Integrated tunable laser controlled by nano-silicon-photonic circuits

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**NANYANG
TECHNOLOGICAL
UNIVERSITY**

INTEGRATED TUNABLE LASER CONTROLLED
BY NANO-SILICON-PHOTONIC CIRCUITS

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NANO-SILICON-PHOTONIC CIRCUITS**

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SCHOOL OF ELECTRICAL AND ELECTRONIC
ENGINEERING
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INTEGRATED TUNABLE LASER CONTROLLED BY NANO-SILICON-PHOTONIC CIRCUITS

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Ren Min

SUMMARY

This doctorate thesis focuses on the design, fabrication and experimental characterization of integrated external cavity tunable lasers realized via nano-silicon-photonic (NSP) integrated circuits. Specifically, the external cavity laser system consists of gain diodes, passive bus waveguides, splitters/combiners and ring resonators. Three different types of wavelength tuning approaches, including thermal-optic, free-carrier injection and opto-mechanical, are demonstrated.

An external cavity tunable laser, controlled by electrical approaches, is demonstrated, which integrates a gain chip and external NSP integrated circuits onto a silicon-on-insulator platform. A coupled ring resonator structure serves as a wavelength selective reflector. The wavelength is electrically tuned by changing the effective refractive index of the ring waveguide, via both thermal-optic and free-carrier effects, to obtain an over 40-nm tuning range and 2-pm tuning accuracy.

An external cavity laser controlled by an opto-mechanical approach, instead of the electrical approach, is reported. A nano-actuator, with a deformable free-standing ring waveguide, is driven by optical force. Thus the lasing wavelength is optically tunable by controlling the deflection of the ring waveguide in the external PIC. The opto-mechanical approach successfully gets rid of the problems caused by the electrical tuning approach, such as thermal dissipation and electrical power consumption.

A ring cavity tunable laser constructed by closed-loop nano photonic circuits is demonstrated. It comprises a semiconductor optical amplifier (SOA) chip with both facets coupled with the external PIC, two separated ring resonators that serve

as wavelength filters, and a special U-shape photonic loop that realizes unidirectional light propagation and eliminates the spatial hole burning effect. A 50-dB side mode suppression ratio within a 50-nm tuning range is obtained in the experiments.

The successful implementation of three different tunable lasers has evidenced the effectiveness of employing NSP integrated circuits in external cavity tunable lasers to improve the specifications and performances.

TABLE OF CONTENTS

Acknowledgements	i
Summary	iii
Table of Contents	v
List of Figures	ix
List of Tables	xix
Nomenclature	xx
1. Introduction	1
1.1 Motivation	1
1.2 Objectives	6
1.3 Major contributions	8
1.4 Organization of the thesis	11
2. Literature Survey	13
2.1 Monolithic external cavity tunable lasers	14
2.1.1 Tunable monolithic diode lasers	15
2.1.2 External cavity tunable lasers	16
2.1.3 Photonic waveguide based lasers	20
2.2 Wavelength tuning via electrical approaches	30
2.2.1 Thermal-optic effect	30
2.2.2 Free carrier effect in P-I-N junction	31

2.3	Opto-mechanical wavelength tuning.....	33
2.3.1	Opto-mechanical effect	33
2.3.2	Resonator enhanced optical force	35
2.3.3	Nano-actuator and resonant wavelength tuning.....	36
2.4	Ring cavity tunable laser	38
2.4.1	Single-mode ring cavity laser	38
2.4.2	Wavelength tunable ring cavity laser.....	39
2.5	Summary	42
3.	Electrically Controlled Tunable Laser	43
3.1	Design of the electrically controlled tunable laser	44
3.1.1	Tunable lasers using ring resonators.....	44
3.1.2	Schematic of electrically controlled tunable laser	46
3.1.3	Working principle for single-mode operation.....	50
3.2	Analysis of the electrically controlled tunable laser	52
3.2.1	Properties of the coupled ring structure	52
3.2.2	Electrically controlled tuning approaches.....	58
3.2.3	Spectral properties of laser output	64
3.3	Fabrication and Packaging Processes.....	70
3.3.1	Fabrication processes flow.....	70
3.3.2	Fabrication Results.....	76
3.4	Experimental results and discussions	79

3.4.1	Reflectance of the CRS	79
3.4.2	Electrically controlled wavelength tuning	80
3.4.3	Parameters of the laser spectrum	84
3.5	Summary	89
4.	Opto-mechanical Tunable Laser	91
4.1	Theoretical analysis of the opto-mechanical tunable laser.....	92
4.1.1	Design of the opto-mechanical nano-actuator	92
4.1.2	Theoretical analysis of the opto-mechanical nano-actuator.....	95
4.1.3	Design of the opto-mechanical tunable laser	108
4.2	Fabrication and Packaging Processes.....	113
4.2.1	Fabrication processes flow.....	113
4.2.2	Fabrication results	116
4.3	Experiments and discussions.....	119
4.3.1	Nonlinear wavelength tuning of the single ring resonator.....	119
4.3.2	Wavelength tuning in the opto-mechanical laser system.....	123
4.4	Summary	129
5.	Ring Cavity Tunable Laser.....	131
5.1	Design of the ring cavity tunable laser.....	132
5.1.1	Schematic of the ring cavity tunable laser	132
5.1.2	Design of the Y-junction.....	134
5.1.3	Analysis of unidirectional operation	136

5.2	Simulation of the ring cavity tunable laser.....	139
5.2.1	Properties of the single-mode wavelength selection.....	139
5.2.2	Parameters of the ring cavity laser.....	144
5.3	Fabrication and Packaging	149
5.4	Experimental results and discussion	152
5.4.1	Effect of the unidirectional operation	152
5.4.2	Single-mode properties at $N = 3$	156
5.4.3	Wavelength tuning properties	162
5.5	Summary.....	166
6.	Conclusions.....	168
6.1	Conclusions	168
6.2	Recommendations	172
	Author's Publications.....	174
	Bibliography	175

LIST OF FIGURES

Figure 2.1:	Typical configurations of developed MEMS external cavity tunable lasers: (a) flat-mirror scheme; (b) curved-mirror scheme; (c) 3D-coupling scheme; (d) Fabry-Pérot etalon scheme; (e) Littrow scheme; (f) Littman scheme; and (g) non-standard grating scheme [6].	19
Figure 2.2:	Schematic of the external cavity tunable lasers based on photonic waveguides: (a) ring resonators are utilized as wavelength filter on InP platform [67]; (b) hybrid integration of a super-luminescent diode and a polymer Bragg reflector [68].	22
Figure 2.3:	(a) The schematic of optical ring resonator as a drop filter, (b) demonstration of the optical spectrum within one period.	26
Figure 2.4:	Demonstration of Vernier effect using two ring resonators which work as wavelength filters.	27
Figure 3.1:	The widely-tuning external cavity lasers which apply passive ring resonators as wavelength filters: (a)-(c) single-ended external cavity tunable lasers using two ring resonators; (d) double-ended linear-cavity and (e) ring-cavity tunable lasers using two ring resonators; (f)-(g) single-ended external cavity tunable lasers using three ring resonators; (h) double-ended linear-cavity and (i) ring-cavity tunable lasers using three ring resonators.	45
Figure 3.2:	The schematic illustration of (a) the external cavity tunable laser using the coupled ring structure as wavelength selective reflector, and the wavelength is electrically tuned via the thermal-optic and the free-	

carrier effects; (b) the equivalent cavity mode of the external cavity tunable laser.....	47
Figure 3.3: Schematic of the cross-section for Ring 2, with the P-I-N junction on a slab-waveguide structure.....	49
Figure 3.4: Demonstration of principles for the single-mode wavelength selection and wavelength tuning under electrical control.	51
Figure 3.5: The schematic of coupled ring structure as a reflective filter.	52
Figure 3.6: The power coupling coefficient K (for bus-ring coupling) and K_2 (for ring-ring coupling), as a function of the coupling gap.	54
Figure 3.7: The maximal value of the reflectance of the coupled ring reflector determined by the coupling coefficient of the ring-ring couple and ring-bus waveguide couple.....	54
Figure 3.8: The power reflectivity as a function of wavelength is calculated for various ring-bus coupling coefficient values while the ring-ring power coupling coefficient is kept at $K_2 = 0.0016$	56
Figure 3.9: The margin of power reflectivity between the main and the first side mode as a function of the coupling coefficient of the ring-ring couple and the ring-bus waveguide couple.	57
Figure 3.10: The reflection spectrum of the coupled ring structure, within the wavelength range from 1520 nm to 1580 nm.....	57
Figure 3.11: Illustration of the mode spreading in three silicon waveguide cross sections, obtained at $\lambda = 1550$ nm: (a) $t = 160$ nm, (b) $t = 220$ nm, (c) $t = 340$ nm, the width is constant at 450 nm.	59

Figure 3.12: The effective index and the group index varies with the propagation wavelength in the silicon photonic waveguide, with a waveguide width of 450 nm, and thickness of 220 and 340 nm, respectively. ...	59
Figure 3.13: The FSR of Ring 1 varies with its radius, obtained at different waveguide thickness (160, 220 and 340 nm), when the width is 450 nm.....	60
Figure 3.14: The maximum wavelength tuning range due to the Vernier effect, dependent on the radius difference of the coupled ring structure.....	61
Figure 3.15: The change of the effective refractive index and the absorption coefficient due to the change of the free carrier concentration.	63
Figure 3.16: The SMSR varies as bus-ring power coupling coefficient under different ring-ring power coupling conditions. The solid lines indicate the situation where of single reflection peak, and the dash lines indicate the situation of multi-reflection peaks of the CRS.	66
Figure 3.17: The SMSR vs. the bus-ring power coupling coefficient K , under different values of the bus waveguide length L_m , and the optical loss coefficient of the nano-silicon waveguide α_{Si}	67
Figure 3.18: The linewidth varies with the bus-ring coupling coefficient, at different bus waveguide lengths.....	68
Figure 3.19: The main process flow of electrically controlled tunable laser integrated on a SOI wafer.....	72
Figure 3.20: The measured profile of the laser diode cavity with the Au/Sn solder. The vertical alignment accuracy is controlled by the bottom of the diode cavity.	74

Figure 3.21: The SEM graph of the integrated tunable laser using flip-chip bonding process.	76
Figure 3.22: The zoom-in view of the nano-silicon-photonic circuits in the external cavity: (a) the coupled ring resonator, (b) the bus-ring coupling region and (c) the ring-ring coupling region.	77
Figure 3.23: The transmission and reflection spectra of the coupled ring structure. The reflection spectrum is measured using a fiber optical circulator with a 1.2-dB insertion loss.	80
Figure 3.24: The tuning of resonance position of a single ring resonator, via the thermal-optic and the free-carrier injection method, respectively.	81
Figure 3.25: The resonance tuning of Ring 2 is controlled by (a) the free-carrier injection and (b) the thermal-optic effect.	82
Figure 3.26: Experimental switching time of the free-carrier injection method, when the modulation frequency is 1GHz. The rise and fall time are 0.78 ns and 0.72 ns, respectively.	83
Figure 3.27: Experimental switching time of the thermal-optic scheme, when the modulation frequency is 25-kHz. The rise and fall time are 3 μ s and 5.5 μ s, respectively.	84
Figure 3.28: The wavelength tuning and SMSR performance versus the thermal voltage applied on Ring 2.	85
Figure 3.29: The comparison of laser performance (output power and SMSR), before and after applying the free carrier effect.	86
Figure 3.30: The optical spectrum of a series of single-mode output, and the lasing wavelength is tuned from 1523.6 nm to 1563.8 nm.	87

Figure 4.1: The schematic illustration of (a) the opto-mechanical nano-actuator; (b) the cross-sectional view of the free-standing arc; (c) the deflection of the arc caused by optical force; (d) the cross-sectional view of the deflected actuator.	92
Figure 4.2: Schematic illustration of the free-standing ring resonator that is deflected by optical gradient force.	93
Figure 4.3: The effective refractive index of the free-standing waveguide.	95
Figure 4.4: The effective refractive index versus the air gap under different waveguide thickness.	96
Figure 4.5: Schematic of the shift of the resonant wavelength versus the deflection x of the arc.	97
Figure 4.6: The optical force as a function of the displacement x and the wavelength of the control light λ	98
Figure 4.7: The illustration of the shift of resonant wavelength of the ring resonator when a control light is provided.	99
Figure 4.8: Comparison of the optical force and the mechanical force under different wavelength detuning conditions.	100
Figure 4.9: The optical spring and system stiffness <i>vs.</i> x at $\Delta = 0.54$ nm.	102
Figure 4.10: The nonlinear relationship between the deflection of the arc and the wavelength detuning Δ	103
Figure 4.11: The contour plot of the displacement d at “pull-back” positions as a function of the effective mechanical stiffness k and the optical power P_{in} of the control light.	105

Figure 4.12: The dependence of the normalized “pull-back” displacement on the mechanical spring constant and the optical power of the free-standing arc.	105
Figure 4.13: Comparison of the optical force and the mechanical force under different power of the control light P_{in}	106
Figure 4.14: The nonlinear relationship between the arc deflection x and the light power P_{in} at different wavelength detuning status of $\Delta = 0.2$ nm and $\Delta = 0$ nm.....	107
Figure 4.15: The schematic of the opto-mechanical tunable laser integrated on a SOI chip.....	108
Figure 4.16: The wavelength tuning range of the opto-mechanical tunable laser, as a function of the deflection of the free-standing arc. The tuning range is also dependent on the radius difference between two coupled ring resonators.	109
Figure 4.17: The amount of wavelength tuning $\Delta\lambda_T$ as a function of the optical power inside the laser cavity.	110
Figure 4.18: The maximum tuning range of the opto-mechanical tunable laser as a function of the Q-factor of the free-standing ring resonator.	111
Figure 4.19: The process flow of the opto-mechanical tunable laser on a SOI chip.	114
Figure 4.20: The SEM graphs of (a) the partially released ring resonator coupled to a bus waveguide; (b) the free-standing arc within the release window, with an initial air gap of 160 nm.	116
Figure 4.21: The SEM graph of the opto-mechanical tunable laser, and the gain chip is flip-bonded onto the SOI substrate.	117

Figure 4.22: The zoomed-in SEM graphs of (a) the actuated ring resonator with released arc; (b) the free-standing arc in the released window.	118
Figure 4.23: The experimental setup for measurement the opto-mechanical wavelength tuning of the sing ring resonator.	119
Figure 4.24: The transmission spectra when the wavelength of the control light λ_c is: (a) red-tuned; (b) blue-tuned.....	121
Figure 4.25: The nonlinear opto-mechanical wavelength tuning controlled by tuning the wavelength of the control light, where the experiments match the simulation well.	122
Figure 4.26: The experimental results of the transmission spectrum of the coupled ring structure. The resonance of the fixed ring and the free-standing ring merges at λ_1 , and is differentiated slightly at λ_2 and λ_3	123
Figure 4.27: The experimental results of a series of single-mode lasing wavelength under different gain currents.	124
Figure 4.28: The process of the single-mode wavelength tuning of the opto-mechanical tunable laser.	125
Figure 4.29: Experimental results of switch time of opto-mechanical effect. The rise and fall time are 0.90 μ s and 0.88 μ s, respectively.	126
Figure 5.1: Schematic illustration of the ring cavity tunable laser with NSP circuits: the sub-loop enables the unidirectional propagation, and the resonant wavelength of the two ring resonators is thermally tuned.	132
Figure 5.2: Schematic of the Y-junction, which serves as the optical splitter and combiner.....	134

Figure 5.3: The optical combining effect of the Y-junction. The combined power is dependent on the power ratio in the two branches of the Y-junction.	135
Figure 5.4: The normalized gain coefficient g_{ccw} and the gain coefficient ratio g_{ccw}/g_{cw} between the counter-directional waves, and both of them are dependent on the Y-junctions number N	138
Figure 5.5: The transmission spectrum of the wavelength filtering effect: (a) the FSR of the double-ring filter is 51 nm, (b) the FSR of Ring 1 is 1.6 nm.....	140
Figure 5.6: The calculation of the FWHM of the filter and the longitude mode spacing of the ring cavity $\Delta\lambda_{mode}$, dependent on the coupling coefficient κ^2 of the ring resonator and the physical length of the bus waveguides in the ring cavity L_m	142
Figure 5.7: The Q -factor of the ring resonator, determined by the optical transmission loss of the waveguide and the radius of the ring resonator.....	143
Figure 5.8: The quality factor of the ring resonator, as well as the normalized optical transmission, as a function of the power coupling coefficient κ^2	144
Figure 5.9: The loss margin $\Delta\alpha$ between the main mode and side mode, as a function of the power coupling coefficient κ^2	146
Figure 5.10: SMSR varies with the bus-to-waveguide power coupling coefficient κ^2 under different mirror coupling efficiency C_m , where the total power in the cavity is 25 mW.....	147

Figure 5.11: Linewidth of the output laser varies with the bus-to-waveguide power coupling coefficient κ^2 under different mirror coupling efficiency C_m , where the total power in the cavity is 25 mW.....	147
Figure 5.12: The SEM graph of the ring cavity tunable laser, which integrates the SOA chip and the NSP circuits.	149
Figure 5.13: The zoom-in SEM graphs of (a) the region where the active waveguide is coupled with the passive waveguide; (b) Ring 2 with metal micro heater and electrical pads on top of the upper cladding SiO ₂	150
Figure 5.14: The output power versus the SOA current for the CCW wave when the Y-junction number is $N = 0$ (no sub-loop).	153
Figure 5.15: The output power versus the SOA current for the CCW and the CW propagating waves when the Y-junction number is $N = 2$	153
Figure 5.16: The output power versus the SOA current for the CCW and the CW propagating waves when the Y-junction number is $N = 3$	154
Figure 5.17: The output power versus the SOA current for the CCW and the CW propagating waves when the Y-junction number is $N = 4$	154
Figure 5.18: Comparison of the P-I curves of CCW wave when $N = 0, 2, 3, 4$. ..	156
Figure 5.19: The optical spectra of the CCW and CW output at different SOA currents ($N = 3$): (a) 280 mA, (b) 310 mA and (c) 360mA.	157
Figure 5.20: Experiments of the CWSR, P_{ccw}/P_{cw} , as the function of the SOA current.....	158
Figure 5.21: Based on the single-mode performance, the working status of the ring cavity tunable laser is divided into 4 periods, as noted with P ₁ -P ₄ . .	159

Figure 5.22: Linewidth measurement of the CCW wave lased at 1524.82-nm, a laser with a narrow linewidth is chosen as the reference.	161
Figure 5.23: The combined optical spectra of a series of single-mode output with a tuning range from 1501.82 nm to 1557.21 nm.....	162
Figure 5.24: The relationship between the output wavelength and the thermal optical voltage.	163
Figure 5.25: The SMSR versus the output wavelength of the CCW wave.	164

LIST OF TABLES

Table 2.1: Basic PIC based laser systems and the equivalent cavity models.	21
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NOMENCLATURE

CRS	coupled ring structure
CWSR	counter-propagation wave suppression ratio
CCW	counterclockwise
CW	clockwise
ECTL	external cavity tunable laser
FWHM	full width at half maximum
MEMS	micro-electromechanical systems
NSP	nano-silicon-photonic
PIC	photonic integrated circuits
SMSR	side mode suppression ratio
SOI	silicon-on-isolator

CHAPTER 1

INTRODUCTION

1.1 Motivation

This PhD research topic is motivated by the potential of significant performance improvement of the external cavity tunable lasers (ECTL) by using nano-silicon-photonic (NSP) integrated circuits.

