components from the photodetector electrical output is separated using the bias tee. The DC signal represents the detected photocurrent (I_0) and the AC signal is amplified through a RF amplifier ($G(f) = 28$ dB, $f = 0$ -15 GHz) and subsequently, linked to the electrical spectrum analyzer. The electrical spectrum analyzer measures the total noise term N_{rf} , which includes the laser RIN and thermal noise N_{th} . The intrinsic laser RIN can be determined through (7.4).

$$RIN(f) = \frac{(N_{rf}(f) - N_{th}(f))/G(f)}{P_{elec.}} \quad (7.4)$$

Fig. 7-24. Measured RIN spectra when $I_{\text{bias}} = 320, 360, 400$ mA.

The intrinsic RIN of the laser when $I_{\text{bias}} = 320, 360, 400$ mA is shown in Fig. 7-24. The lowest RIN obtained is -118 dB/Hz when $I_{\text{bias}} = 400$ mA.

Following, the linewidth of the laser is characterized by integrating a fiber loop into the delayed self-heterodyne technique as illustrated in Fig. 7.25. Prior to the self-heterodyne experiment, laser emission is sent through a 1×2 coupler (10:90) where 10% of the power is fed into the SOA for spectra monitoring. The remaining laser emission (90%) is used for linewidth characterization. The displacement in length of a single round-trip is 35 km with an acoustic-optic modulator (AOM) operating at 80 MHz. As such, one should expect to observe beat signals at frequencies corresponding to the number of times that the laser emission has circulated the fiber loop, multiplied by 80 MHz. When the laser emission has circulated the fiber loop four times, the displacement in length with regards to the interferometer is 140 km, enabling reliable linewidth measurements lower than 1 KHz. As such, the objective is to observe the beat signal at 320 MHz ($80 \times 4 = 320$ MHz). The inset of Fig. 7-26 indicates 4 beat signals, amongst which the first two at 80 and 160 MHz are sub-coherent. With regards to the beat signal at 320 MHz, the 3-dB linewidth of the beat signal is 1.4 kHz, which corresponds to a laser linewidth of 0.7 kHz, assuming a Lorentzian lineshape.

Fig. 7-25. Fiber-loop integrated delayed self-heterodyne setup.

Fig. 7-26. Laser linewidth at 320 MHz, fitted using the Lorentzian lineshape; inset indicates incoherent peaks at 80, 160, 240 MHz, coherent peak at 320 MHz.

7.7 CONCLUSION

This chapter, by leveraging on the feasibility of the hybrid III-V/silicon photonics platform, seeks to extend the operation region of silicon lasers to exploit further applications beyond the traditional O and C-bands. This is driven by the inherent broadband property of the SOI platform, as well as the ability of III-V to be bandgap engineered.

The first part of this chapter is concerned with the 2 μm waveband. To that effect, SHREC wavelength tunable laser diodes operating from 1881-1947 nm and 1955-1992 nm are demonstrated for the first time. The coupling gap between the silicon MRR and bus waveguide (Gap_{mrr}), being the smallest feature in the assemble, is highly influential to the characteristics of the SHREC. As such, trends in hybrid laser performance with respect to Gap_{mrr} are systematically measured and analyzed. η_s , on-chip output power and SMSR of 0.232 W/A, 28 mW and 42 dB respectively are obtained across the developed lasers under RT-CW condition. It is concluded that influence of Gap_{mrr} on laser performance is multi-faceted, under the condition that the roll-off value of Gap_{mrr} is not violated, improving a specific performance index will lead to the degradation of another. Laser design should therefore be aimed at optimizing the value of Gap_{mrr} to fulfil the performance requirement of the targeted application. This section provides useful trends and references for future Vernier-based laser designs.

In the last section, a highly coherent SHREC wavelength tunable laser diode operating from 1647-1690 nm is developed for the first time. The realization of laser linewidth lower than 1 kHz was only recently demonstrated in 2019. Under RT-CW condition, slope efficiency, on-chip output power and side-mode suppression ratio of 0.312 W/A, 31.03 mW and 46.01 dB are shown. The current approach with regards to the characterization of ultra-narrow laser linewidth on the order of kHz or lower have focused on the measurement of the frequency noise spectrum, which will allow one to obtain the quantum noise limited Lorentzian linewidth.