Wavelength tunable lasers are of great importance for many applications, especially in the optical communication and the spectroscopy analysis [1,2]. For instance, it is the key element in dense wavelength division multiplexing systems (DWDM) and all-optical networks. DWDM uses a light source at standard wavelength spacing (100 GHz, 50 GHz, etc.) according to the International Telecommunication Union (ITU) G694.1, to enhance the transmission capacity in optical fiber based optical communication. Thus the tunable laser lowers the cost and volume by replacing multiple single-mode lasers. In addition, tunable lasers improve the network functionalities by combining a passive wavelength router to control the optical signals flexibly without optical cross-connects, and even realize the source-controlled optical switch and routing in large-scale all optical network with the help of the wavelength converter.

The external cavity tunable laser is usually a laser system, which comprises of an internal cavity that provides gain and an extended cavity for wavelength tuning. Conventionally, external cavity tunable lasers are constructed in free space

and have a large volume [3,4]. The free space configurations require multiple discrete optical elements, such as optical lens, Fabry-Par (FP) filters, optical isolators, mirrors, etc. Moreover, it is a great challenge to align these separated elements in a compact size, without degradation in stability performance. Although the chip-scale micro-electrical-mechanical-systems (MEMS) tunable laser realizes more compact and stable integration [5], the light path is still in free-space. Thus it suffers high optical loss caused by beam divergence in the air-medium external cavity [6,7]. This disadvantage limits the performance of the tunable laser and causes conflicts between the key parameters. For instance, it is hard to achieve simultaneously (a) broadband tuning range (> 40 nm) which requires a longer cavity, and (b) relatively high output power (mW-scale) which requires shorter cavity, by using a MEMS tunable laser with a mirror or grating configuration.

The development of photonic integrated circuits (PIC) [8,9] has provided a new opportunity for the ECTLs. Its fabrication processes, including spin coating, photo lithography, reactive ion etching and deposition, are utilized to fabricate the PIC on semiconductor wafers. Different from the tunable laser system based on free-space external cavity, the light propagates in micro-size or nano-size waveguides, and thus it permits a longer external cavity length with limited optical transmission loss. This merit provides the possibility for broadband wavelength tuning with relative high power and narrow linewidth. Several different broadband wavelength tunable lasers have been reported, applying various materials such as InGaAsP/InP [10], polymer [11] and SiON [12]. However, these materials have their intrinsic limitations: the optical transmission loss in the InGaAsP/InP circuits is still at a relative high level (~ 10 dB/cm) and the III-V wafer fabrication is expensive; the polymer costs less, but the optical properties are not stable and the

fabrication is not comparable with complementary metal-oxide-semiconductor (CMOS) industry; the silicon dioxide waveguides is not able to provide sufficient light confinement within nano-scale dimensions due to the relative low refractive index, and its low thermal-optic coefficient degenerates the wavelength tuning efficiency.

The rapid development of silicon photonics fabrication technology [13,14] plays a key role in the on-chip integration of tunable laser. Specifically, it enables the evolution of tunable lasers from a free-space optical path to an integrated waveguide guided one with low transmission loss, high output power, high stability, large tuning range and high tuning accuracy. The tunable laser based on nano-silicon-phonic (NSP) circuits is a real multidisciplinary research, which involves fundamental knowledge, including photonics, mechanics and electronics.

One of the main approaches for wavelength tuning is to change the effective refractive index of the silicon waveguide, and thus the resonance of the silicon ring resonator via electrical control. Both thermal-optic and free-carrier effects [15] have been demonstrated to change the refractive index of silicon photonic waveguides. On one hand, the refractive index of the photonic waveguide is able to be largely changed by heating due to the high thermal-optic coefficient of silicon material ($1.86 \times 10^4 / ^\circ\text{C}$), but the tuning accuracy is limited at high voltage since the thermal power is proportional to the square of the applied thermal voltage. On the other hand, the refractive index is tuned using the free-carrier dispersion effect when the free carriers are injected to the P-I-N junction formed across the micro ring resonator. This effect is widely used for high speed switch and modulation (GHz level) of the silicon photonic elements. Although the free carrier injection causes additional optical loss in the photonic waveguide, it is able to tune the refractive

index within a small range (i.e. $< 10^{-4}$) with negligible additional loss. As a result, both large tuning range and high accuracy are expected by grouping these two electrical tuning schemes.

The obvious drawbacks of the electrically controlled wavelength tuning are that it requires complex electrical circuit designs and it causes thermal issues such as thermal dissipation to the chip-scale devices. To avoid these limitations, a possible approach for wavelength tuning is to utilize the opto-mechanical scheme. The optical gradient force, which can deform the free-standing nano-structures, has been recently demonstrated in a series of theoretical and experimental works [16-18]. For the ring resonator, its resonance is changeable by deforming the ring waveguide. As a result, a novel scheme for wavelength tuning in a tunable laser is made possible when the ring resonators are adopted as the optical filters. In this thesis, both the electrically and optically controlled tunable lasers will be demonstrated using a linear cavity configuration, with one facet of the gain diode connected with the external NSP circuits.

Beside the linear cavity configuration, ring cavity tunable lasers have been widely studied, due to their various applications. Ring cavity tunable lasers constructed in free-space have been employed for remote sensing, accurate angular velocity measurements [19]. Fiber ring tunable lasers have also been widely utilized in optical communication networks and radio-over-fiber systems [20,21]. However, the reported ring cavity tunable laser has big volume which is not portable; the long cavity length results in dense longitude modes which degenerates the stability of single-mode lasing. It is eagerly expected to demonstrate the miniaturization of the ring cavity tunable lasers.

In summary, the studies and developments of monolithically integrated tunable lasers based on NSP circuits have been a goal which is actively pursued by not only academia but also industry. The utilization of NSP circuits provides the opportunity to improve the laser performance, benefited from the high light-confinement capability of the nano-silicon waveguides, the intrinsic ability for compact integration of photonic circuits, and the proper electrical, optical and mechanical properties of silicon material. The study of electrically controlled tunable lasers, opto-mechanical tunable lasers and ring cavity tunable lasers are chosen as the topics of this thesis.

1.2 Objectives

The main objective of this research is to innovate and develop integrated tunable lasers using NSP circuits, including both the theoretical investigations and experimental implementations. Specifically, three types of NSP-based tunable lasers are to be investigated: (i) the electrically controlled tunable laser; (ii) the opto-mechanical tunable laser; and (iii) the ring cavity tunable laser. The arrangement of these three types tunable lasers follows the logics that the configurations are from linear cavity to ring cavity, and the tuning methods from convenient electrical schemes to a novel opto-mechanical scheme. Furthermore, the latter ones are based on the former ones, for example, for the electrically controlled tunable laser and the opto-mechanical tunable laser, they share the similar wavelength selective reflector served by a coupled ring resonator (CRS) structure, while the ring laser utilizes similar wavelength tuning scheme, but more complex photonic elements and different cavity configurations. Research investigations include schematic design, theoretical analysis, fabrication process development and experimental studies.

The electrically controlled tunable laser consists of an optical fiber, a gain diode, and a pair of coupled ring resonators which are both coupled to a bus waveguide in the NSP circuits. All of them are integrated in a single chip. Two electrical tuning schemes, applying the thermal-optic and free-carrier effect respectively are adopted, in order to acquire the large wavelength tuning range and the high tuning accuracy as well. The theory for the reflection spectrum of the CRS will be analyzed, and based on which the specifications of the tunable laser are to be investigated. The NSP circuits will be fabricated with the silicon photonic technology and integrated with the gain diode. The specifications of the tunable laser will be demonstrated experimentally, including the wavelength tuning range,

tuning accuracy, tuning speed, side-mode-suppression-ratio (SMSR) and output power.

The opto-mechanical tuning laser has a similar configuration with the electrically tuning one. Differently, the ring resonator is made a free-standing arc and is able to be actuated by optical force. For lasing wavelength tuning, convectional electrical circuits design is not needed, alternatively, the opto-mechanical scheme is adopted, which changes the refractive index by deflecting the free-standing arc. The theory about optical gradient force and the opto-mechanical resonant wavelength tuning are studied in detail. The fabrication and packaging processes are developed and the experiments are carried out to verify the analyses.

The ring cavity tunable laser utilizes more complex optical circuits. It consists of a semiconductor optical amplifier (SOA), a closed main-loop, a U-shape sub-loop and two separated ring resonators, and all the passive elements are formed using nano-silicon waveguides. In the theoretical analyses, the unidirectional effect of different sub-loop designs are compared, and the specifications of the laser are predicted. The ring cavity tunable laser is fabricated and integrated onto a single chip. The experiments are carried out to investigate the counter-propagation wave suppression ratio (CWSR), the spectrum purity in terms of the SOA current, the SMSR, linewidth, and wavelength tuning.

1.3 Major contributions

The major contributions of this PhD thesis lie in various aspects of the designs, theoretical analyses, and experiments of three types of external cavity tunable laser based on NSP circuits. The details are listed below:

- (1) The theoretical mode of the external cavity tunable laser using the NSP coupled ring structure is established. As a wavelength selective reflector, the utilizing of CRS escapes high-reflective coating or mirrors. The relationship between the reflective filtering properties of the CRS and the specifications of the tunable laser such as tuning range, SMSR and output power have been theoretically investigated in details (See Chapter 3).
- (2) Two electrically controlled wavelength tuning schemes, using the thermal-optic and the free-carrier dispersion effects, are utilized for tuning the effective refractive index of the silicon photonic waveguides. As a result, over 40-nm wavelength tuning range and 2-pm tuning accuracy have been realized simultaneously. The SMSR of the tunable laser is optimized to above 40 dB due to the high tuning accuracy (See Chapter 3).
- (3) The fabrication and packaging processes for the external cavity tunable laser have been developed, using both the silicon photonic technology (for NSP circuit fabrication) and the MEMS technology (for III-V to Si hybrid integration). (See Chapter 3). The alignment accuracy for III-V/Si waveguides integration is controlled to 100-nm and 300-nm in the vertical and lateral direction respectively, providing the possibility for a high coupling coefficient.

- (4) A new wavelength tuning scheme, the opto-mechanical effect, has been applied in an external cavity tunable laser. In the experiments, a 24-nm tuning range with 2.9 nm wavelength spacing has been demonstrated. The opto-mechanical tuning scheme gets rid of the dependence on electrical circuits and avoiding the thermal issues (See Chapter 4).
- (5) The principle of resonance shift induced by the optical force in both a single-ring nano-actuator and the coupled ring structure has been demonstrated. A novel physical phenomenon named ‘pull-back’ nonlinearity in a nano-actuator is proposed by analyzing the force equilibrium and the system stability. The experiment matches the theoretical analysis in the aspects of opto-mechanical wavelength tuning coefficient, maximum tuning range and pull-back position (See Chapter 4).
- (6) For the first time, an integrated ring cavity tunable laser based on the NSP circuits, has been proposed and developed. Specially, all the optical functions required in a ring cavity tunable laser, such as optical transmission, coupling, reflection and isolation are realized with nano-silicon-waveguide elements, avoiding the separated passive elements (See Chapter 5).
- (7) A U-shape sub-loop is proposed and designed. It is integrated in the ring cavity to function as a planar optical isolator, in order to obtain the unidirectional light propagation. The unidirectional operation effect of different sub-loop designs has been compared and predicted theoretically, and then is demonstrated in the experiments (See Chapter 5).
- (8) The ring cavity tunable laser has been fabricated and integrated on a SOI chip, and the prototype has a dimension of 3 mm × 1.5mm × 0.7 mm. In the

experiments, it has obtains excellent unidirectional operation (55-dB CWSR), perfect single-mode spectrum purity (50-dB SMSR and 180-kHz), and widely tuning range (55.4-nm) using the thermal-optic tuning scheme (See Chapter 5).

1.4 Organization of the thesis

The thesis is organized into six chapters. The introduction of the thesis covers the motivation, objective, and major contributions as presented in this chapter. The motivation section explains why and how the PhD research is carried out. The objective states the main focus of this thesis, and the contribution section lists the innovations and important findings in both the theoretical and experimental aspects.

In Chapter 2, the external cavity tunable lasers based on photonic integrated circuits are reviewed, including the principle and development of the monolithic single-mode tunable lasers, the photonic integrated circuits and elements, the electrically and optically controlled wavelength tuning schemes, and the ring cavity tunable lasers. These literature works provide the technological roadmap, guidance and research impetus as well.

In Chapter 3, the design, simulation, fabrication, packaging and experiments of the electrically controlled tunable laser are demonstrated and discussed. The mechanism of optical feedback is analyzed theoretically. Then, the electrically controlled external laser based on NSP circuits is designed and the laser specifications in terms of the electrical control schemes are discussed. Subsequently, the fabrication and packaging processes are presented. Finally, the experimental results of the electrically controlled tunable laser are presented and discussed.

In Chapter 4, the design, analyses, fabrication and experiments of the optomechanical tunable laser based on NSP circuits are elaborated. The design and working principle of a nano-actuator is presented, followed by the theoretical

analysis of wavelength tuning using the opto-mechanical effect. Then the opto-mechanical tunable laser is designed and theoretically investigated. Subsequently, the fabrication and packaging processes are developed and discussed. In the experiments, the wavelength tuning capability of a single ring resonator is firstly demonstrated, which shows a good consistency between the simulation and the experiments. Finally, the experimental results of the opto-mechanical tunable laser are illustrated and discussed.

In Chapter 5, the ring cavity tunable laser based on NSP circuits are elaborated theoretically and experimentally. The design and the principle of ring cavity tunable laser are illustrated. Specifically, the design of a U-shape sub-loop and its contribution to the unidirectional light propagation are theoretical analyzed through equation derivation. The laser specifications based on the ring cavity design are theoretically studied as well. Then, the fabrication results of the ring cavity tunable laser are presented. Finally, the experimental results of various key specifications of the tunable laser are examined and explained qualitatively and quantitatively.

Chapter 6 concludes the major contributions of this thesis, and followed by the recommendations for future work.

CHAPTER 2

LITERATURE SURVEY

The literature survey in this chapter is divided into four parts. The first part focuses on the roadmap of monolithic external cavity tunable lasers, with a general survey on tunable monolithic diode lasers, external cavity tunable lasers, and photonic waveguide based lasers, as presented in Section 2.1. Then, the lasing wavelength tuning achieved by electrical schemes, applying both the thermal-optic and free-carrier effects, is presented in Section 2.2. Section 2.3 presents the lasing wavelength tuning using the opto-mechanical effect. Finally, the review about the ring cavity tunable laser is detailed in Section 2.4.

2.1 Monolithic external cavity tunable lasers

Tunable lasers refer to the lasers whose wavelength of operation can be altered by certain approaches. Wavelength tunable lasers are desirable for improving the capacity, functionality, specialty and flexibility of the all-optical devices and networks. The important specifications of tunable diode lasers include the tuning range, tuning accuracy, tuning speed, side mode suppression ratio (SMSR), spectral purity, wavelength linewidth, output power, stability and reliability. Tunable laser have attracted continuous interest in the past decades as they are indispensable for a wide range of applications, such as optical communication, spectroscopic analysis, bioengineering and military applications. Dependent on the different gain media, the available wavelength range of the tunable lasers may span from visible to near-infrared and mid-infrared part of the electromagnetic spectrum, i.e., some of the dye lasers or solid-state lasers work in the visible range [22], the semiconductor diode lasers usually work in the near-infrared range [23], and the quantum cascade laser cover the mid-infrared range [24,25]. This study focuses on the tunable diode lasers working in the communication band. Particularly, tunable diode lasers are employed to reduce inventory of spare lasers with specific wavelengths for cost-effective wavelength division multiplexing systems.

There are various possible techniques for tuning the wavelength of semiconductor diode lasers. One of the practical approaches is employing the external cavity tunable lasers. The external cavity tunable lasers could provide widely wavelength tuning ability for monolithic semiconductor diode lasers. The external cavity tunable laser system usually consists of a semiconductor gain diode

with antireflection coatings on one on both two facets, a collimator for coupling light to the extended cavity, and a single or multiple external wavelength-selective filters. Generally, the wavelength (or frequency) of such a laser system is dependent on the properties the external cavity, for example, the length of the external cavity, the feedback strength, the central wavelength of the filters, etc.

2.1.1 Tunable monolithic diode lasers

This section reviews the state-of-the-art of monolithic single-mode tunable diode lasers. The tunable monolithic semiconductor diode lasers have been widely implemented in various fields such as wavelength-division multiplexing (WDM) in the optical communication systems, advanced optical measurement systems and optical sensors. Due to these important applications, tunable monolithic diode lasers have attracted continuous interest in scientific and engineering areas, and various designs have been developed, for example, the distributed Bragg reflector (DBR) lasers and the distributed feedback (DFB) lasers.

The DBR and DFB lasers are able to achieve stable single-mode frequency tuning in the monolithic configuration. A DFB laser, constructed on a heterostructure, consists of an active medium in which a periodic thickness variation is produced in one of the cladding layers. The grating is actually along the entire length of the active region. When the Bragg condition, $\lambda = 2n\Lambda$, is satisfied, both forward and backward propagation beams of the DFB laser are effectively coupled to each other. Once the single wavelength of the stimulated light satisfies the Bragg condition, it can be tuned by changing the refractive index n or the pitch Λ . Different from the DFB lasers, the grating in the DBR lasers is fabricated in an area separated from the active layer. The III-V active region provides the gain, and

the Bragg grating serves as a wavelength selector. The tuning range of the DFB and DBR lasers is limited by the wavelength working principle of $\Delta\lambda/\lambda = \Delta n/n$, although these two kinds of lasers have the merits of perfect integration and easy fabrication. Generally, the tuning range is limited within 7 nm at 1550 nm [1].

In the recent decades, the sampled grating distributed Bragg reflector (SGDBR) monolithic tunable lasers, which are able to offer above 30-nm tuning range, have been successfully developed [23,26]. These SGDBR tunable lasers could be integrated with both electro-absorption and Mach-Zehnder modulators on the InP platform, for potential applications such as wavelength conversion and wavelength routing. Besides the tunable lasers integrated on the expensive InP platform, another promising choice is the external cavity tunable lasers, which are able to be integrated on cost-effective platforms, such as silicon.

2.1.2 External cavity tunable lasers

Widely tunable semiconductor lasers can be achieved by adopting an external cavity in the laser system. This section will explore the properties of the tunable external cavity lasers. The first experimental demonstration on a laser diode coupled to an external cavity was presented in 1964 [27], which was constructed with a GaAs diode coupled to a flat mirror as the external reflector. Afterwards, continuous researches about the external cavity diode laser (ECDL) have been done, motivated by various applications, such as optical communication, optical testing, spectroscopy analysis, and sensing [4,28-31].

Generally, the features of the external cavity diode lasers can be changed, in terms of the variation of the feedback intensity, the length of the external cavity, the material index of the external cavity, and the parameters of the diode laser [31-33].

According to the difference in configurations, the external cavities are constructed in free-space or with photonic integrated circuits.

2.1.2.1 Free-space external cavity

Conventional external cavities are built in free-space, with several filters aligned in the external cavity for wavelength selection. Divided by the methods of wavelength tuning, the external cavity tunable lasers include the discrete and the continuous tuning ones.

The early stage of the discretely tunable lasers utilized the mirror configurations, using a GaAs diode as the internal cavity, and a flat mirror as the external reflector [27]. The flat mirror was later replaced by a FP interferometer, which provides more accurate wavelength selection [28,29]. The drawback of these tunable lasers with mirror or FP interferometry configurations is obvious: the optical spectrum usually contains multiple longitudinal modes, since the flat mirror is not a dispersive component [34,35], and thus limits the performance such as single-mode operation, SMSR and output power.

In order to obtain continuous wavelength tuning in a certain range, grating elements are applied in the external cavity serving as the dispersive reflector. A Littrow configuration was proposed, which induced a blazed grating in a dye laser and obtaining a 10-nm tuning range by rotating the grating [36]. Afterwards, a number of works continued to improve the specifications, such as a dye laser with large tuning range from 437 nm to 642 nm is demonstrated later [37], and a 0.04 nm linewidth has been obtained using Hänsch's Littrow structure [30]. The motion of the grating is strictly controlled: the grating is translated to change the cavity length, and is also rotated to change the grating diffraction angle for the wavelength selection [38].

Besides, the Littman configuration, which consists of a gain medium, a blazed grating and two mirrors, has been proposed in a series of works [3,39]. The light emitted from the gain chip is projected to the blazed grating and then is diffracted back to the gain chip, with the 0th order of the grating diffraction selected as the lasing wavelength [4]. The wavelength tuning is achieved by rotating the grating with a pivot. For both the Littrow and Littman structures, the wavelength selection is based on geometric optics and the scalar diffraction theory.

2.1.2.2 Monolithic MEMS external cavity tunable lasers

From pervious discussion, the conventional external cavity tunable laser usually has a long cavity length and a large size. The long cavity length results in the wavelength tuning range constraint, and the bulky size causes engineering inconveniences including low portability and low mechanical stability. Miniaturization and integration are pursued to solve these problems. The application of micro electromechanical system (MEMS) provides the possibility to realize the monolithically-integrated external cavity tunable laser [29,34,40-43]. The length of MEMS external cavity is designed from 5 μm to 20 μm . The MEMS technology has a great superiority to be used in external cavity tunable lasers: the tuning range of the laser wavelength (0.4 - 2 μm) matches with the fine tuning feature of micro-actuator, and the overall size of the diode chip is comparable with that of the MEMS external cavity.

Various types of MEMS external cavity configurations have been reported [6,7,44-52]. The typical configurations of developed MEMS external cavity tunable lasers are shown in Fig. 2.1 [6]. For example, the MEMS tunable laser with curved-mirror configuration is demonstrated for discrete wavelength tuning, obtaining a 13.5 nm tuning range with 1-ms tuning speed [46]. The MEMS tunable laser with

Littrow configuration achieves continuous wavelength tuning within a 30.3 nm range, at a resolution of 0.05 nm/V², and the chip dimension is 2.0 mm × 1.5 mm × 0.6 mm [47,48]. The injected-locking and coupled-cavity configurations are developed, which are able to provide over 25-dB SMSR or above a 15-nm tuning range [49-51].

Figure 2.1: Typical configurations of developed MEMS external cavity tunable lasers: (a) flat-mirror scheme; (b) curved-mirror scheme; (c) 3D-coupling scheme; (d) Fabry-Pérot etalon scheme; (e) Littrow scheme; (f) Littman scheme; and (g) non-standard grating scheme [6].

MEMS external cavity tunable lasers have special merits such as low packaging cost and high stability. However, it is hard for MEMS tunable lasers to achieve both broadband tuning range (which requires longer cavity) and relatively high output power (which requires shorter cavity) simultaneously due to the high optical loss induced by the beam divergence in the air-medium external cavity.

2.1.3 Photonic waveguide based lasers

The performance of the external cavity tunable laser built in free-space is limited due to the large optical loss. To tackle the challenge, a new generation external cavity tunable laser, utilizing a photonic integrated circuit (PIC) light path instead of a free-space light path, has been developed recently. Benefitting from the strong optical confinement of the photonic waveguides, the tunable lasers with a high degree of integration and a wide wavelength tuning range can be achieved for future low-cost and on-chip scale telecommunication application.

2.1.3.1 Photonic circuits based lasers

Semiconductor photonic integrated circuits (PIC), which focus on the monolithic integration of guided-wave optoelectronic devices, are a long-standing goal for developing highly integrated optical communication components [8,53]. Research interests on the PIC are driven by the advantages seen in the integrated electronics function on various electronic integrated circuits, which are ubiquitously used in modern society. To bend, split, couple, filter, switch, and modulate light, the PIC is fabricated with silicon [13,54-59], polymer [60-63], III-V group [8,64-66] and Si/III-V hybrid materials. The PIC is expected to offer a compact optical function at low-cost, and to realize package robustness associated with replacing individually aligned optical connects between discrete optoelectronic devices.

Analogous to electronic integrated circuits, the PIC on a single chip allows the potential of a more cost-effective and more compact optical system with improved performance.

Table 2.1: Basic PIC based laser systems and the equivalent cavity models.

Laser system	Cavity model
<p>Photonic waveguide</p>	<p>No filter effect</p>
<p>Feedback loop</p>	<p>No filter effect</p>
<p>Bragg grating</p>	<p>Single band-pass filter</p>
<p>MZ structure</p>	<p>Periodical band-pass filter</p>
<p>Ring resonator</p>	<p>Periodical band-pass filter</p>

Due to the multiple functions of the photonic elements, the tunable lasers can be developed based on the PIC, which have been demonstrated on various wavelength-selective elements, such as the Bragg grating, the Mach-Zehnder (MZ) interferometer, and the ring resonator. A summary of the basic PIC based lasers, as well as their equivalent cavity models are shown in Tab. 2.1. Light emitted from the right facet of the gain diode is confined and transmitted in the straight photonic

waveguide, and can be reflected either by coating high-reflective film on the waveguide or by designing a feed-back loop. The Bragg grating structure formed on the straight waveguide also functions as a mirror; simultaneously it serves as a band-pass filter with only one reflection peak. Both the MZ structure and the ring resonator serve as periodic band-pass filters with multiple interference peaks.

(a)

(b)

Figure 2.2: Schematic of the external cavity tunable lasers based on photonic waveguides: (a) ring resonators are utilized as wavelength filters on InP platform [67]; (b) hybrid integration of a super-luminescent diode and a polymer Bragg reflector [68].

The PIC based lasers have been realized with different materials. In the telecommunication band wavelength of 1550 nm, InGaAsP/InP is an attractive choice for the external cavity tunable laser. As an III-V material, the InGaAsP waveguide can function as both active and passive circuits, thus the tunable laser system is easily monolithically integrated on an InP substrate [10,67,69,70]. It uses the stack-layer structure, enabling fabrication with a single regrowth step [69,70]. Ring resonator structures are employed as the wavelength filters in the external PIC, and a typical tunable laser based on InP platform is shown in Fig. 2.2 (a) [67]. Although the convenience in monolithic integration is clear, the III-V group material suffers some intrinsic drawbacks: the high cost for the wafer process and the optical loss in the III-V photonic waveguides, which is usually no smaller than 10 dB/cm. The high optical loss may degrade the laser performance such as output power, gain power consumption and the external cavity efficiency.

The PIC based tunable laser can be achieved by hybrid integration of a super-luminescent diode and a polymer Bragg reflector [11,68,71,72]. The polymer Bragg reflector provides an external feedback of a certain wavelength into the broad gain spectrum of the diode, there the wavelength is tuned by thermal-optic effects. A tuning range up to 26 nm is demonstrated, with the tuning efficiency of $-2.48 \times 10^{-4}/\text{K}$, and the schematic is shown in Fig. 2.2 (b) [68]. The polymer optical devices advance in the high thermal-optic tuning efficiency and low fabrication cost. However, the reliability of the electrode fabricated on the polymer material limits the possibility for larger tuning range. Besides, the local heating in the waveguide center induces an abrupt discontinuity of the refractive index along the propagation direction, causing additional radiation loss and small mode hopping [73].

2.1.3.2 Nano-silicon-photonic integrated circuits

The platform of nano-silicon-photonics (NSP) fabrication technology is compatible with standard complementary metal oxide semiconductor (CMOS) technology. High-yield fabrication can be realized by the feasible integration of photonic and electronic devices on a common SOI platform. It is highly desirable to use the silicon material as the platform for the integrated photonic circuit, since silicon is the dominant material in the modern microelectronic industry. Silicon on insulator (SOI) is a promising material platform for the large-scale photonic integration, since it could rely on the massive electronics processing infrastructure to process the optical components.

Silicon material has been used for fabricating multiple classical electronic integrated circuits. An SOI wafer consists of a Si layer on top of a buried thermal SiO₂ layer, built on a Si substrate. The buried thermal SiO₂ layer creates a high refractive index contrast in the vertical direction, between the top Si structure layer ($n_{\text{Si}} = 3.46$) and the SiO₂ layer ($n_{\text{oxide}} = 1.45$), thus the top layer is able to guide the near-infrared ($\lambda \geq 1.1 \mu\text{m}$) light in the silicon waveguide. During the fabrication process, the silicon waveguide is formed by laterally etching, and thus the nano-silicon waveguide is surrounded by air and the bottom SiO₂ cladding with low refractive index. The patterned nano-silicon waveguides can be clad through a PECVD SiO₂ deposition process and consequently the waveguides are wholly surrounded with SiO₂ cladding, which confine the light inside the core more effectively due to total internal reflection. In order to restrain the light in the nano silicon waveguide to a single optical mode at 1.3 μm and 1.55 μm , a typical area for the waveguide cross-section should be smaller than 0.1 μm^2 [74].

As light is tightly confined into the nano-silicon waveguides, the ultra-compact optical functions, including the high Q -factor ring resonators, the waveguide bends with μm -scale radius, and the sub- μm scale photonic waveguide gap with negligible crosstalk, can be integrated on a SOI chip. Furthermore, the tight confinement and associated high power densities in the photonic waveguide allow the nonlinear optical phenomenon to be exploited at moderate optical power levels.

2.1.3.3 Ring resonator

The optical ring resonator was named as fiber resonator at its earlier stage. It is based on the coupling between optical fibers via Whispering Gallery modes, where the waveguide loop is directly formed by the optical fibers [75-77]. Although the fiber resonators have the merits such as low cost, low optical loss and high Q -factor, it suffers low stability and poor repeatability [78,79].

With the development of the semiconductor fabrication technology, the micro-size ring resonators can be fabricated. The principle and fabrication processes of micro ring resonators have been extensively described in the literature [80-82]. The ring resonator works at the resonance condition when $\varphi = 2\pi R$, where φ the round trip phase shift in the loop and R is the radius of the ring resonator. A special fabricated ring resonator known as toroid, which adopted a CO_2 illumination process to smooth the surface of the waveguide, is able to obtain a high Q -factor of 10^8 [83]. Although having the advantage of a high Q -factor, it is still impossible to realize on-chip device integrality, when the toroid ring resonator uses a tapered fiber for light coupling.

Figure 2.3: (a) The schematic of optical ring resonator as a drop filter, (b) demonstration of the optical spectrum within one period.

The integrated ring resonator, including the bus and the ring waveguides, has been developed with various materials. Due to the difference in dimension [84], surface roughness [85] and material properties [86,87], the Q -factor of the waveguide based ring resonator varies within in the range of 10^3 to 10^6 . The optical ring resonator has various attractive applications such as narrow linewidth optical filters, optical switches, low threshold lasers, optical modulators and slow light controllers [81,88-90]. Since the light at the resonance circulates multiple times in the resonator, the intensity is enhanced by constructive interference. The ring resonator made of gain materials can be used as a laser cavity. Successful ring resonator lasers have been fabricated using GaInAsP-InP materials [91], quantum-dot gain media [92] and dye-doped polymers [88,93].

The basic function of the optical ring resonator is to be used as an optical filter [89,90]. As shown in Fig. 2.1, when broadband light is injected to the input port of the bus waveguide, the light that satisfies the resonant conditions, will build up to a certain intensity because of the constructive interference during multiple round-trips and will be output to the other port of the bus waveguide. Fig. 2.1(a) is

the configuration of the optical ring resonator as a drop filter, and Fig. 2.1(b) demonstrates the optical spectrum of the drop filter.

Figure 2.4: Demonstration of Vernier effect using two ring resonators which work as wavelength filters.

Due to the priority of the micro ring resonators, they are able to be utilized as wavelength filters in the external cavity tunable lasers. For ring resonators based tunable filters and tunable lasers, Vernier effect is usually applied in order to extend the wavelength tuning range [94]. The name ‘Vernier effect’ comes from the measurement instrument ‘Vernier scale’, which enables precise measurement of distance or scale. The working principle of Vernier effect are demonstrated using two ring resonators as shown in the Fig. 2.4. The radii, thus the free spectrum ranges of the two ring resonators differ slightly. Certain wavelength is selected when the resonances of the two ring resonators match. A tiny resonance shift of Ring 2, $\delta\lambda$, is able to cause a much larger tuning amount of the selected wavelength $\Delta\lambda$, thus the wavelength tuning range is dramatically increased.

2.1.3.4 III-V/Si photonics hybrid integration

SOI is a promising platform for photonic integration. Various passive optical components, such as wavelength selective elements (ring resonators, waveguide gratings), optical splitters/couplers [95-98], optical modulators [58,99] and all-optical wavelength converters [100], could be realized on the SOI platform. However, the use of silicon as a medium for stimulated light emission for high efficiency laser is hampered due to the indirect bandgap of silicon material, even with remedies like exploiting its optical nonlinear effects [101,102], or by constructing Si lasers with nanostructures [103-105]. Therefore, the full functional photonic integration circuits are usually hybrid, integrating the direct bandgap III-V material laser diode with the SOI chip [74,106-108]. The integration process should maintain the advantages of the CMOS manufacturing process. Generally, there are three main routes to integrate the optical, optoelectronic and electronic components, namely heteroepitaxial growth, wafer bonding technology and flip-chip mounting.

Heteroepitaxial growth is a method which grows the III-V material directly on the host silicon substrate. It is a promising approach which could realize the wafer level integration. However, it is limited by the large lattice mismatch between the silicon substrate and the III-V material. For example, growing InP/InGaAsP material on the silicon substrate needs thick buffer layers to avoid the growth defects in the active layer. As a result, the lattice mismatch between the active layer and the silicon is 8%, which leads to large misfit dislocation densities in the active layer, and thus will degenerate the optical properties of the grown materials [109].

The wafer bonding approach to combine silicon with III-V materials directly integrates the III-V source on the top of the silicon wafer, using either divinylsiloxane–benzocyclobutene (DVS–BCB) adhesive wafer bonding [110,111]

or molecular wafer bonding [112]. The semiconductor wafer bonding takes the advantages of bonding convenience, i.e., no need for highly accurate alignment as the absence of structures on the III-V dies. After bonding, the substrate of the III-V dies is removed, and then the laser diodes are fabricated on the III-V epitaxial layers. Unfortunately, one limitation of wafer bonding is that the electrical and thermal surface needed to be patterned in post-bonding process. Another drawback is the strict requirement for the bonding environment: special care is required to avoid particles at the bonding interface, thus a cleanroom environment is required. Otherwise, a particle may cause a large un-bonded area that reduces the bonding quality.

The flip-chip integration requires tight alignment tolerance between components. The flip-chip integration process, which integrates the III-V diode on a SOI chip, can be divided into three major parts. Firstly, the silicon waveguide and other passive waveguide-based devices are fabricated with silicon photonics fabrication process. Secondly, the III-V active devices are connected with the silicon waveguides through low-temperature bonding process. Finally, the post-processing after bonding is executed to get electronic connections, such as wire bonding, fiber wedding, and finally butterfly packaging. Due to the sensitivity to misalignment, the flip-chip bonding is complicated and time consuming. However, the flip-chip integration is the most rugged technology and has been well developed. Moreover, it has the potential to obtain highly accurate bonding by fine alignment. Therefore, the flip-chip bonding technologies have been widely adopted nowadays for die-to-chip integrations and packages.

2.2 Wavelength tuning via electrical approaches

Various schemes using electrically controlled electro-optic tunable lasers have been demonstrated and analyzed. The tuning is realized by changing the voltage or current applied to the tunable filters. The voltage control scheme includes the static electrical control, the piezoelectric control, the thermal-optic effect and the free carrier effect. For the PIC based tunable laser, the thermal-optic effect and the free carrier effect, are the most commonly used for wavelength tuning, as reviewed in this section.

2.2.1 Thermal-optic effect

The thermal-optic effect is the scheme to change the optical properties of materials through temperature variation. The gain section of the tunable laser system can be tuned by the thermal-optic effect. The change of temperature is able to control the central emission wavelength of the laser diode. The laser's output power and wavelength are dependent on the chip temperature and the injected current level, both of which require precise voltage control. In a laser cavity, the phase shift of the roundtrip in the cavity is $\varphi = 2k_0 n_{\text{eff}} L$, which is proportional to both the effective index n_{eff} and the cavity length L . The cavity modes of a laser diode could be tuned by the electronic control of the real part of the effective refractive index or the cavity length.

Both the bandgap energy and the Fermi distribution of the semiconductor are temperature sensitive. Therefore, the gain peak wavelength and the refractive index of the active medium are dependent on the operation temperature. The central wavelength increases with temperature. For the DFB and DBR lasers, the thermal

tuning efficiency is 0.1 nm/ °C [113]. A thermal tuning range up to 15 nm has been reported with large temperature variation [114]. However, the excess heating is not acceptable which may lead to an ultra large threshold current, and thus degrading the laser performance (such as the optical power reduction and the SMSR downgrade).

The other way to perform the thermal tuning, which is to change the selected wavelength of the optical filters, has been widely used in external cavity tunable laser systems. The thermal-optic tuning efficiency is dependent on the material properties. This tuning scheme, which is achieved by the pattern heating circuit on the top of the photonic waveguide, is compatible with wafer process and achievable with multiple materials. The thermal-optical tuning efficiency of the polymer materials is negative at 1550 nm, varying from $-1 \times 10^{-4}/^{\circ}\text{C}$ to $-3 \times 10^{-4}/^{\circ}\text{C}$, and the effective refractive index of the polymer materials decreases with temperature. On the contrary, most of the semiconductor materials have positive thermal-optical tuning efficiency at 1550 nm, and the effective refractive index increases with the increase of temperature. Typically, in the near-IR range, the coefficient is $\sim 1 \times 10^{-4}/^{\circ}\text{C}$ for the InGaAsP material, $\sim 1 \times 10^{-5}/^{\circ}\text{C}$ for silica, and $1.86 \times 10^{-4}/^{\circ}\text{C}$ for silicon. Obviously, the silicon materials are promising for photonic waveguide based devices because of the large thermal-optic tuning efficiency.

2.2.2 Free carrier effect in P-I-N junction

The free carriers, such as the electrons and holes in semiconductors, also affect the optical properties of materials. The free-carrier effect is the most frequently used physical mechanism for wavelength-selective filters tuning,

especially for the DFB/DBR laser with the grating filter. The tuning range $\Delta\lambda_{\text{tune}}$ is given by

$$\frac{\Delta\lambda_{\text{tune}}}{\lambda_0} = \frac{|\Delta n'|}{n_{\text{eff}}}, \quad (2.1)$$

where $\Delta n'$ is the maximum change of the real part of the effective refractive index, λ_0 is the central wavelength within the filter tuning range.

The changing of the refractive index of the III-V materials is caused by the injection of the electro-hole plasma into a semiconductor. There are two physics mechanisms contributing to the index change: the polarization variation of the free carriers, and the spectral shift of the absorption edge [15,115,116]. Normally, the dominant one is the carrier polarization effect, which exhibits a much larger bandgap energy compared with the photon energy [117]. Supposed the injected carrier density is $\Delta N = \Delta P$, the change in the real part of the effective refractive index is given by [116]

$$\Delta n' = -\frac{e^2 \lambda^2}{8\pi^2 c^2 n_{\text{eff}} \epsilon_0} \left(\frac{1}{m_e} + \frac{1}{m_h} \right) \Delta N, \quad (2.2)$$

where m_e and m_h are the effective masses of the injected electrons and holes, respectively. The negative sign denotes that the real part of the effective refractive index decreases as the increase of the carrier injection, thus the wavelength is blue-tuned. The imaginary part of the refractive index $\Delta n''$ is also changed, causing the additional optical loss due to carrier scattering, as expressed as $\alpha = -2k_0 \Delta n''$.