As such, the values reported correspond to the lower limit in terms of laser linewidth. In this work, for the first time with respect to III-V/Si hybrid/heterogenous lasers, a Lorentzian linewidth of 0.7 kHz under a fiber length offset of 140 km was characterized via integrating a fiber loop into the traditional self-heterodyne setup. The linewidth reported in this case corresponds to the actual linewidth of the laser. This measurement is enabled by the decent on-chip output power of the laser, and the relatively low fiber propagation loss at the 1.65 μm wavelength region. Furthermore, the relative intensity noise of the laser diode is also measured.

CHAPTER 8

CONCLUSION

- 8.1 Summary of accomplishments
- 8.2 Prospective work

8.1 SUMMARY OF ACCOMPLISHMENTS

“Is silicon photonics truly a transformative technology or just another fad”, that seems to be the billion-dollar question that is currently perplexing industry? Thus far, several obstacles have hindered enthusiastic uptake in regard to industry. Silicon has an indirect bandgap, as such, the realization of a monolithic electrically-pumped laser is unlikely. While the data center transceiver market is attractive, there is a lack of a singular solution to all requirements due to different reach, multisource agreements and standards. This implies that the cost of the technology will be high, unless the optical industry makes a concerted effort for standardization. Furthermore, the chip volumes required by the data and tele-com industries might not be sufficient to attract the attention of chip-making giants such as TSMC, who bring with them the economies of scale. This work posits that for silicon photonics to be viable, its range of applications must be pervasive. The greater the adoption of silicon photonics in industry, the lower its cost, that is the beauty of silicon manufacturing.

To that effect, this work focuses on the development of silicon photonic technologies outside the incumbent wavebands at O and C. To tout the broadband properties of the SOI platform, in **Chapter 3**, ultra-broadband, low loss, compact arbitrary power splitters (50:50, 60:40, 70:30) operating at the longer transparency edge of SOI are developed. Broadband operation with low insertion loss of 0.11-0.6 dB is demonstrated across the 3660-3890 nm wavelength region (230 nm). This proof of concept, which in all aspects, rivals the devices developed at the traditional O and C wavebands, provides indication that silicon photonics can be exploited throughout its entire transparency region without compromise in device performance.

The 2 μm waveband initially attracted significant attention due to its potential as a window for optical communication. This waveband also enables further applications such as spectroscopy, LIDAR, optical logic and signal processing. In **Chapter 5**, $1 \times N$ silicon selector switches

operating near the 1.9 μm wavelength region are reported. As an elementary cell ($N = 2$), an insertion loss as low as 1.1 dB, P_π of 23 mW, 10-90% switching time of lower than 38 μs and a crosstalk of lower than -25 dB from 1880-1955 nm has been determined. In order to prove scalability, the 1×8 switch ($N = 3$) is demonstrated, indicating crosstalk as low as -21 dB, considering all possible switching configurations across the abovementioned wavelength region. **Chapter 4** extends the Si-SiN multilayer platform from the near-infrared to the 1.9 μm wavelength region. Waveguide propagation loss as low as 2.32 dB/cm has been attained. Following, trends in radiation loss with regards to bending radius is analyzed. A high performance 3-dB power splitter with insertion loss and bandwidth of 0.05 dB and 55 nm (1935-1990 nm) respectively is introduced. Lastly, Si-SiN transition loss as low as 0.04 dB is demonstrated. Optical modulation and multiplexing are two key functionalities that would enable the realization of high-bandwidth optical links. Spatial-multiplexing, specifically, can facilitate large degrees-of-freedom in terms of optical modes while maintaining structural simplicity in comparison to technologies such as wavelength-multiplexing. As a proof-of-concept, both functionalities are integrated at the 2 μm waveband by combining a (de)multiplexer (TE00, TE01) with 2 identical micro-ring modulators based on the carrier-depletion effect on a Si-SiN multilayer platform (**Chapter 6**), utilizing the strengths of each device layer. With regards to the (de)multiplexer, TE00 and TE01 crosstalk as low as -20.3 and -19.2 dB respectively are measured within 1.9-2.0 μm wavelength region. Highly-efficient modulation (0.278 V.cm) and electro-optic response of up to 15.7 GHz was characterized from the abovementioned integrated device.

In **Chapter 7**, SHREC wavelength tunable laser diodes operating from 1881-1947, 1955-1992 and 1647-1690 nm for the first time. With regards to the laser diodes operating near the 2 μm waveband, device performance with respect to different Gap_{mrr} is systematically analyzed. η_s , on-chip output power and SMSR of 0.232 W/A, 28 mW and 42 dB are obtained across the developed laser diodes respectively. For the SHREC wavelength tunable laser diodes operating at the application-rich 1.65 μm wavelength region, η_s , on-chip output power and SMSR as high as 0.312 W/A, 31.02 mW and 46.01 dB are demonstrated. Furthermore, assuming a Lorentzian lineshape, the linewidth of the laser is determined to be 0.7 kHz through a fiber length offset of 140 km by integrating a fiber loop into the delayed self-heterodyne technique; amongst the narrowest linewidth in the world. The laser diodes shown in **Chapter 7**, indicates an improvement in performance over monolithic III-V lasers. This is due to the integration of a low-loss passive silicon photonic extended laser cavity which reduces the degree of

spontaneous emission in the laser cavity. As such, it might be argued that the solution towards realizing a on-chip laser source has been partially resolved.

8.2 PROSPECTIVE WORK

The work in this thesis focuses on device development with regards to technologies beyond the O and C bands. With respect to prospective work, it is imperative that these technologies be integrated to realize some tangible applications. That might just be the kind of work that would help straighten out the undercurrent of ambivalence surrounding silicon photonics in industry.

As shown in **Chapter 3**, high performance silicon photonic devices can be implemented throughout the transparency window of the SOI platform. This gives impetus to the realization of fully-integrated silicon photonic systems that would be topical to applications from 3.66-3.89 μm . Instances include the spectroscopy (CO_2 and CO (2-2.5 μm), CH_4 (~1.65 μm), H_2O (~1.9 μm)), free space communications (3-3.89 μm), surgery and medical diagnostics (~1.65 μm), LIDAR (~1.65 μm) and fiber communications (~1.65, 1.9 μm).

The 2 μm waveband, specifically, in the region of 1.9 μm has garnered significant interest in view of its potential as adjunct to the present communication infrastructure. **Chapter 4, 5, 6, 7** contributed to devices that would be handy in a novel physical layer technology at the 1.9 μm wavelength region. Moving forward, it is still early days for 2 μm silicon photonics and much more can be done (i.e. III-V/silicon photonic hybrid DFB/DBR lasers).

As of now, the optical industry is focused on the development of transceivers that would be compatible to the IEEE 400G Ethernet standard. The current opinion involves four optical channels, each enabled by a separate DFB laser. The number of channels in this approach is inherently difficult to scale as one optical channel is represented by one laser; laser to silicon photonic chip alignment is expensive. In this work, by exploiting the multiwavelength spectra of a mode-locked laser and the hybrid III-V/silicon photonic platform developed in **Chapter 7**, a large number of multi-colour optical channels can be coupled onto silicon photonics with just

a solitary mode-locked laser. Through wavelength division multiplexing (Vernier filter in **Chapter 7**), the emission of the mode-locked laser will be distributed among a series of channels, which will undergo subsequent optical modulation and detection. The proposed next generation transmitter would be able to support much greater data rates in comparison the traditional architecture.