2.3 Opto-mechanical wavelength tuning

Generally speaking, the effective index of the nano-silicon waveguide is changed through the electrical schemes, as discussed in Section. 2.2. A novel method with all-optical scheme is required, in order to avoid the electrical power consumption and the reliance on electrical circuits. The most promising scheme is to employ the opto-mechanical effect.

2.3.1 Opto-mechanical effect

As a branch of physics, opto-mechanics studies the interaction between light and mechanical objects on the low-energy scales. The opto-mechanical effect is a phenomenon whereby beams of light can provide an attractive or repulsive force to each other, or to the particles at the focus of the beam. The optical force, in terms of the electric and magnetic fields, originates from the Lorentz force. According to the Maxwell's equations, it is defined as the resultant force of the Lorentz force within a closed unit volume, and calculated by the surface integral of the time-averaged Maxwell stress tensor, which is expressed as [118],

$$\overline{F} = \left\langle \int_S T \cdot \overline{n} dS \right\rangle, \quad (2.3)$$

where T is the Maxwell stress tensor whose component is given by

$$T_{ij} = \varepsilon\varepsilon_0(E_i E_j - \delta_{ij} \frac{E^2}{2}) + \frac{1}{\mu\mu_0}(B_i B_j - \delta_{ij} \frac{B^2}{2}), \quad (2.4)$$

where ε_0 and μ_0 are the permittivity and permeability of the vacuum respectively, ε and μ are the permittivity and permeability of the medium surrounding the particle respectively, δ_{ij} is the Kronecker delta, E_i and E_j are components of the electrical

field E , B_i and B_j are the components of magnetic B . The optical forces include two major categories: (a) the optical radiation force and (b) the optical gradient force. Both the scattering and the gradient force can be calculated using Eq. 2.4.

The optical radiation (scattering) force results from the transfer of the optical momentum, from the radiating field to the dielectric medium. The optical momentum is changed by optical reflection or optical scattering when an object is on the path of the light beam, which results in an optical scattering force to the object. For example, it was first investigated in large-scale Fabry-Pérot interferometers for excitation of a gravitational wave [119]. The optical radiation force has been recently studied in micro-scale structures, where the cavity field and the mechanical motion affect each other [120,121]. In an opto-mechanical cavity [122], the mechanical oscillation could be amplified (heating) [122-125] or dampened (cooling) [126-129] via the coupling between photons, when the photon lifetime exceed the mechanical oscillation period. Consequently, the quantum mechanical behavior is observed in the micro-mechanical resonator [124-129].

The optical gradient force is caused by the gradient of the optical field. A well-known example is the optical tweezers [130-132], which use the forces of laser radiation pressure to trap the small particles. When a small polarizable particle is placed in the laterally varying optical field, a dipole will be induced in the particle. Consequently, the charged particle will be accelerated towards the region with the strongest field. Thus, a distributed gradient force field is generated, and the small particles can be trapped in the evanescent field close to the dielectric interfaces [133,134].

Recently, it has been demonstrated that the strong field gradient closed to the nano-photonic guided wave structures can also lead to optical gradient force,

both theoretically and experimentally [16]. An internal total reflection in the nano-waveguide can generate the evanescent field beyond the waveguide boundary, and consequently the optical gradient force is triggered. The optical gradient force exploited on the nano-waveguide can be utilized for actuating opto-mechanical devices [16,135,136]. Compared with the optical scattering force, the gradient force is able to provide a much larger force per photon when strong field gradients are formed [136].

The nano-actuators driven by optical gradient force have attracted increasing interest recently. It was firstly theoretically predicted that the gradient force between the two parallel nano-waveguides can lead to both attractive and repulsive force in 2005 [16]. Then the experimental verification was presented since 2009 [137-139]. The attractive optical force between the nano-waveguide and the dielectric substrate, which actuates the free-standing nano-waveguide, has been demonstrated both theoretically and experimentally [17,118,140]. Besides the straight waveguide structures, the optical gradient force is demonstrated with various cavity structures. For instance, the optical force could be enhanced by the photonic crystal cavity [135,141-143]. The attractive and repulsive gradient forces are built along the vertical direction, based on a double-layer structure [144,145].

2.3.2 Resonator enhanced optical force

The optical gradient force scales with the energy in the nanostructure. The electrical field amplitude has been investigated in a simple structure with a single ring resonator coupled to a bus waveguide [81,146]. The effects of the optical force are increased due to using the high- Q factor of the optical resonator structures.

The static and the dynamic properties of the opto-mechanical ring resonators have been widely studied due to their distinctive merits and wide applications. The static study focuses on the displacement of the mechanical structure in a nano-actuator. As enhanced by high- Q optical cavity [147,148], the optical gradient force in the photonic waveguide is several nN to 100 nN [147]. This feature determines that the optical force is strong enough for driving the nano-scale mechanical structures [146,149,150]. The dynamic study focuses on the interaction between the mechanical frequency of the structure and the change of optical frequency. The typical application of this study is in sensing, including the mass spectroscopy, the force detection, as well as the charge sensing. For example, the change in the mass of the mechanical structure results in the variation in the mechanical frequency, which can be read-out through the optical signal in a spectrum analyzer. In addition, the amount of the optical force is a function of the displacement, thus the virtual stiffening or softening of the nano-mechanical structure is generated, which is called the optical spring effect. The optical spring effect changes the mechanical resonance frequency of the free-standing structure [146,151,152].

2.3.3 Nano-actuator and resonant wavelength tuning

The application of the wavelength tuning in a laser system, requires the stable and static displacement of the nano-opto-mechanical actuator. Therefore, the literature of static properties will be further expanded, especially on the optical force induced resonance change of a silicon ring resonator.

Sweeping the laser frequency across the cavity resonance can be used to actuate the nano-structure due to the internal light field built up near the cavity resonance. For instance, part of the ring waveguide can be made on a clam-clam

free-standing waveguide by removing the sacrificial layer underneath in a silicon ring resonator. The effective refractive index of the free-standing waveguide changes following the amount of displacement. The larger the deflection corresponds to the larger the tuning of the resonant wavelength. As the enhanced optical force induces the deflection of the free-standing waveguide, the resonance of the ring resonator is tuned. The overall magnitude of the cavity resonance tuning is expressed as [18]

$$\Delta\omega_0 = g_{OM}\Delta x_{static} = \frac{g_{OM}^2 P_d}{k\omega_0\Gamma_0}. \quad (2.5)$$

where $\Delta\omega_0 = 2\pi c\lambda^2/\Delta\lambda$ is the resonance frequency shift, k is the intrinsic spring constant of the free-standing waveguide, Δx_{static} is the static mechanical displacement, P_d is the power coupled into the ring resonator, and Γ_0 is the intrinsic photon decay rate, which is inversely proportional to the optical quality factor.

A series of experiments have demonstrated the phenomenon that the resonant wavelength shift is induced by the optical force. A 4.4-nm wavelength shift is obtained at 1.7-mW dropped-in optical power, with a ring resonator constructed by double laser spiderweb [18]. In a double-layer Si_3N_4 ring structure, a wavelength shift of 1.5-nm is obtained at pump power of 3 mW, controlled by changing pump wavelength [144]. One point to be emphasized, the opto-mechanical tuning approach is purely dispersive in nature and it preserves the channel quality completely during the wavelength tuning process. Therefore, the opto-mechanical tuning approach is superior to the electro-optic approach using carrier injection where the quality of the filtering spectrum is degraded by the carrier induced material absorption.

2.4 Ring cavity tunable laser

Shortly after the discovery of lasers, a type of new laser called as ring laser was proposed [153]. In the ring cavity, two light beams can propagate in opposite directions. If the laser frequency coincides with the cavity resonance, an optical field, whose intensity can be much stronger than that of the uncoupled laser beams, is built up inside the cavity. In many cases, the unidirectional operation is enforced by introducing an element (i.e. optical isolator) into the ring cavity, leading to different losses for the counter-propagating laser beams. If unidirectional operation is achieved, there is no standing-wave interference pattern in the laser gain medium, and consequently no spatial hole burning. Therefore, the single-frequency operation is achieved. The review begins with the single-mode ring cavity lasers and then moves to the wavelength tunable ring cavity laser.

2.4.1 Single-mode ring cavity laser

The solid-state ring lasers that have single-mode high power output have been designed using unidirectional the non-planar oscillators [154,155]. The ring laser is constructed from a single Nd: YAG crystal, and is also called monolithic isolated single-mode end-pumped ring (MISER) design [154]. This is a monolithic laser design, where the laser cavity consists of a single coated crystal, and the light oscillates inside the cavity due to the total internal reflection effect. Despite of the complex fabrication of such crystals cavity, the alignment is fairly easy, and the laser performances are stable and robust. This ring laser source can be applied for the long-range coherent Doppler anemometer, and also potentially used in the coherent communications, the coherent optical radar and the internal rotation

sensing. This MISER design can also be used for pulse generation. By attaching an intra-cavity saturable absorber, a single frequency Nd: YAG ring laser with a 100-nm pulse length was demonstrated using passive Q -switching [156]. The nano-second pulses emitted from the Nd: YAG ring lasers were reported later [157]. These lasers have shown extremely good stability in term of amplitude and lasing frequency, and thus can be used for lidar systems and nonlinear optics. In this kind of monolithic ring laser, the crystal medium provides the Faraday effect, but the Q -switching is precluded unfortunately.

For most applications, the unidirectional single-mode operation is preferred. In another type of design, a solid-state ring laser is built up by integrating an acousto-optic modulator, to enforce the unidirectional operation and hence to obtain the single-mode operation [158,159]. The system is constructed in the free-space, including the pumped diode laser, the crystal rod, the acousto-optic modulator, the reflective mirrors, and the prism. Although it has a smaller dimension compared to the MISER design, it is not integrated and requires complex free-space optical path alignment.

2.4.2 Wavelength tunable ring cavity laser

A tunable ring cavity laser usually contains a semiconductor gain medium and an external feedback path. Both facets of the gain medium are antireflective coated and coupled to the external feedback path [2]. Although the alignment for external cavity on both facets is more complex compared with the single-facet coupling, it still has the advantages of increased solitary resonance suppression due to the adoption of reflectance suppression on both facets.

A ring cavity tunable laser constructed in the free-space usually comprises complex optical elements, such as the lens, the mirrors, and the filters, etc. The intra-cavity birefringent filters in a diode-pumped Nd: YAG laser scheme is an attractive technique for the oscillation wavelength tuning. For example, the wavelength tuning can be achieved by the thermal tuning of the birefringent filter. As the temperature changes, the birefringent crystal length changes, and thus the refractive index difference changes as well, providing the possibility for wavelength tuning via the thermal method. However, the reported wavelength tuning range is limited (smaller than 10 nm) with this approach [160,161].

Another approach for wavelength tuning is utilizing a single-plate quartz birefringent filter in the Brewster-angled orientation, and the filter is rotated around the intra-cavity beam axis. In this way, a broad wavelength tuning range of above 100 nm was achieved obtained [19]. This widely tunable single-frequency ring laser is expected to be used in spectroscopic and remote sensing applications.

Besides the ring cavity tunable lasers constructed in the free-space, another group of tunable ring lasers are constructed with the optical fibers. Fiber ring laser are fiber lasers with ring configurations, for example, the mode-locked lasers [162] and the single-frequency lasers [20,163-166]. A mode-locked fiber ring laser contains a nonlinear loop mirror as the effective saturable absorber [167,168]. This geometry follows the principle of the artificial saturable absorber as required for pulse shaping, it is able to avoid spatial hole burning effect as well.

Thanks to the advantages of narrow linewidth and high output power, the single-longitudinal-mode erbium doped fiber lasers are of great interest in the applications of the optical communications, the high-resolution spectroscopy, and the sensors. Compared with the linear cavity configuration, the unidirectional fiber

ring configuration is more attractive for the tunable single mode laser design, since it allows the lower phase noise and the smaller linewidth.

The longitudinal mode spacing of the fiber ring is unavoidable with high-density, due to its long cavity length (usually several meters or even longer). Consequently, laser output from the fiber ring laser suffers a large linewidth because of multimode oscillation, modes competition and mode hopping [164,169]. In order to achieve stable single-longitudinal-mode operation, a lot of effort has been made to suppress the multimode operation, and to improve the ability of spectral selection. One effective approach is to concatenate two FP etalon filters with different free-spectral ranges [170]. As discrete elements, the FP etalons exhibits high insertion loss and are hard to align and integrate. Another approach is to use a tunable fiber Bragg grating Fabry-Pérot (FBG FP) etalon, using the ultraviolet-induced fiber grating technology [164,171]. Compared with the FP etalon filter, the all-fiber FBG FP is easier to be fabricated in all-optical fiber system, with smaller insertion loss. The multimode suppression can also be realized by adopting a tunable saturable absorber with a tunable FBG, with a section of unpumped erbium-doped fiber (EDF) in a Sagnac loop [163,172,173]. The refractive index of the EDF is spatially changed due to the spatial-hole-burning effect, thus ultra-narrow bandwidth is obtained in the self-induced FBG., the laser linewidth can be narrowed down to hundreds of kHz and even to several kHz because of the long cavity length of the fiber ring laser [20,166].

Although the ring cavity tunable laser constructed in free-space or using optical fibers have been well developed, the miniaturization and single-chip integration of a ring cavity tunable laser are still a challenge, and seldom reported.

2.5 Summary

This chapter provides an overview of reported research works on the following four aspects: (a) the principle and achievement on the monolithic external cavity tunable laser, including the tunable monolithic diode lasers, the external cavity tunable lasers and the photonic waveguide based lasers; (b) two electrical schemes to tune the refractive index of the silicon waveguides, applying the thermal-optic and free-carrier effect respectively; (c) the principle and development of nano-actuators applying opto-mechanical effect; (d) conventional ring cavity tunable lasers.

Furthermore, this review shows the limitation of the reported external cavity tunable lasers, thus it leaves plenty of space for further exploring the tunable lasers based on the NSP circuits, such as the theoretical analysis, the photonic circuits design, the fabrication and integration processes, and the improvement of the laser specifications. This chapter also provides an overview of the technological basics related to the three types of NSP circuits based tunable lasers, which will be further discussed in the subsequent chapters.

CHAPTER 3

ELECTRICALLY CONTROLLED TUNABLE LASER

Based on nano-silicon-photonics circuits, a linear cavity tunable laser is presented, which consists of a gain chip and a pair of ring resonators that is connected with a nano-silicon waveguide. The wavelength tuning is electrically controlled through changing the effective refractive index of the ring waveguides, using both the thermal-optic effect and the free-carrier effect. In this chapter, firstly, the schematic and working principle are introduced, followed by the numerical simulations; then the fabrication processes are described; finally, the experimental results are discussed in details, presenting the key laser specification such as the tuning range, the SMSR, the output power and the tuning speed.

3.1 Design of the electrically controlled tunable laser

The tunable laser consists of a semiconductor gain chip that serves as the internal cavity and the NSP circuits that serve as the external cavity. The schematic and the working principle of the electrically controlled tunable laser based on NSP circuits are introduced in this section.

3.1.1 Tunable lasers using ring resonators

The passive ring resonators are promising candidates to be applied as the wavelength selection elements in the tunable laser system, because the resonant wavelength of the ring resonator is easily tuned through changing the refractive index. This study focuses on the external cavity tunable lasers based on the nano-silicon-photonics integrated circuits.

Several different designs of the external cavity tunable lasers which use ring resonators as wavelength filters are presented in Fig. 3.1. In order to achieve a wide tuning range (> 20 nm), two or even more ring resonators with different radii are required, applying Vernier effect. Considering the normal ring radius ($10 \sim 200$ μm), the achievable fabrication accuracy of radius (< 50 nm) and the 3-dB gain spectrum of the commercial gain chip ($20 \sim 60$ nm), two ring resonators are good enough to provide above 40-nm tuning range within the communication band (around 1550 nm). The system with three ring resonators has the potential for larger tuning range (> 100 nm), if the gain spectrum could cover this wavelength range. In addition, the third ring resonator requires a more complex optical circuit and electrical control circuit design, it therefore increases the total optical loss of the optical filters as well.

Figure 3.1: The wide-tuning external cavity lasers which apply passive ring resonators as wavelength filters: (a)-(c) single-ended external cavity tunable lasers using two ring resonators; (d) double-ended linear-cavity and (e) ring-cavity tunable lasers using two ring resonators; (f)-(g) single-ended external cavity tunable lasers using three ring resonators; (h) double-ended linear-cavity and (i) ring-cavity tunable lasers using three ring resonators.

The single-ended external cavity lasers are shown in Figs. 3.1 (a)-(c) and (f)-(g): the photonic circuits are distributed at the single side of the gain chip, and coupled to the gain chip with photonic waveguides. The left facet of the gain chip functions as a mirror, while the other mirror is formed by the photonic circuits. The double-ended external cavity lasers are shown in Figs. 3.1 (d)-(e) and (h)-(i): the photonic circuits are distributed at both sides of the gain chip. Both facets of the gain chip are anti-reflection coated in order to reduce the coupling loss, and both mirrors of the laser configuration are formed by the photonic circuits.

Several different tunable lasers using ring resonators as wavelength filters have been reported, applying InP/InGaAsP, silicon dioxide or silicon materials [12,69,174]. However, plenty of space is still there for further development, such as, carrying out a complete theoretical study of wavelength selection and wavelength tuning schemes, using the nano-silicon waveguide to scale down waveguide dimension to nanometer and obtain more efficient wavelength tuning, using the novel wavelength tuning schemes to improve laser performance, and realizing fully monolithic integration with chip-level bonding.

3.1.2 Schematic of electrically controlled tunable laser

The schematic of the electrically controlled external cavity tunable laser based on the NSP circuits is illustrated in Fig. 3.2(a), which is integrated on a silicon-on-insulator (SOI) platform. It consists of a gain chip as the internal cavity, as well as a coupled ring structure (CRS) connected with the nano-silicon waveguide in the external cavity. The gain chip, with its right facet anti-reflective coated, provides gain.

(a)

(b)

Figure 3.2: The schematic illustration of (a) the external cavity tunable laser using the coupled ring structure as wavelength selective reflector, and the wavelength is electrically tuned via the thermal-optic and the free-carrier effects; (b) the equivalent cavity mode of the external cavity tunable laser.

In the CRS, the two silicon ring resonators are coupled with each other, are both coupled to the bus waveguide. The CRS functions as a wavelength selecting reflector: the optical wavelength, which meets the resonance of both ring resonators, can obtain the highest reflectivity. When this optical wavelength matches one of the longitudinal modes of the entire laser cavity, the single-mode lasing is obtained. The wavelength tuning is realized by tuning the effective refractive index of the ring waveguides. The micro-heaters are patterned on top of both ring resonators, and a P-I-N junction is formed across Ring 2. The gain chip and the passive NSP circuits are optically connected by a nano-silicon inverse taper waveguide to obtain the optical mode-size match. The gain chip has a physical length of 250 μm , with 2.2 μm in width and 0.26 μm in height for the active waveguide. The nano-silicon channel waveguides, for both the bus and the ring resonators, have a dimension of 450 nm in width and 220 nm in height. The radius of the Ring 1 and Ring 2 is 62 μm and 59.5 μm respectively, which are chosen to ensure 40-nm tuning range without mode-hopping. The wavelength tuning is realized by tuning the effective refractive index of the ring waveguides. The micro-heaters are patterned on top of both ring resonators. Furthermore, a P-I-N junction is specially formed across Ring 2.

The equivalent cavity model of the external cavity tunable laser, which consists of the internal and external cavity, is shown in Fig. 3.2(b). The gain chip serves as the internal cavity, and the NSP circuit serves as the external cavity. The left facet of the gain chip, Mirror 1, has a reflectance of $r_1 = 10\%$. The right facet of the gain chip, Mirror 2, is anti-reflection coated with a reflectance of $r_2 < 0.1\%$. Mirror 3 is the equivalent mirror of the coupled ring structure, whose reflectance $r_3(\lambda)$ is dependent on the propagation wavelength. The two ring resonators with

different radii are considered as two optical filters with different free-spectrum range (FSR). The single-mode light is stimulated out from Mirror 1.

The external cavity laser is simplified to a Fabry-Férot cavity, when Mirror 2 and 3 are equivalent to one effective mirror. Combining the optical filtering effect of the CRS, the equivalent Mirror has a wavelength dependent reflectance $r_{2\text{eff}}(\lambda)$, given as

$$r_{2\text{eff}}(\lambda) = \frac{r_2 + (r_2^2 + t_f^2)r_{\text{CRS}}(\lambda)e^{-\alpha L_m}e^{-j\beta L_m}}{1 + r_2 r_{\text{CRS}}(\lambda)e^{-\alpha L_m}e^{-j\beta L_m}}, \quad (3.1)$$

where t_f is the coupling coefficient between the active and the passive waveguides, $r_{\text{CRS}}(\lambda)$ is the power reflectance of the coupled ring structure, α is the optical loss coefficient for the nano-silicon waveguide, $\beta = 2\pi n_{\text{eff}}/\lambda$ is the transmission constant in the nano-silicon waveguide and n_{eff} is the effective refractive index of the nano-silicon waveguide, and L_m is the length of the bus waveguide from the right facet of the gain chip to the CRS.

Figure 3.3: Schematic of the cross-section for Ring 2, with the P-I-N junction on a slab-waveguide structure.

The absorption coefficient difference between the bus and curve waveguide is neglected for simplicity, since the radius is larger than 10 μm . The power

reflectance of the CRS, $r_{\text{CRS}}(\lambda)$, is wavelength dependent, because the CRS in the NSP circuits serves as a band-pass optical filter.

The cross-section of Ring 2 is illustrated in Fig. 3.3. The waveguide of the ring resonator is formed on a slab-waveguide structure, with a 220-nm total waveguide height, and an 80-nm slab height. A P-I-N junction is formed through doping the silicon-slab area, where the inner area of the ring is doped to P-type and the outer area is doped to N-type. The effective refractive index of the ring waveguide, n_{eff} , is decreased, when the plasma current is injected to the intrinsic region under the voltage V_{PIN} . The 120-nm thick TaN micro heater, 1.5 μm above the nano-silicon waveguide, is isolated by the SiO_2 interface layer which provides the optical confinement to the photonic waveguide. When a thermal voltage V_{th} is applied on the micro heater, the effective refractive index of the ring waveguide is increased.

3.1.3 Working principle for single-mode operation

In this design, the effective cavity length is much larger than its physical length, due to the adoption of ring resonators, especially under the weak coupling condition (bus-ring coupling coefficient $\ll 1$). This distinctive feature of the ring resonator benefits the compact optical circuit design, and thus it is possible to obtain a long external cavity within a limited area dimension. At the resonance of the CRS, the longitudinal mode spacing is expressed as

$$\Delta\lambda_m = \frac{\lambda^2}{2(n_{\text{int}}L_{\text{int}} + n_{\text{eff}}L_m) + n_{\text{eff}}L_{\text{CRS}}(\lambda_0)}, \quad (3.2)$$

where n_{int} and L_{int} are the effective index and the physical length of the active waveguide respectively, $L_{\text{CRS}}(\lambda_0)$ is the effective length of the CRS under resonance.

Figure 3.4: Demonstration of principles for the single-mode wavelength selection and wavelength tuning under electrical control.

The principles for single-mode wavelength selection and wavelength tuning under electrical control are presented in Fig. 3.4. Based on Eq.2, the mode spacing of the cavity modes is determined by the equivalent cavity length, and only the modes in the 3-dB gain spectrum are able to get enough gain for lasing. The CRS, as a reflective filter, obtains a peak reflection at λ_0 when the thermal voltage is V_1 . One of the longitude cavity modes is selected as the lasing mode once its wavelength is consistent with λ_0 . When the voltage is changed to V_2 , the peak reflection wavelength is tuned to λ_0' , thus the stimulated single-mode wavelength is changing as well. In this way, the wavelength tuning is realized through electrical control.

3.2 Analysis of the electrically controlled tunable laser

The theoretical analysis and numerical results of the electrically controlled tunable laser system with coupled ring structure are discussed in detail, including the design of CRS, the wavelength selection principle, the wavelength tuning and the key specification of the tunable laser system.

3.2.1 Properties of the coupled ring structure

The schematic of the coupled ring structure is shown in Fig. 3.5. Both ring resonators are coupled to a bus waveguide, the bus-ring gap is G_{wr} ; the two ring resonators are coupled with each other, and the ring-ring gap is G_{rr} . The ring-waveguide and ring-ring cross-coupling coefficients are κ and κ_2 , respectively, the self-coupling coefficients are t and t_2 , respectively. These four parameters satisfy $\kappa^2 + t^2 = 1$ and $\kappa_2^2 + t_2^2 = 1$. The power-normalized field amplitudes in the three distinct coupling regions are $A^{a/c}$, $B^{a/c}$, $C^{a/c}$, and a/c stands for the forward or backward wave. The spectral properties of this coupled ring resonator structure can be analyzed using the scattering matrix formalism [175].

Figure 3.5: The schematic of coupled ring structure as a reflective filter.

The power reflectance of the coupled ring structure is expressed as [175]:

$$r_{CRS}(\lambda) = \frac{\kappa_2 K^2 (1 + \alpha^2)^2}{2\alpha t} \cdot \frac{(\cos \varphi - \cos \varphi_0 + \chi_a P)^2 + \chi_a^2 \sin^2 \varphi}{[(\cos \varphi - \cos \varphi_0)^2 + \rho^2]^2}, \quad (3.3)$$

where $\varphi = n_{eff} 2\pi R_1 2\pi / \lambda + j \ln \alpha$, $\cos \varphi_0 = \frac{t_2(1+\alpha^2 t^2)}{2\alpha t}$, $\rho = \frac{\kappa_2(1-\alpha^2 t^2)}{2\alpha t}$, $P = \frac{t_2(1-\alpha^2 t^2)}{2\alpha t}$,

$\chi_a = \frac{1-\alpha^2}{1+\alpha^2}$, φ is the round trip phase of Ring 1, and α is the round trip amplitude

loss factor, The coupling coefficient is dependent on the coupling gap between the waveguides. $K = \kappa^2$ is defined as the optical energy coupling coefficient over the interaction region, which can be calculated by integrating the energy of light within the coupled area, expressed as [176]

$$K = \kappa^2 = \sin^2 \left(\int_{-\pi/2}^{\pi/2} \frac{\omega \epsilon_0}{4} \oint_S (n_{eff}^2 - 1) E^2 ds \cos \theta d\theta \right), \quad (3.4)$$

where S is the area of the coupling region, ϵ_0 is the vacuum permittivity, n_{eff} is the effective refractive index of ring waveguide.

The power coupling coefficient for both bus-ring ($K = \kappa^2$) and ring-ring coupling ($K_2 = \kappa_2^2$) is a function of the coupling gap. Both K and K_2 decrease exponentially with the coupling gap. The numerical analysis of the relationship between the power coupling coefficient and the coupling gap is shown in Fig. 3.6. The waveguide width is 450 nm for both bus and ring resonators, and the radius of ring resonator is 62 μm . When the coupling gap varies from 100 to 500 nm, K is decreased from 0.95 to 1.6×10^{-4} exponentially, and K_2 is decreased from 0.37 to 4.2×10^{-5} exponentially.

Figure 3.6: The power coupling coefficient K (for bus-ring coupling) and K_2 (for ring-ring coupling), as a function of the coupling gap.

Figure 3.7: The maximal value of the reflectance of the coupled ring reflector determined by the coupling coefficient of the ring-ring couple and ring-bus waveguide couple.

It is desirable to operate the external cavity laser in the regime of strong external feedback in order to maintain good tuning linearity, low output power ripple, and to avoid those undesirable effects such as bistability and axial mode instability [2]. To satisfy this requirement, the gain cavity loss is expected to exceed the external cavity loss by at least 20 dB. The commercial gain chip has a facet reflectance of $0.5 \sim 1 \times 10^{-3}$, thus the reflectance of the external feedback circuit is expected to be larger than 0.05.

The maximal reflectance is reached at the common resonance λ_0 of the two ring resonators; the reflectance is degraded at the dis-matched resonances due to the Vernier effect. High reflectance is required to increase the external cavity efficiency and to provide strong external feedback. The reflectance $r_{\text{CRS}}(\lambda)$ is dependent on the power coupling coefficients K and K_2 . It is supposed that K_2 varies from 0 to 0.004, and K varies from 0 to 0.3. Assume the reasonable round trip loss of $\alpha = 0.985$, which corresponds to the waveguide transmission loss of 2 dB/cm, the relationship between $r_{\text{CRS}}(\lambda)$ and the power coupling coefficients are shown in Fig. 3.7. The region where there are two or more reflection peaks is filled with shadow. The single-peak profiles are obtained under the condition of weak interring coupling between the two ring resonators ($\kappa_2 \leq 0.2\kappa^2$). In the single peak reflection region, the value of the power reflectivity varies in the range from 0.12 to 0.76, and it increases as K_2 increases.

The relationship between the power reflectivity and wavelength is simulated for various ring-bus coupling coefficient values while the ring-ring power coupling coefficient is kept at $K_2 = 0.0016$, as shown in Fig. 3.8. As the magnitude of K_2 increases, the spectrum changes from four reflection peaks, to two reflection peaks and finally broaden into a single peak. The single reflection peak, which works as a

flat-top filter, makes the CRS reflector possible to work as an integrated mirror for the single-mode tunable laser.

Figure 3.8: The power reflectivity as a function of wavelength is calculated for various ring-bus coupling coefficient values while the ring-ring power coupling coefficient is kept at $K_2 = 0.0016$.

The Lorentzian filtering mechanism due to the high- Q ring resonator provides a strong mode selection, and it is essential for single-mode operation. Besides the consideration of high power reflectivity, a large loss margin between the main and the side modes, is essential for obtaining a high SMSR. The loss margin $\Delta\alpha$ is determined by the spectrum properties of the CRS, as expressed as

$$\Delta\alpha L_{\text{int}} = \ln\left(\frac{r_{\text{CRS}}(\lambda_0)}{r_{\text{CRS}}(\lambda_1)}\right), \quad (3.5)$$

where $r_{\text{CRS}}(\lambda_0)$ and $r_{\text{CRS}}(\lambda_1)$ are the reflectivity of the main mode and the first side mode, respectively.

Figure 3.9: The margin of power reflectivity between the main and the first side mode as a function of the coupling coefficient of the ring-ring couple and the ring-bus waveguide couple.

Figure 3.10: The reflection spectrum of the coupled ring structure, within the wavelength range from 1520 nm to 1580 nm.

The margin of power reflectivity between the main and the first side mode, is a function of the coupling coefficients of the ring-ring couple and the ring-bus waveguide couple, as shown in Fig. 3.9. The region where two or more reflection peaks is filled with shadow and is not considered. The value of the reflectivity difference increases as the decreases of K and K_2 , and its maximal value is 3.5 dB in this design.

The optical spectrum for the reflection of the CRS, within a 60 nm spectrum range, is shown in Fig. 3.10. This reflection spectrum is obtained when $K = 0.16$, $K_2 = 0.0008$, wavelength transmission loss of 1.5 dB/cm and radius difference of 2.5 μm . The reflectance is 0.72 for the main mode and 0.37 for its adjacent side mode, thus the loss margin is $\Delta\alpha = 2.9$ dB.

3.2.2 Electrically controlled tuning approaches

Supposed the 3-dB gain spectrum covers all possible channels, the maximum wavelength tuning range $\Delta\lambda_{\text{max}}$ is dependent on the FSR of the CRS, which is the space between two reflection peaks, and can be expressed as.

$$\Delta\lambda_{\text{max}} = FSR_1 \cdot M, \quad (3.6)$$

where $M = R_1/\Delta R$ is the magnification factor resulted from the Vernier effect, $\Delta R = R_1 - R_2$ is the radii difference. $FSR_1 = \lambda^2/2\pi R_1 n_g$ is the FSR of Ring 1, n_g is the group index of silicon waveguide. The group index describes the light velocity as the envelope of the pulse propagates in a dispersive waveguide. The group index is the function of the wavelength λ , as expressed as:

$$n_g = n_{\text{eff}} - \lambda \frac{dn_{\text{eff}}}{d\lambda}, \quad (3.7)$$

Figure 3.11: Illustration of the mode spreading in three silicon waveguide cross sections, obtained at $\lambda = 1550$ nm: (a) $t = 160$ nm, (b) $t = 220$ nm, (c) $t = 340$ nm, the width is constant at 450 nm.

Figure 3.12: The effective index and the group index varies with the propagation wavelength in the silicon photonic waveguide, with a waveguide width of 450 nm, and thickness of 220 and 340 nm, respectively.

The effective refractive index of the photonic waveguide n_{eff} , as a function of the propagation wavelength, is acquired using BPM method with the software RSOF. The refractive index of the bulk Si is 3.5, and bulk SiO₂ is 1.48. In the calculation, the width of the silicon waveguide is set to 450 nm, while the thickness

has three values: 160 nm, 220 nm and 340 nm, which corresponds to three kinds of silicon-on-isolator wafers. The illustration of the mode spreading at $\lambda = 1550$ nm in the silicon waveguides is expressed in Fig. 3.11.

For the interested wavelength range (1300~1700 nm), the effective refractive index n_{eff} decreases with λ , while the group index n_g , increases slightly with λ , as shown in Fig. 3.12. Due to the better light confinement ability of the thicker structure layer, the value of index n_{eff} (or n_g) at $t = 340$ nm is larger than $t = 220$ nm.

Figure 3.13: The FSR of Ring 1 varies with its radius, obtained at different waveguide thickness (160, 220 and 340 nm), when the width is 450 nm.

The FSR of Ring 1 is dependent on its radius, which is shown in Fig. 3.13. However, according to Eq. 3.6, the maximum wavelength tuning range $\Delta\lambda_{\max}$ is independent with the value of radius, but dependent on the radii difference ΔR . The relationship between $\Delta\lambda_{\max}$ and ΔR is shown in Fig. 3.14. As ΔR decreases from 5 to 1 μm , the tuning range increases from 20 to above 100 nm. In order to achieve a

wide tuning range of above 40 nm, ΔR should be smaller than 2.55 μm . In order to obtain the maximum tuning range without mode hopping, two conditions are required to be satisfied: (a) the 3-dB bandwidth of the gain spectrum can cover $\Delta\lambda_{\text{max}}$, and (b) the required refractive index change could be electrically provided. The reflection peak wavelength of the CRS is able to be changed by the electronic control of the effective refractive index n_{eff} of one or both of the ring resonators.

Figure 3.14: The maximum wavelength tuning range due to the Vernier effect, dependent on the radius difference of the coupled ring structure.

For simplification of analysis, the effective index of Ring 2 is electrically changed while Ring 1 is kept constant. The voltage induced refractive index change is Δn_{eff} , and the change of the resonance wavelength of the Ring 2 is $\Delta\lambda_{\text{SR}}$, the relationship between them is expressed as

$$\frac{\Delta\lambda_{\text{SR}}}{\lambda_i} = p \frac{\Delta n_{\text{eff}}}{n_{\text{eff}}}, \quad (3.8)$$

where λ_i is the initial central wavelength of the coupled ring structure, $p \sim 0.9$ is a constant which stands for the ratio of the heating part. The tuning range of the lasing wavelength, $\Delta\lambda_{\text{tune}}$, is expressed as

$$\frac{\Delta\lambda_{\text{tune}}}{\lambda_i} = M \frac{\Delta\lambda_{SR}}{\lambda_i} = \frac{R_1}{\Delta R} \cdot p \frac{\Delta n_{\text{eff}}}{n_{\text{eff}}}, \quad (3.9)$$

where $M = R_1/\Delta R$ is the magnification coefficient of the wavelength tuning due to the Vernier effect, $R_1 = 62 \mu\text{m}$ is the radius of Ring 1, $\Delta R = 2.5 \mu\text{m}$ is the radius difference between the two rings. The achievable wavelength tuning range $\Delta\lambda_{\text{tune}}$ is determined by the maximum refractive index change Δn_{eff} ; the wavelength tuning accuracy is determined by the minimal tuning step of the refractive index change.

The effective refractive index is controlled by either carrier injection (free-carrier plasma effect) or temperature control (thermal-optic tuning). Both approaches have distinct merits and disadvantages as discussed in Chapter 2. The change of the real part of the refractive index is expressed as:

$$\Delta n_{\text{eff}} = \Delta n_{th}(V_{th}) + \Delta n_{PIN}(V_{PIN}) = \int_0^{V_{th}} \frac{\partial n_{\text{eff}}}{\partial V_{th}} dV_{th} + \int_0^{V_{PIN}} \frac{\partial n_{\text{eff}}}{\partial V_{PIN}} dV_{PIN}, \quad (3.10)$$

The thermal-optic efficiency for silicon is $\delta n_{\text{eff}} / \delta T = 1.86 \times 10^{-4} / ^\circ\text{C}$, for the interested wavelength of 1550 nm. It leads to a resonance shift rate of $\sim 0.105 \text{ nm} / ^\circ\text{C}$ for the single ring resonator, and $\sim 2.55 \text{ nm} / ^\circ\text{C}$ for the peak reflection wavelength of the CRS. The free-carrier dispersion effect is caused by the variation of the concentration of the free electrons and holes. Due to the free-carrier dispersion effect, the change in the refractive index and absorption is expressed as

$$\Delta n_{\text{PIN}} = -8.8 \times 10^{-22} \Delta N_e - 8.5 \times 10^{-18} (\Delta N_h)^{0.8}, \quad (3.11a)$$

$$\Delta \alpha = 8.5 \times 10^{-18} \Delta N_e + 6.0 \times 10^{-18} (\Delta N_h)^{0.8}, \quad (3.11b)$$

where Δn_{PIN} is the changes of real part of the effective refractive index, caused by free-carrier injection, $\Delta\alpha$ is the change of absorption, ΔN_e is the change of the free electron concentration, and ΔN_h is the change of the free hole concentration. It is able to reach $\Delta n_{\text{PIN}} = 1 \times 10^{-3}$ when increasing the free carrier concentration. Meanwhile, a serious optical loss $\Delta\alpha = 16 \text{ dB/cm}$ is induced in silicon waveguide unfortunately. Consequently it is not suitable to applying the free-carrier effect for wide effective index tuning.

Figure 3.15: The change of the effective refractive index and the absorption coefficient due to the change of the free carrier concentration.