Publications

Journals/Letter

1. **J. X. B. Sia**, W. Wang, X. Guo, J. Zhou, Z. Zhang, M. S. Rouifed, X. Li, Z. L. Qiao, C. Y. Liu, C. G. Littlejohns, G. T. Reed and H. Wang, "Mid-infrared, Ultra-Broadband, Low-Loss, Compact Arbitrary Power Splitter Based on Adiabatic Mode Evolution," *IEEE Photonics J.*, vol. 11, no. 2, p. 6601111, 2019.
2. **J. X. B. Sia**, W. Wang, Z. Qiao, X. Li, X. Guo, J. Zhou, C. G. Littlejohns, Z. Zhang, C. Liu, G. T. Reed and H. Wang, "Compact, High-Power, Silicon Photonic Hybrid Ring External Cavity (SHREC) GaSb-based Wavelength-Tunable Laser Diode for Future 2 μm Technologies," *Opt. Express*, vol. 28, no. 4, pp. 5134-5146, 2020.
3. **J. X. B. Sia**, W. Wang, X. Guo, J. Zhou, Z. Zhang, X. Li, Z. Qiao, C. Liu, C. G. Littlejohns, G. T. Reed and H. Wang, "SiN Passives based on SIN-SOI Platform for Prospective Applications at 2 μm ," *IEEE Photonics J.*, vol. 11, no. 6, p. 6603809, 2019.
4. **J. X. B. Sia**, W. Wang, Z. Qiao, X. Li, X. Guo, J. Zhou, C. G. Littlejohns, C. Liu, G. T. Reed and H. Wang, "Analysis of Compact Silicon Photonic Hybrid Ring External Cavity (SHREC) Wavelength-Tunable Laser Diodes Operating from 1881-1947 nm," submitted to *IEEE J. Quantum Electron.*, vol. 56, no. 6, p. 2001311, 2020 (featured on the cover of the December issue of *IEEE J. Quantum Electron.*).
5. **J. X. B. Sia**, W. Wang, X. Guo, J. Zhou, X. Li, Z. Qiao, C. Liu, C. G. Littlejohns, G. T. Reed and H. Wang, "1 $\times$ 8 silicon thermo-optic switch for prospective technologies at the 2 μm waveband," *IEEE Photonic Tech. L.*, vol. 32, no. 18, pp. 1127-1130, 2020.
6. **J. X. B. Sia**, W. Wang, Z. Qiao, X. Li, X. Guo, J. Zhou, C. G. Littlejohns, C. Liu, G. T. Reed and H. Wang, "Compact, hybrid Silicon Vernier laser diode operating from 1955-1992 nm," submitted to *IEEE Photonic Tech. L.*.
7. **J. X. B. Sia**, X. Li, W. Wang, Z. Qiao, X. Guo, J. Zhou, C. G. Littlejohns, C. Liu, G. T. Reed and H. Wang, "Sub-kHz linewidth, III-V/silicon hybrid ring external cavity (SHREC) wavelength-tunable laser diode operating at the application-rich 1.647-1.690 μm ," *Opt. Express*, vol. 28, no. 17, pp. 25215-25224.
8. Z. Zhang, G. I. Ng, T. Hu, H. Qiu, X. Guo, W. Wang, M. S. Rouifed, C. Liu, **J. Sia**, J. Zhou, C. G. Littlejohns and G. T. Reed, "Mid-Infrared Sensor Based on a Suspended Microracetrack Resonator With Lateral Subwavelength-Grating Metamaterial Cladding," *IEEE Photonics J.*, vol. 10, no. 2, p. 6801608, 2018.
9. Z. Zhang, G. I. Ng, T. Hu, H. Qiu, X. Guo, W. Wang, M. S. Rouifed, C. Liu, **J. Sia**, J. Zhou, C. G. Littlejohns and G. T. Reed, "Experimental Demonstration of Thermally Tunable Fano and EIT Resonances in Coupled Resonant System on SOI Platform," *IEEE Photonics J.*, vol. 10, no. 3, p. 6801608, 2018.
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12. C. Liu, Z. Qiao, X. Li, **J. X. B. Sia**, W. Wang, X. Guo, J. Zhou, X. Guo, Y. Qu, B. Bo and H. Wang, "Study on the Quantum Dot Mode-locked Laser by Sidewall Spontaneous Emission and Facet Amplified Spontaneous Emission," submitted to *IEEE J. Quantum Electron.*.

13. W. Wang, **J. X. B. Sia**, X. Guo, J. Zhou, X. Li, Z. Qiao, C. Liu, C. G. Littlejohns, G. T. Reed and H. Wang, "Spatial Multiplexing + Optical Modulation on the SiN-SOI Multilayer Platform at 2 μm ," submitted to *J. Lightwave Technol.*
14. X. Li, **J. X. B. Sia**, W. Wang, Z. Qiao, X. Guo, G. I. Ng, Y. Zhang, C. Tong, H. Wang and C. Liu, "Phase noise reduction of a 2 μm passively mode-locked laser through its hybrid integration with a silicon photonic circuit," submitted to *Optica*.

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4. M. Rouifed, C. G. Littlejohns, G. X. Tina, **J. X. Sia**, H. Qiu, J. S. Penades, M. Nedeljkovic, Z. Zhang, C. Liu, D. J. Thomson, G. Z. Mashanovich, G. T. Reed and H. Wang, "Silicon photonic devices for the mid-infrared," *Conference on Lasers and Electro-Optics Pacific Rim (CLEO-PR)*, 2017.
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