On the contrary, when the change of the effective refractive index Δn_{PIN} is smaller than 1×10^{-4} , it corresponds to $\Delta\alpha \leq 0.13 \text{ cm}^{-1}$ (0.56 dB/cm) as shown in Fig. 3.15. In this situation, the free optical loss caused by the carrier dispersion is acceptable for the wavelength tuning application.

The resonant wavelength of the ring resonator experiences a red-tuning due to the thermal-optic effect, and a blue-tuning due to the free carrier injection. It

requires $\Delta n_{\text{eff}} = 2 \times 10^{-3}$ for a 40-nm wavelength tuning range. The thermal-optic tuning can provide the required amount of effective index change. In order to obtain perfect consistency between the peak wavelength of the CRS and the longitude cavity mode, the tuning accuracy for the effective refractive index is required to be no more than 3.0×10^{-6} , since the space between two adjacent longitudinal modes is 0.06 nm. The free-carrier tuning is able to satisfy this requirement. Consequently, the requirement for a large tuning range and a high tuning accuracy are both satisfied, when applying the thermal-optic and the free-carrier effects simultaneously.

The discrete wavelength tuning is obtained when only the resonance wavelength of Ring 2 is electrically controlled, and the wavelength spacing between two discrete wavelength is $FSR_1 = 1.6$ nm. The quasi-continuous wavelength tuning could be achieved by electrically controlling the resonance wavelength of both Ring 1 and Ring 2.

3.2.3 Spectral properties of laser output

The output power for an external cavity tunable laser is given by [2]

$$P_{\text{out}} = \frac{h\lambda}{q} \frac{\alpha_l}{\alpha_{\text{mir}} + \alpha_{\text{int}}} (I - I_{\text{th}}), \quad (3.12)$$

where h is the Planck's constant, ν is the laser frequency, q is the electron charge, I_{th} is the threshold current, and α_{int} is the intrinsic loss due to the absorption or scattering in the gain chip. The symbols α_l and α_{mir} stand for the distributed loss of the emission facet (Mirror 1) and the total mirror loss, which are further expressed as

$$\alpha_l = \frac{1}{L_{\text{int}}} \ln \frac{1}{r_1}, \quad (3.13)$$

$$\alpha_{\text{mir}} = \frac{1}{L_{\text{int}}} \ln \frac{1}{r_1 r_{2\text{eff}}(\lambda)}, \quad (3.14)$$

where $r_{2\text{eff}}(\lambda)$ is the distributed mirror loss at the equivalent mirror, accounting for the coupling loss between the active and passive waveguide, and the optical transmission loss in bus waveguide and the coupled ring structure. The total cavity loss is the sum of the intrinsic loss and the mirror loss, as given by

$$\alpha_{\text{tot}} = \alpha_{\text{int}} + \alpha_{\text{mir}}. \quad (3.15)$$

The threshold condition requires that the magnitude and phase of the optical field are periodic with respect to one round trip of the laser cavity, which is expressed as

$$I_{\text{th}} = I_{\text{tr}} \cdot \exp\left(\frac{\alpha_{\text{int}} + \alpha_{\text{mir}}}{\Gamma \alpha_0}\right), \quad (3.16)$$

where Γ is the optical confinement factor, α_0 is the absorption coefficient of the gain medium, and $I_{\text{tr}}(\lambda)$ is the transparency current which is expressed

$$I_{\text{tr}} = \frac{q N_{\text{tr}} V_{\text{act}}}{\tau_c}, \quad (3.17)$$

where N_{tr} is the transparency carrier density (typically $1 - 2 \times 10^{18} \text{ cm}^{-3}$ for GaAs and InGaAsP at 1,310 – 1,550 nm [1]), V_{act} is the volume of the active region, and τ_c is the carrier lifetime (typically 10 – 20 ns).

SMSR

The expression for the SMSR is given expressed in the form of [1]

$$\text{SMSR} = \frac{P_{\text{tot}} \Delta g}{h \nu n_{\text{sp}} v_g a_{\text{tot}} a_{\text{mir}}}, \quad (3.18)$$

where Δg is the gain difference between the main mode and the adjacent side mode. In this external cavity tunable laser, Δg results from the wavelength dependent reflectance of the CRS, which is decided from wavelength spectrum of the CRS filter. According to Eq. 3.5, it is written as:

$$\Delta g = \Delta \alpha = \frac{1}{L_{\text{int}}} \ln \left(\frac{r_{\text{CRS}}(\lambda_0)}{r_{\text{CRS}}(\lambda_1)} \right). \quad (3.19)$$

Figure 3.16: The SMSR varies as bus-ring power coupling coefficient under different ring-ring power coupling conditions. The solid lines indicate the situation where of single reflection peak, and the dash lines indicate the situation of multi-reflection peaks of the CRS.

As indicated in Eq. 3.18, the SMSR is proportional to the gain difference Δg (loss margin $\Delta \alpha$) and the total output power. The loss margin is dependent on the power coupling coefficients K and K_2 . In Fig. 3.16, the SMSR varies nonlinearly with K_2 and has a peak value when K increases from 0 to 0.4. When the total output power is set to $P_{\text{tot}} = 30$ mW, the three curves with different colors stand for the

three cases of $K_2 = 0.0004$, 0.0009 and 0.0016 . The solid line stands for the condition when the single reflection peak occurs, and the dash line stands for the condition when multi-reflection peaks occur. The SMSR is kept above 40 dB as $K_2 = 0.0009$ and K is in the range from 0.15 to 0.4.

Figure 3.17: The SMSR vs. the bus-ring power coupling coefficient K , under different values of the bus waveguide length L_m , and the optical loss coefficient of the nano-silicon waveguide α_{Si} .

In addition, the SMSR is dependent on the physical length of the bus waveguide L_m , and the optical loss coefficient of the nano-silicon waveguide α_{Si} , as shown in Fig. 3. 17. The increases of waveguide loss degenerates the performance of the SMSR obviously. The value of the SMSR drops by 5 dB when α_{Si} increases from 1.5 dB/cm to 5 dB/cm, under the conditions of $K_2 = 0.0009$, $L_p = 5$ mm, and $K = 0.15$. Therefore, in order to obtain a performance of $\text{SMSR} \geq 40$ dB, it is preferred that: (a) to control the coupling gap and thus proper values for both K and K_2 ; (b) to shorten the physical length of the bus waveguide to $L_m \leq 5$ mm; (3) to reduce the

silicon waveguide loss to $\alpha_{Si} \leq 3$ dB/cm.

Linewidth

For the single-mode FP diode laser without external cavities, the linewidth $\Delta\nu_{FP}$ is expressed as [1]

$$\Delta\nu_{int} = \frac{h\nu n_{sp} \nu_g^2 a_{tot} a_{mir}}{8\pi P_{tot}} (1 + \alpha_H^2), \quad (3.20)$$

where, n_{sp} is the spontaneous emission coefficient (typical value 2~3), α_H is the linewidth broadening factor of the gain medium, which has typical value in range of 4 to 7 near the middle of the optical gain band, and rises to 10~20 as the photon energy approach to the band gap [2].

The traveling of the light in the external cavity extends the lifetime of the photons and thus further narrows down the linewidth, which is given by

$$\Delta\nu_{ext} = \Delta\nu_{int} \left(1 + \frac{n_{eff} L_{ext}}{n_{int} L_{int}}\right)^{-2}, \quad (3.21)$$

Figure 3.18: The linewidth varies with the bus-ring coupling coefficient, at different bus waveguide lengths.

As shown in Fig. 3.18, the linewidth of the external cavity tunable laser is proportional to L_{ext}^{-2} and P_{tot}^{-1} . The length of the effective external cavity is determined by the value of K and L_m . Assuming $P_{\text{tot}} = 30$ mW, $K_2 = 0.0009$, and $\alpha_H = 6$, the linewidth of the designed laser is able to be narrowed to below 100 kHz when the ring-bus power coupling coefficient K is less than 0.3. Besides, the linewidth is expected to be further narrowed down by increasing the length of the bus waveguide L_m .

3.3 Fabrication and Packaging Processes

3.3.1 Fabrication processes flow

The fabrication processes of the tunable laser system are developed on a SOI wafer. The whole fabrication processes combines the processes of silicon photonics (for the NSP integrated circuits) and the MEMS processes (for the integration of gain diode and the SOI chip). These processes mainly include photolithography, reactive ion etching (RIE), doping, low-pressure chemical vapor deposition, sputtering deposition, lift-off and flip-chipped bonding.

The SOI wafer consists of a 700- μm thick silicon substrate, a 2- μm thick buried thermal-oxide layer, and a 220-nm thick top silicon layer. The top silicon layer is used as the function layer for the photonic waveguide. The buried oxide layer is used as the lower-cladding of the waveguide for the electrical isolation. A 100-nm thick SiO_2 layer is deposited, serving as the hard mask for waveguide etching, as shown in Fig. 3.19 (a). After the photolithography process, the nano-waveguide structures are patterned. The SiO_2 hard mask layer is etched firstly following the photoresist pattern. The photoresist is removed afterward, and the silicon-based structures are fabricated through the RIE process. The oxide hard mask provides better protection, as well as a better selectivity for etching silicon, compared with directly using photoresist as the hard mask. To reduce the optical loss, it is crucial to control the sidewall roughness of the silicon waveguide to be within 5 nm, and thus to ensure a good uniformity. Since the formation of the P-I-N junction structure requires a rib-configuration, only a 140-nm thickness of the silicon layer is etched off, and an 80-nm slab-silicon residue remains, as shown in Fig. 3.19 (b). Then, the residue slab-silicon are partially moved off, as shown in Fig.

3.19 (c). Next, the slab areas inside and outside of the ring resonators are doped to P and N types, respectively, as shown in Fig. 3.19 (d) and Fig. 3.19 (e). a 10-nm USG-SiO₂ thin film is deposited to protect the rib regions during the doping processes. The P-type silicon is formed by the boron implantation with a dose concentration of $2 \times 10^{14}/\text{cm}^2$ at 16-keV doping energy. The N-type silicon is formed by phosphorus implantation with a dose concentration of $2 \times 10^{14}/\text{cm}^2$ at 40-keV doping energy. Anneal preprocess after doping helps to re-adjust the doping concentration distribution profile in the vertical direction. The gap between the edge of the rectangle waveguide and the doping area is 500~600 μm , which is an optimized distance for a low resistance while avoiding additional optical loss in the rib waveguide. In the following, a $\sim 1.6\text{-}\mu\text{m}$ SiO₂ layer is deposited at low-temperature by the plasma enhanced chemical vapor deposition (PECVD). The SiO₂ layer is chosen to form the upper cladding of the silicon waveguide, and also to provide the electrical isolation between the electrical pads and the silicon waveguides, as shown in Fig. 3.19 (f). Later, the via-hole is patterned as shown in Fig. 3.19 (g): the upper SiO₂ cladding on top of the doped slab regions is removed by the RIE process, and the minimum dimension for the via-hole is $10 \mu\text{m} \times 10 \mu\text{m}$, followed by a thin film TaN layer (50 nm), which is used to create ‘glue’ layer between the silicon and aluminum layers. This deposited thin film is also used for thermal heating of the surface mount resistors. Finally, a 750-nm aluminum layer is deposited and the metal pads for electrical probes are patterned, as shown in Fig. 3.19 (h).

Figure 3.19: The main process flow of electrically controlled tunable laser integrated on a SOI wafer.

After the fabrication of the nano-silicon-photonics circuits, the commercial III-V gain chip is integrated on the SOI platform via the flip-chip bonding process. The cavity, which is fabricated for chip bonding, is patterned twice in order to control the alignment accuracy in the vertical direction. The first cavity with normally a width of 350- μm is patterned as shown in Fig. 3.19 (i). A totally 3.6- μm dielectric layer (1.6- μm upper cladding SiO_2 and 2- μm thermal oxide) is etched with a stop layer of silicon by the RIE process. Then, the 300-nm silicon in the cavity is etched by controlling the etching time accurately. The bottom of this cavity is contacted with surface of the bonded gain chip, and the accuracy of silicon etch determines the bonding alignment accuracy. The etch rate and process time is measured with a test wafer before processing, and the accuracy can be controlled within 50 nm. The second cavity, which has a smaller width ($\sim 210\ \mu\text{m}$) is patterned within the first cavity, as shown in Fig. 3.19 (j). Silicon in the second cavity is continuously etched to form a depth of 3 μm , which is used for containing the bonding solder. Next, the under bump metallurgy (UBM) and Au/Sn solder are deposited with the PVD Evaporator. A 6- μm thick negative photoresist is spray coated on the top of the wafer, in order to cover the 30- μm deep trench (pre-patterned for chip dicing). The UBM consists of 100-nm Ti, 200-nm Pt and 300-nm Au. The solder includes 2- μm Au at the bottom, 2.1- μm Sn in the middle, and 50-nm Au on the top. The total height for the UBM and solder is 4.75 μm . Then, the photoresist and the solders on top of the negative photoresist are removed by the lift-off process as shown in Fig. 3.19 (l). Finally, the wafer is diced into separate dies and ready for chip level operation.

Figure 3.20: The measured profile of the laser diode cavity with the Au/Sn solder. The vertical alignment accuracy is controlled by the bottom of the diode cavity.

The gain chip, which has a dimension of $250\text{ }\mu\text{m} \times 250\text{ }\mu\text{m} \times 100\text{ }\mu\text{m}$, is integrated with the SOI chip by the flip-chip bonding process. The active waveguide in the gain medium is buried and has a $3\text{-}\mu\text{m}$ distance from the top surface of the gain chip. The width of the silicon waveguide is $3\text{ }\mu\text{m}$ at the taper end, and is reduced to 450 nm (the standard width) gradually within a length of $300\text{ }\mu\text{m}$. The measured profile of the laser diode cavity with the Au/Sn solder is presented in Fig. 3.20. The solder is deposited into the solder cavity, and the vertical alignment accuracy is controlled by the bottom diode cavity. According to the simulation, the coupling efficiency is above 50% when the gap between the two waveguides is smaller than $20\text{ }\mu\text{m}$ in the z -direction. The waveguide gap is designed as $5\text{ }\mu\text{m}$. In the experiments, the hybrid package is processed using the bonding machining named ‘Toray’ from the company ‘Toray Industries, Inc.’, which is able to reach an alignment accuracy of less than 200 nm .

For the demonstrated tunable lasers using NSP circuits, the fabrication processes for the silicon photonic circuits are standard, which is compatible with the CMOS industry. The fabrication processes for the laser diode cavity and solders are developed using the MEMS technology. All these processes have been integrated with standard 8 inch silicon-on-insulator wafer. It is successfully demonstrated in the lab, and is possible to be further duplicated by the standard foundry industry.

3.3.2 Fabrication Results

Figure 3.21: The SEM graph of the integrated tunable laser using flip-chip bonding process.

The SEM graph of the integrated tunable laser using the flip-chip bonding process is shown in Fig. 3.21. The nano-silicon waveguides in the external cavity is highlighted by the gray color. The length of the bus waveguide L_m , from the taper end to the coupled ring structure is 1.2 mm. The micro heaters, with 1.8- μm in width, are patterned on top of both ring resonators. The P-I-N junction is formed across Ring 2, due to the space limitation of the single metal layer design. Both the bus waveguide and the ring resonator have a width of 450 nm.

Figure 3.22: The zoom-in view of the nano-silicon-photonic circuits in the external cavity: (a) the coupled ring resonator, (b) the bus-ring coupling region and (c) the ring-ring coupling region.

The zoom-in views of the nano-silicon-photonic circuits are shown in Fig. 3.22. These SEM graphs, which show the profile of the photonic waveguides clearly, are taken before the process of SiO₂ cladding deposition. Ring 1 and Ring 2 have radii of 62 and 59.5 μm , respectively, as shown in Fig. 3.22(a). The gap between the bus waveguide and the ring resonator is 190 nm, and the race-track length is 3 μm to obtain a power coupling efficient of 0.16, as shown in Fig. 3.22(b). The ring-ring gap is 280 nm as shown in Fig. 3.22(c), to obtain a power coupling efficiency of 0.0009. The sidewall roughness of the waveguide is less than 3 nm, which ensures the optical transmission loss to be less than 2-dB/cm.

3.4 Experimental results and discussions

This section presents the experimental results and discusses of the electrically controlled tunable laser. The spectral properties of the CRS, the comparison between the two electrical tuning schemes, and the laser spectrum specifications are measured and discussed.

3.4.1 Reflectance of the CRS

In order to investigate the properties of the CRS, the measured transmission and reflection spectrums of the CRS are shown in Fig. 3.23. Without the gain chip integration in the experiment, the two ends of the bus waveguide are connected with the light source and the optical spectrum analyzer (OSA) through lens fibers. For the transmission spectrum testing, the broadband light source is coupled into the input port of the bus waveguide, and the output signal is detected by the OSA. The power of the input broadband light is 3 mW and the average optical intensity on the optical spectrum is -16.0 dBm, when the broadband light is directly measured by the OSA. Because the coupling loss between the bus waveguide and the lens fiber is ~ 2.5 dB, either for the input or output port, the average optical intensity is -21.0 dBm on the transmission spectrum as shown in Fig. 3.23. The reflection spectrum is obtained by inserting a fiber optical circulator between the ASE light source and the input port of the bus waveguide. The maximum reflection of the CRS is obtained at $\lambda_0 = 1564.14$ nm. The insertion loss of the optical circulator is 1.2 dB. Compared with the power level of the transmission spectrum, the reflection spectrum is 2.9 dB lower, thus the optical loss on the coupled ring structure is 1.7 dB, which is corresponding to a reflectance of 68%. The loss margin between the main reflection peak and the adjacent peak is 2.1 dB.

Figure 3.23: The transmission and reflection spectra of the coupled ring structure. The reflection spectrum is measured using a fiber optical circulator with a 1.2-dB insertion loss.

As shown in Fig. 3.23, the filtering bandwidth at the peak reflection resonance λ_0 is 0.16 nm, which corresponds to a quality factor of 9.8×10^3 for the reflection resonance. The total physical length of the laser cavity is 3.8 mm, thus the longitudinal mode spacing is ~ 0.09 nm based on Eq. 3.2. Consequently, the resonance bandwidth is comparable with the longitudinal mode spacing of the laser cavity, which ensures the spectrum purity of the single mode lasing.

3.4.2 Electrically controlled wavelength tuning

The wavelength tuning is controlled by two methods: (a) the heating temperature induced index change (thermal-optic effect) and (b) the free-carrier injection induced index change. The resonance shift of a single ring resonator is experimentally studied, as shown in Fig. 3.24. The tuning efficiency of the thermal-optic effect increases with the applied voltage. For the free-carrier injection method,

the free-carrier injection occurs when the voltage applied on the P/N regions is above 0.7 V.

Figure 3.24: The tuning of resonance position of a single ring resonator, via the thermal-optic and the free-carrier injection method, respectively.

The free-carrier injection results in the reduction of the effective index, and thus the blue shift of the resonant wavelength. As shown in Fig. 3.25(a), the blue shift of the resonance of Ring 2 is 0.103 nm, when V_{PIN} increases from 0.8 to 1.7 V, corresponding to a wavelength tuning efficiency of -0.114 nm/V. The increase of optical absorption, due to the free-carrier injection, degrades the Q -factor of the ring resonator. According to the measurement of the absorption peaks on the transmission spectrum, the Q -factor decreases from 1.63×10^4 to 1.32×10^4 when V_{PIN} increases from 0.8 to 1.7 V. Despite the tendency, the degradation of the Q -factor is neglected when the wavelength is changed within 0.1 nm. The heating to the ring waveguide results in the increase of the effective index, and thus the red shift of the resonant wavelength. As shown in Fig. 3.25(b), the red shift of the resonance is 0.94 nm, when V_{ther} increases from 0 to 0.9 V. The thermal wavelength

tuning efficiency is dependent on V_{ther} , increasing from < 0.1 nm/V (at $V_{\text{ther}} = 0$ V) to 19.5 nm/V (at $V_{\text{ther}} = 0.9$ V).

Figure 3.25: The resonance tuning of Ring 2 is controlled by (a) the free-carrier injection and (b) the thermal-optic effect.

The switching speeds of the two tuning schemes are shown in Figs. 3.26 and 3.27, respectively. A single-mode laser source is coupled to the bus waveguide. The transmitted optical signal is converted to electrical signal by a photodetector, and tested by the oscilloscope. The wavelength of the input laser is consistent with the

resonant wavelength of the ring resonator. For the free carrier injection tuning, the P-I-N junction works at a bias voltage of 1.0 V and a modulation voltage of 1.6 V. The modulation frequency is set to 1 GHz. The rise and fall time are 0.78 ns and 0.72 ns, respectively. The rise and fall time are comparable with each other.

Figure 3.26: Experimental switching time of the free-carrier injection method, when the modulation frequency is 1GHz. The rise and fall time are 0.78 ns and 0.72 ns, respectively.

For the thermal-optic tuning scheme, the heating voltage is biased at 0.5 V and modulated at 1 V, with a modulation frequency of 25 kHz. As shown in Fig. 3.27, the measured rise and fall time are 3 μs and 5.5 μs , respectively. The free-carrier injection effect obtains a GHz-level tuning speed, which is much higher than the thermal-optic effect (MHz-level tuning speed). When the wavelength is tuned by the both schemes, the speed of the wavelength tuning is determined by the slower thermal-optic effect.

Figure 3.27: Experimental switching time of the thermal-optic scheme, when the modulation frequency is 25-kHz. The rise and fall time are 3 μ s and 5.5 μ s, respectively.

3.4.3 Parameters of the laser spectrum

The packaged device is placed on a sub-mount, connecting with a thermoelectric cooler, and the working temperature is kept constant at 25 $^{\circ}$ C. The light emitted from the left facet of the gain chip is collected using a lens fiber, and measured by an optical spectrum analyzer (OSA, Advantest Q8384). The gain diode has a 3-dB bandwidth of 50 nm and a saturation output power of 7 dBm. During the experiments, when the gain diode is pumped at 185 mA, its gain spectrum is centered at 1533 nm, with a 3-dB spectrum range of 1508 - 1560 nm. For wavelength tuning, the thermal voltage V_T and the P-I-N voltage V_{PIN} are applied to Ring 2. The minimal voltage tuning step is 0.01V in the experiments.

Figure 3.28: The wavelength tuning and SMSR performance versus the thermal voltage applied on Ring 2.

Fig. 3.28 shows the wavelength tuning and SMSR performance versus the thermal voltage V_T applied on Ring 2. The wavelength tuning is discrete, with a 1.6 nm wavelength spacing. When the thermal voltage V_{ther} increases from 0 to 1.48 V, the single-mode lasing wavelength is tuned from 1564.2 nm to 1522.6 nm. A certain wavelength is kept constant within a certain thermal voltage range ΔV_{ther} . The highest SMSR is obtained only when the longitudinal mode of the laser cavity is tuned to the center of the main filtering band of the CRS. For example, when V_{ther} is tuned between 0 and 0.18 V ($\Delta V_{\text{ther}} = 0.18$ V), the lasing wavelength is kept at 1564.2 ± 0.05 nm. The SMSR is tuned from 12 dB to 42 dB, and the maximum value of 42 dB is obtained. Because the thermal power is proportional to the square of V_{ther} , the thermal tuning efficiency increases with V_{ther} , and thus ΔV_{ther} drops correspondingly. As a result, the SMSR is degraded when $V_{\text{ther}} > 0.8$ V due to the limitation of thermal tuning accuracy. For instance, when V_{ther} is tuned between 1.42 V to 1.43 V ($\Delta V_{\text{ther}} = 0.02$ V), the single-mode lasing wavelength is kept at

1529.8 ± 0.05 nm, but the maximum achievable SMSR is only 26.5 dB. In order to improve the tuning accuracy to achieve optimal spectrum purity, the effective refractive index is adjusted by the free-carrier injection.

Figure 3.29: The comparison of laser performance (output power and SMSR), before and after applying the free carrier effect.

The effect of the accurate wavelength tuning via free-carrier injection is shown in Fig. 3 29. Initially, Ring 2 is heated at the condition $V_T = 1.42$ V and $V_{PIN} = 0$, the lasing wavelength is at $\lambda_r = 1529.8$ nm, with -2.5 dBm optical power and 26.5 dB SMSR. Based on the minimal voltage step of 0.01V, the thermal-optic tuning accuracy is 0.24 nm. This accuracy is unable to refine the position of the longitudinal mode within the 0.16-nm filtering bandwidth. When V_{PIN} is increased from 0.7 to 0.85V, the SMSR is refined to 40 dB and the output power is refined to 3 dBm, λ_o has a tiny red-shift of 0.03 nm as well. Therefore, the free-carrier induced tuning accuracy is 2 pm/0.01 V. Besides, the fine tuning is achieved with an

injection current of 3 μA , and the additional optical loss caused by this small injection current is limited and thus neglected.

Figure 3.30: The optical spectrum of a series of single-mode output, and the lasing wavelength is tuned from 1523.6 nm to 1563.8 nm.

Applying these two tuning schemes, a series of single-mode lasing wavelengths are achieved, as shown in Fig. 3.30. The lasing wavelength is tuned from 1522.6 nm to 1564.2 nm. The average SMSR is above 40 dB with a tuning range of 41.6 nm. The maximum output power is 2 mW with a vibration of 3 dB. The temperature of the gain chip is kept constant at 25 $^{\circ}\text{C}$ during the experiments. Supposed the temperature of the gain chip is increased, there is a red-shift of the gain spectrum. The lasing wavelength is controlled by the filtering properties of the coupled ring structure, which prevents the shift of the lasing wavelength. However, the shift of the gain spectrum may result in the increase of the optical intensity at side modes, which degrades the SMSR. The accurate wavelength tuning using the free-carrier injection is helpful to refine the SMSR performance under this situation.

The laser performance is dependent on the design of the external NSP circuits, in several aspects. Firstly, the output power and the SMSR are dependent on the bus-ring and ring-ring power coupled coefficients: In this design, the optimized values of $K = 0.2$ and $K_2 = 0.0009$ are achieved at the coupling gap of 190 nm and 280 nm, respectively. Secondly, the external cavity efficiency and thus the output power are dependent on the coupling coefficient between the active and the passive waveguides. According to the experimental results, the external cavity efficiency is estimated to be ~20%, obtained at a 2.5-dB coupling loss. Thirdly, the optical transmission loss in the nano-silicon waveguide is also a key factor, which affects the linewidth, the SMSR and the output power.

3.5 Summary

This chapter focuses on the theory, fabrication and experiments of an electrically controlled tunable laser using the NSP in the external cavity. The theoretical analysis explores the schematic and the equivalent model of the external cavity laser system. It is shown that the coupled ring structure works as a reflective filter for single-mode oscillation. Further study reveals the properties of the two electrical tuning schemes, the thermal-optic and the free-carrier effect. The NSP circuits are fabricated on a SOI chip with a dimension of $3\text{mm} \times 1\text{mm} \times 0.7\text{mm}$. The integration of the gain chip and the passive NSP circuits is realized through the flip-chip bonding technology. The experimental results demonstrate the wavelength tuning effects of the two electrical schemes, obtaining 41.6 nm tuning range with 2 pm tuning accuracy. The SMSR is able to be optimized above 40-dB using the free-carrier effect.

This tunable laser showcases the important advantages of the NSP circuits based tunable lasers. Compared with III-V platform tunable lasers [23, 67], it has lower cost and better compatibility with CMOS processes, benefited from the silicon platform. In contrast to the non-negligible transmission loss in the free-space structures due to the beam divergence [6, 7], this tunable laser has a much lower optical transmission loss ($< 2\text{ dB/cm}$). As a result, it has the capability to construct a longer external cavity as compared with MEMS tunable lasers, lengthening from several tens of μm to several mm, which is helpful for obtaining narrow linewidth. Another merit is the flexibility of waveguide photonic elements, i.e. the two coupled ring resonators can serve as the reflective filters, and ensure a large tuning range due to Vernier effect. In addition, the nano-silicon waveguides provide

possibility for multiple tuning schemes. These advantages pave the way for large tuning range, high tuning accuracy, high SMSR, and narrow linewidth.

CHAPTER 4

OPTO-MECHANICAL TUNABLE LASER

This chapter presents an opto-mechanical tunable laser based on a nano-actuator driven by the optical force. It consists of a gain chip and a pair of ring resonators which are connected with a nano-silicon waveguide. The optical tuning scheme, instead of an electrical scheme, is adopted for the lasing wavelength tuning through changing the refractive index of the free-standing waveguide of the nano-actuator. In this chapter, the schematic and principle for opto-mechanical wavelength tuning of the nano-actuator is illustrated firstly. Then, the opto-mechanical tunable laser is constructed and numerically studied, followed by the fabrication and integration processes. Finally, the experimental results are discussed, including the wavelength tuning effect of both the single ring resonator and the tunable laser based on the coupled ring structure.

4.1 Theoretical analysis of the opto-mechanical tunable laser

The concept of resonant wavelength tuning driven by optical gradient force is firstly demonstrated with a single ring resonator, which is called a nano-actuator, then the concept is used in an external cavity tunable laser.

4.1.1 Design of the opto-mechanical nano-actuator

Figure 4.1: The schematic illustration of (a) the opto-mechanical nano-actuator; (b) the cross-sectional view of the free-standing arc; (c) the deflection of the arc caused by optical force; (d) the cross-sectional view of the deflected actuator.

The schematic of the opto-mechanical ring resonator is illustrated in Fig. 4.1(a). Both the ring resonator and the bus waveguide have a dimension of 450-nm width and 220-nm height. Both a broadband probe light and a control light inject are injected into the bus waveguide. The probe light is of low-power and broadband, and is used to detect the deflection of the arc of the ring resonator. The control light is of high-power and monochromatic, and is used to generate an optical force to actuate the arc. The gap between the ring resonator and the bus waveguide is 200 nm. The air gap between the free-standing arc and the silicon dioxide (SiO_2) layer is 160 nm, as shown in Fig. 4.1(b). The deflection of the arc caused by the optical force is illustrated in Fig. 4.1(c). The cross-sectional length of the arc is 11.2 μm , as shown in Fig. 4.1(d).

Figure 4.2: Schematic illustration of the free-standing ring resonator that is deflected by optical gradient force.

Figure 4.2 shows the schematic illustration of the free-standing ring resonator which is deflected by the optical gradient force. The free-standing arc is bent in the vertical direction to the SiO_2 substrate when the control light matches

with the resonance of the single ring resonator. The ring resonator is called an opto-mechanical nano-actuator. The displacement of the arc is at the nano-meter scale.

4.1.2 Theoretical analysis of the opto-mechanical nano-actuator

The free-standing waveguide is separated from the dielectric layer by an initial gap of g_0 . The light travelling in the free standing waveguide is coupled evanescently to the substrate, which induces an attractive optical gradient force and drives the free-standing arc to bend towards the substrate. When the arc is bent with a central deflection x , the air gap is changed to $g = g_0 - x$. As presented in Fig. 4.3, the effective refractive index of the arc, n_{eff} , is dependent on the air gap g and the propagation wavelength λ , and is calculated using the commercial software RSOF. The effective refractive index varies from 2.332 to 2.412, when the air gap varies from 0 to 1000 nm, and the wavelength varies from 1500 to 1600 nm. Supposed the propagation wavelength λ is a constant, n_{eff} decreases exponentially with the increase of the air gap; supposed the air gap is a constant, n_{eff} decreases with the increase of λ .

4.1.2.1 Effective refractive index

Figure 4.3: The effective refractive index of the free-standing waveguide.

The thickness of the waveguide also contributes to the refractive effective index of the free-standing waveguide. Fig. 4.4 shows two curves which stands for waveguide thickness $T = 160$ and 220 nm, respectively. The differential coefficient $\partial n_{eff} / \partial g$ is a key factor that determines the value of the optical force. At the identical gap, the differential coefficient at $T = 160$ nm is larger than that at $T = 220$ nm. This is because the evanescent wave is more dominant in the thinner waveguide.

Figure 4.4: The effective refractive index versus the air gap under different waveguide thickness.

4.1.2.2 Opto-mechanical wavelength tuning coefficient

Corresponding to the change of n_{eff} , the resonant wavelength λ_r of the ring resonator varies with air gap g (deflection x). As shown in Fig. 4.5, the opto-mechanical wavelength tuning coefficient is exponentially fit to $\partial \lambda_r / \partial x = A_1 \exp(A_2 x)$, where $A_1 = 2.3 \times 10^{-2}$ and $A_2 = 1.35 \times 10^{-2}$ at $T = 220$ nm and $g = 160$ nm. The resonant wavelength of the ring resonator is dependent on the effective index of the waveguide. Although the nano-scale deflection is not able to be directly

observed, the deflection x can be indirectly detected by monitoring the shift of the resonant wavelength $\delta\lambda_r$ in the transmission spectrum.

Figure 4.5: Schematic of the shift of the resonant wavelength versus the deflection x of the arc.

4.1.2.3 Analysis of the optical force

The gradient optical force which bends the free-standing arc is given by the derivative of the optical energy [18]

$$F_{opt} = -\frac{\partial U}{\partial g} = -\frac{U}{\lambda_r} \frac{\partial \lambda_r}{\partial x}, \quad (4.1)$$

where U is the optical energy stored in the ring resonator,

$$U = |a|^2 = a \cdot a^*, \quad (4.2)$$

where a is the amplitude of the optical energy [81]

$$a = \frac{-j\sqrt{2\tau_e^{-1}}P_{in}}{j(\omega_c - \omega_r) + (\tau_i^{-1} + \tau_e^{-1})} S_{in}, \quad (4.3)$$

where S_i is the electrical field of the incident light with constant power, $\omega_c = 2\pi c/\lambda_c$ is the resonant frequency of the ring resonator, $\omega_r = 2\pi c/\lambda_r$ is the frequency of the incident light, $1/\tau_e$ the extrinsic decay rate due to the external coupling of the transmitted wave, $1/\tau_i$ the intrinsic decay rate due to the internal cavity loss. Thus the optical energy is written as

$$U = \frac{2\tau_e^{-1}P_{in}}{((\lambda_c - \lambda_r) \cdot 2\pi c \lambda_r^{-2})^2 + (\tau_i^{-1} + \tau_e^{-1})^2}, \quad (4.4)$$

where P_{in} is the power of the control light injected into the bus waveguide.

Substituted Eq. 4.4 to Eq. 4.1, the optical gradient force exerted on the arc is given by

$$F_{opt} = - \frac{2\tau_e^{-1}P_{in}}{(\lambda_c - \lambda_r)^2 \cdot (2\pi c)^2 \lambda_r^{-3} + \lambda_r (\tau_i^{-1} + \tau_e^{-1})^2} \cdot \frac{\partial \lambda_r}{\partial x}. \quad (4.5)$$

Figure 4.6: The optical force as a function of the displacement x and the wavelength of the control light λ .

The amount of the optical gradient force is plotted in Fig. 4.6, which is considered as a function of the displacement x and the wavelength of the control light λ . According to Eq. 4.5, the optical force, subject to a control light of a fixed wavelength and power, is a nonlinear function of the deflection x . The nonlinearity of gradient optical force results from the interaction between the mechanical motion and the optical field.

When the control light is pumped into the bus waveguide, the optical force causes the deflection of the arc, and thus tunes the resonant wavelength of the ring (initially at λ_{r0}) toward the wavelength of the control light λ_c . Consequently, the optical force increases, as illustrated in Fig. 4.7. The wavelength detuning is defined as $\Delta = \lambda_c - \lambda_{r0}$. On the contrary, the optical force decreases when the deflection of the arc tunes the resonant wavelength of the ring away from the wavelength of the control light. The nonlinear curve of optical force versus displacement is indicated in Fig. 4.8.

Figure 4.7: The illustration of the shift of resonant wavelength of the ring resonator when a control light is provided.

The defection of the arc can be varied by changing either the wavelength λ_c or the power P_{in} of the control light. Based on Eq. 4.5, $x \propto F_{opt}(x) \propto (\lambda_c - \lambda_r)^{-2}$, and $x \propto P_{in}$. Hence, the defection dependence on λ_c and P_{in} are illustrated in the following paragraphs, respectively.

4.1.2.4 Displacement x versus λ_c

The mechanical spring constant of the arc is $k_{mech} = 0.14$ N/m, which is calculated by using the finite-element software COMSOL. The shape of the arc reaches a state of equilibrium when the optical force balances the mechanical force, and the balance condition is as following,

$$F_{opt}(x) + k_{mech}x = 0. \quad (4.6)$$

Figure 4.8: Comparison of the optical force and the mechanical force under different wavelength detuning conditions.

Once the free-standing arc is deflected, the mechanical force, F_{mech} , tends to pull the arc back to its original position. There are two forces in this system: the

mechanical force is linear and the optical force is nonlinear in the deflection. The two forces balance each other at the equilibrium points.

Owing to the cavity effect of the ring resonator, the optical force depends on the resonant wavelength, when the power and wavelength of the control light is constant. The deflection of the arc modifies the effective refractive index and thus tunes the resonant wavelength of the ring. Hence, the deflection provides a “feedback” to the amount of the optical force, and the function $F_{opt}(x)$ is non-monotonic, as shown in Fig. 4.8.

Supposed the input power P_{in} is constant and the wavelength detuning Δ is set to different values, the deflection position predicted by the force analysis is shown in Fig. 4.8. In Eq. 4.5, the variable part is $(\lambda_c - \lambda_r)^2(2\pi c)^2\lambda_r^{-3} \approx (\lambda_c - \lambda_r)^2(2\pi c)^2\lambda_{r0}^{-3}$, as P_{in} is kept constant. When the deflection x increases, the value of $(\lambda_c - \lambda_r)^2$ decreases to zero and then increases again. Thus the curve of $|F_{opt}|$ is quasi-Lorentzian, which reaches the maximum value at $\lambda_r(x) = \lambda_c$ approximately. The curve is asymmetrical with respect to the peak point because the opto-mechanical wavelength tuning coefficient varies with the deflection.

4.1.2.5 “Pull-back” nonlinearity

Since the optical force is a nonlinear function in terms of the deflection, the arc may deflect to multiple states of equilibrium, as shown in Fig. 4.8. When the optical power is $P_{in} = 2.8$ mW, the curve of $|F_{opt}|$ under $\Delta = 0.54$ nm is highlighted. The two curves (F_{mech} and $|F_{opt}|$) intersect at three points, a , b , and c . When $\Delta = 0.46$ nm, points a and b merge to a single point. When $\Delta < 0.46$ nm, the merged point disappears, and only one state of equilibrium c still exists. Consequently, when Δ is reduced, the arc undergoes the “pull-in” instability, jumping toward state

c. On the contrary, when Δ increases, points b and c move closer, while point a approaches to the zero-deflection position. At the critical detuning value of $\Delta = 1.51$ nm, points b and c merge (at the stable point p). At point p , the largest deflection, $x_p = 40.8$ nm is obtained. When $\Delta > 1.51$ nm, the situation of $F_{mech} > |F_{opt}|$ is always satisfied, therefore the largest deflection is not maintainable and the free-standing arc is expected to be pulled back to point a , which is nearly at the initial status of $x = 0$ nm. This phenomenon is called “pull-back” instability. The linear mechanical force becomes too large to be balanced by the nonlinear optical force when the deflection is above a certain value, which is the reason for the “pull-back” phenomenon. Therefore, the actuation of the free-standing arc is controllable when $x \leq x_p$. The normalized controllable actuation range is $x_p / g_0 = 25.5\%$.

Figure 4.9: The optical spring and system stiffness vs. x at $\Delta = 0.54$ nm.

In order to analyze the stability of the states of equilibrium, the concept of optical spring and system stiffness is invoked. Employing the analogy with the mechanical stiffness, the stiffness of the optical spring is defined by $k_{opt} = \partial F_{opt} / \partial x$. According to Eq. 4.5, the stiffness of the optical spring can be expressed as

$$k_{opt} = \frac{U}{\lambda_{r0}^2} \left(2 \left(\frac{\partial \lambda_r}{\partial x} \right)^2 - \lambda_{r0} \frac{\partial^2 \lambda_r}{\partial x^2} \right). \quad (4.7)$$

Figure 4.10: The nonlinear relationship between the deflection of the arc and the wavelength detuning Δ .

Through modifying the intrinsic mechanical spring constant, the optical spring can either “soften” or “harden” the free-standing arc. The system stiffness of the arc is expressed as $k_{syst} = k_{mech} + k_{opt}$. An equilibrium position with negative stiffness ($k_{syst} < 0$) is unstable, because it has a higher positive stored energy, compared with those neighboring equilibrium positions. In order to obtain the stable equilibrium state, the system stiffness is required to be positive, which is expressed as

$$k_{syst} = k_{mech} + \frac{U}{\lambda_{r0}^2} \left(2 \left(\frac{\partial \lambda_r}{\partial x} \right)^2 - \lambda_{r0} \frac{\partial^2 \lambda_r}{\partial x^2} \right) > 0. \quad (4.8)$$

Substitute Eq. 4.6 and 4.7 to Eq. 4.8, the stable condition for an equilibrium state is

$$\lambda_r \frac{\partial \lambda_r}{\partial x} + 2 \left(\frac{\partial \lambda_r}{\partial x} \right)^2 x - \lambda_r \frac{\partial^2 \lambda_r}{\partial x^2} x > 0. \quad (4.9)$$

The variation of k_{opt} and k_{syst} with x under special condition of $\Delta = 0.54$ nm is shown in Fig. 4.9. The three intersection points are labelled as a , b , and c . Note that $k_{syst} > 0$ at points a and c , corresponding to the two stable states of equilibrium. Note that $k_{syst} < 0$ at point b , corresponding to the unstable state.

The relationship between the amount of deflection x and the wavelength of the wavelength detuning Δ (corresponds to λ_c) is a nonlinear function, as shown in Fig. 4.10. Three different parts of the curve corresponds to the three types of equilibrium states. Curve C consists of all the stable states of equilibrium like point c , curve B consists of all the unstable states of equilibrium like point b , and curve A consists of all the stable states of equilibrium like point a . These curves suggest a hysteretic behavior. When Δ is increased by changing the wavelength of the control light, the deflection x of the arc follows curve C , until x_p (point p) is reached at the “pull-back” detuning $\Delta = 1.51$ nm. When $\Delta > 1.51$ nm, the deflection follows curve A . When Δ is decreased, the deflection follows curve A first until $\Delta = 0.46$ nm, and then the deflection follows curve C .

For this nano-actuator, the “pull-back” instability dominates the nonlinear behavior of the arc positioning. Although the normalized “pull-back” displacement, x_p / g_0 , is 25.5% under the condition of $P_{in} = 2.8$ mW and $k_{mech} = 0.14$ N/m, it can be increased through increasing the optical power P_{in} , and decreasing the mechanical spring constant k_{mech} , as shown in Fig. 4.11. For example, the value of x_p / g_0 is increased to 50% when $P_{in} = 3.0$ mW and $k_{mech} = 0.12$ N/m, as shown in Fig. 4.12.

Figure 4.11: The contour plot of the displacement d at “pull-back” positions as a function of the effective mechanical stiffness k and the optical power P_{in} of the control light.

Figure 4.12: The dependence of the normalized “pull-back” displacement on the mechanical spring constant and the optical power of the free-standing arc.

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Substitute $\partial \lambda_r / \partial x = A_1 \exp(A_2 x)$ to Eq. 4.9, the stable condition for the equilibrium state is always satisfied when the initial gap is $g_0 = 160$ nm. It means that the stable actuation range of the free-standing arc is theoretically able to cover the 100% of the nano-air-gap under the extremely ideal situations (when the Van der Waals force is neglected, the light power is ideally increased and k_{mech} is ideally reduced). Recall that in a parallel-plate MEMS actuator, the pull-in instability occurs when the deflection is 1/3 of its initial gap. Thus this nano-actuator has the potential for superior performance in the controllable actuation.

4.1.2.6 Displacement x versus P_{in}

Figure 4.13: Comparison of the optical force and the mechanical force under different power of the control light P_{in} .

Fixed the wavelength of the control light ($\Delta = 0.2$ nm), the deflection positions corresponding to different control power P_{in} are predicted by the force analysis, as plotted in Fig. 4.13. When $P_{in} = 2.7$ mW, the curve of $|F_{opt}|$, which intersects with the curve of F_{mech} at three points, a , b , and c , is highlighted. When $P_{in} = 5.0$ mW, points a and b merge to a single point. When $P_{in} > 5.0$ mW, the merged point disappears, and only one state of equilibrium c still exists. Consequently, the arc jumps towards state c , with the increase of P_{in} . On the contrary, when P_{in} decreases, points b and c move closer, while point a approaches to the zero-deflection position. With further reduce of P_{in} , i.e., at $P_{in} = 0.7$ mW, only one state of equilibrium a still exists.

Figure 4.14: The nonlinear relationship between the arc deflection x and the light power P_{in} at different wavelength detuning status of $\Delta = 0.2$ nm and $\Delta = 0$ nm.

When the wavelength detuning is kept constant, for instance, $\Delta = 0.2$ nm, the nonlinear relation between the displacement of the arc x and the light power P_{in} is plotted in Fig. 4.14. It shows a bi-stable behavior dependent on the increase or

decrease of P_{in} , and the unstable points are plotted with a red dash-line. When the wavelength detuning approaches $\Delta = 0$, the bi-stable behavior is eliminated, and the displacement x increases continuously with the optical power and there is no unstable points in the curve.

4.1.3 Design of the opto-mechanical tunable laser

Due to the ability of resonant wavelength tuning using the opto-mechanical method, and the integration compatibility of the fabrication between the NSP circuits and the free-standing nano-actuator, it provides the possibility to construct a chip-scale tunable laser via the opto-mechanical tuning scheme.

Figure 4.15: The schematic of the opto-mechanical tunable laser integrated on a SOI chip.

The opto-mechanical tunable laser is integrated on a SOI chip, as shown in Fig. 4.15. It is constructed by a gain chip and a linear external cavity, in which a pair of coupled ring resonators serving as the reflective filter. The principle of the

wavelength selection of the CRS has been discussed in Chapter. 3. One ring is made free-standing and can be actuated (Ring 1), while the other ring is fixed on the SiO₂ layer (Ring 2). Both the bus-waveguide and the ring resonators are of 450-nm width and 160-nm height. The air gap is formed between the free-standing ring resonator and the SiO₂ layer is 160 nm. The broadband light from the gain chip is coupled to the NSP circuits via the taper silicon waveguide, and reflected back to the gain chip by the CRS. The wave whose wavelength satisfies the resonance condition of the CRS, is able to obtain the highest gain during the oscillation, and is stimulated from the left facet of the gain chip. The opto-mechanical method is utilized to change the effective refractive index of the free-standing arc, thus the wavelength tuning is optically controlled through tuning the center resonance the CRS.

Figure 4.16: The wavelength tuning range of the opto-mechanical tunable laser, as a function of the deflection of the free-standing arc. The tuning range is also dependent on the radius difference between two coupled ring resonators.

Based on the opto-mechanical tuning coefficient of the single-ring nano-actuator, the achievable tuning range $\Delta\lambda_T$ of the tunable laser is express as

$$\Delta\lambda_r = \frac{R_1}{\Delta R} \cdot \int_0^x \frac{\partial\lambda_r}{\partial x} dx, \quad (4.10)$$

where $\partial\lambda_r / \partial x = A_1 \exp(A_2 x)$ is the opto-mechanical tuning coefficient of the single-ring nano-actuator, $R_1 = 30 \text{ } \mu\text{m}$ is the radius of the free-standing ring, ΔR is the radius difference between Ring 1 and Ring 2. When the initial gap is $g_0 = 160 \text{ nm}$, $A_1 = 2.3 \times 10^{-2}$ and $A_2 = 1.35 \times 10^{-2}$. Figure 4.16 expresses the relationship between the tuning range $\Delta\lambda_T$ and the deflection of the free-standing arc x . Due to the Vernier effect of the two resonators, the wavelength tuning range is amplified from a few nm to tens of nm.

Figure 4.17: The amount of wavelength tuning $\Delta\lambda_T$ as a function of the optical power inside the laser cavity.

The amount of wavelength tuning $\Delta\lambda_T$ is a function of the optical power inside the laser cavity as shown in Fig. 4.17. Actually the amount of the displacement is determined by the total optical power in the laser cavity, and the optical power is proportional to the optical energy confined in the free-standing ring

resonator. In this design, the oscillated optical power in the laser cavity is provided by the gain diode chip, and the change of the pump currents of the gain diode results in the change of optical powers inside the laser cavity.

There is a dynamic equilibrium process that masters the operation of the laser system: at gain current I_1 , the wavelength, which satisfies the resonance condition of the CRS, gains the highest energy and becomes the lasing wavelength. The single-mode light causes the deflection of the free-standing arc and the resonant condition is thus shifted, which is a negative feedback to the lasing wavelength. When the dynamic equilibrium is built up, the lasing wavelength is stabled at λ_1 , corresponding to the arc displacement of x_1 . The equilibrium inside of the laser cavity is broken when gain current is changed to I_2 , then a new balance is obtained and the lasing wavelength is tuned to λ_2 .

Figure 4.18: The maximum tuning range of the opto-mechanical tunable laser as a function of the Q-factor of the free-standing ring resonator.

Besides the optical power in the laser cavity, the maximum tuning range is dependent on the Q -factor of the free-standing ring resonator as well, since the gradient optical force is determined partially by the Q -factor of the ring resonator, as expressed as

$$Q = \omega\tau / 2 = \frac{\pi c}{\lambda} \cdot \frac{\tau_i \tau_e}{\tau_i + \tau_e}. \quad (4.11)$$

Supposed the external decay rate $1/\tau_e$ is constant, the value of the Q -factor is determined by the internal decay rate $1/\tau_i$. The internal decay rate is mainly related with the round-trip optical loss in the ring resonator, including the scattering loss due to the side-wall roughness of the nano-silicon waveguide and the optical absorption of the material.

The relationship between the maximum wavelength tuning range and the value of Q -factor is shown in Fig. 4.18, when the intra-cavity optical power is constant at 20 mW and the bus-ring power coupling coefficient is $\kappa^2 = 0.04$ (corresponds to $1/\tau_e = 1.45 \times 10^{10}$ Hz). The tuning range increases exponentially with the increase of the Q -factor, where a 20-nm tuning range is expected when the Q -factor is above 1.3×10^4 . The Q -factor of the fabricated ring resonator usually ranged from 1×10^4 to 2×10^4 , indicating that the achievable tuning range is about 20 nm when applying the opto-mechanical effect. A larger tuning range requires a higher bus-ring power coupling coefficient.

4.2 Fabrication and Packaging Processes

This section presents the fabrication and packaging processes of the opto-mechanical tunable laser. The processes include photolithography, reactive ion etching (RIE), low-pressure chemical vapor deposition, sputtering deposition, lift-off and vapor hydrogen fluoride (HF) release.

4.2.1 Fabrication processes flow

The fabrication processes flow of the opto-mechanical tunable laser is shown in Fig. 4.19. The structure layer of the SOI wafer is chosen to be 160-nm or 220-nm. Firstly, a 100-nm thick SiO₂ layer is deposited as the hard mask for waveguide etching as shown in Fig. 4.19(a). The SiO₂ hard mask layer is patterned with a 193-nm photolithography process, followed by the silicon structure layer etching as shown in Figs. 4.19(b) and(c). Then a ~1.6- μ m thick SiO₂ layer is deposited at low-temperature by PECVD process, as shown in Fig. 4.19(d). The via-hole is patterned by etching through both the upper and under SiO₂ cladding as shown in Fig. 4.19(e). The minimal dimension for the via-hole is 10 μ m $\times$ 10 μ m. Following this, a 750-nm aluminum layer is deposited to fill the via-hole and form the metal deposition layer, as shown in Fig. 4.19(f). The metal pads, which are used for providing electrical power to the bonded gain chip, are then patterned as shown in Fig. 4.19(g). Afterwards, a 500-nm thin film SiO₂ layer is deposited as shown in Fig. 4.19(h). This layer is used to protect the metal pads in subsequent processes. Next, the trench areas are patterned for chip dicing as shown in Fig. 4.19(i). The trench is ~25 μ m deep into the Si substrate, which is a proper depth by considering two requirements: (a) deep enough for wafer dicing; (b) the trench

Figure 4.19: The process flow of the opto-mechanical tunable laser on a SOI chip.

cavity is able to be covered by the spray coated photoresist during the solder deposition. Then a 30-nm Al_2O_3 film is deposited as the hard mask for SiO_2 etch as shown in Fig. 4.19(j). The window is patterned by etching off the Al_2O_3 hard mask, as shown in Fig. 4.19(k). Next, the SiO_2 inside the window area is partially removed, which is stopped at the metal layer, as shown in Fig. 4.19(l).

The cavity of the gain chip is patterned twice in order to control the vertical alignment accuracy for chip bonding. The first cavity, in terms of a 350- μm width, is patterned as shown in Fig. 4.19(m). A totally 3.6- μm thick SiO_2 layer is etched by the RIE process (1.6- μm upper-cladding SiO_2 and 2- μm thermal SiO_2), with the stop layer of silicon. Then 300-nm silicon in the cavity is etched by accurately control the etching time. The bottom of this cavity is the interface contacted with the flipped gain chip, and the accuracy of silicon etching determines the bonding accuracy in the vertical direction. The second cavity, which has a smaller width (~210 μm) is patterned within the first cavity, as shown in Fig. 4.19(n). Silicon in the second cavity is continuously etched to form a depth of 3 μm . Next, the UBM and Au/Sn solder is deposited by PVD Evaporator. Then a 6- μm thick negative photoresist is spray coated on the top of the wafer, in order to cover the 25- μm deep trench. The UBM consists of 100-nm Ti, 200-nm Pt and 300-nm Au, and the solder consists of 2- μm Au at the bottom, 2.1- μm Sn in the middle and 50-nm Au on the top, thus the total height of metal deposition is 4.75 μm , as shown in Fig. 4.19(o). Following it, the photoresist and the solders on top of the photoresist are removed by lift-off process. Finally, The SiO_2 inside the release window is partially removed by vapor as shown in Fig. 4.19(p). The air gap between the silicon waveguide and the remaining SiO_2 layer can be controlled via the vapor HF etching time.

The gain chip is integrated on the SOI chip by flip-chip bonding. The bonding processes have been presented in Chapter 3.

4.2.2 Fabrication results

Figure 4.20: The SEM graphs of (a) the partially released ring resonator coupled to a bus waveguide; (b) the free-standing arc within the release window, with an initial air gap of 160 nm.

The SEM graph of the free-standing ring resonator is shown in Fig. 4.20(a). The radius of the ring resonator is $30 \mu\text{m}$ and the released window is $65 \mu\text{m} \times 15 \mu\text{m}$. The zoomed view of the arc inside of the released window is shown in Fig. 4.20(b). The air gap g_0 between the free-standing arc and the SiO₂ layer is approximately 160 nm.

Figure 4.21: The SEM graph of the opto-mechanical tunable laser, and the gain chip is flip-bonded onto the SOI substrate.

The SEM graph of the opto-mechanical tunable laser is shown in Fig. 4.21. The nano-waveguide in the external cavity is highlighted with dashed lines. The dimension of the gain chip is $250\text{ }\mu\text{m} \times 250\text{ }\mu\text{m} \times 100\text{ }\mu\text{m}$. The length of the bus waveguide L_m from the taper end to the coupled ring structure is $350\text{ }\mu\text{m}$. For both the bus and the two ring resonators, the waveguide width is 450 nm and the thickness is 160 nm . Ring 1, which is closed to the gain chip, is released. Ring 2 is covered completely by the upper and under cladding. Ring 1 and Ring 2 have a radius of 30 and $29\text{ }\mu\text{m}$, respectively. All the nano-silicon waveguides are highlighted with gray color.

The SEM graphs of the zoom-in view of the coupled ring structure are shown in Fig. 4.22. Ring 1 is partially released and a quarter of its circumference is made free-standing within the $45\text{ }\mu\text{m} \times 25\text{ }\mu\text{m}$ released window, as shown in Fig. 4.22(a). The gap between the bus waveguide and the ring resonator is 200 nm , and the gap between two rings is 305 nm . The zoom-in view of the free-standing arc in

the released window is shown in Fig. 4.22(b). The air gap between the free-standing arc and the residual SiO_2 oxide is 180 nm, which is controlled by the release time of the vapor HF etching process.

(a)

(b)

Figure 4.22: The zoomed-in SEM graphs of (a) the actuated ring resonator with released arc; (b) the free-standing arc in the released window.

4.3 Experiments and discussions

This section presents the experimental results. Firstly, the nonlinear wavelength tuning of the single ring resonator is experimentally demonstrated. Then the wavelength tuning of the opto-mechanical tunable laser is measured and discussed.

4.3.1 Nonlinear wavelength tuning of the single ring resonator

Figure 4.23: The experimental setup for measurement the opto-mechanical wavelength tuning of the sing ring resonator.

The experimental setup which measures the opto-mechanical wavelength tuning of a single ring resonator is shown in Fig. 4.23. Both a control light and a probe light are coupled into and out of the bus waveguide (with mode size converter at the tips) through the two taper fibers. An optical polarization controller is used to select only the TE mode injected into the bus waveguide. The lasing wavelength of the control light is tuned with a 0.01-nm step and the optical power injected into the bus waveguide is maintained at 2.8-mW. The probe light is a broadband light ranging from 1535 nm to 1625 nm, with a power density of -15 dBm/nm. Compared with the control light, the power density of the probe light is weaker and does not generate any optical force. An optical spectrum analyzer with 0.001-nm resolution is used to measure the transmission spectrum of the opto-mechanical nano-actuator.

The measured transmission spectra are shown in Fig. 4.24. A 4-dBm offset power is set for each optical spectrum, in order to differentiate the resonance shift of the single ring resonator clearly. The black lines stand for the response in the spectrum when the broadband probe light passes through the device, without the control light. There are two resonant wavelengths within the interested wavelength range, which are initially at $\lambda_{r0}' = 1598.67$ nm and $\lambda_{r0} = 1601.72$ nm, respectively. At 1601.72 nm, a 9-dB drop of the transmission power is observed. The FWHM bandwidth of the resonance dip is 0.055 nm, corresponding to a loaded Q -factor of 2.88×10^4 .

When the control light λ_c is injected to the nano-actuator, the shift of the resonant wavelength, $\delta\lambda_r$, is detected on the transmission spectrum. As shown in Fig. 4.24(a), the wavelength of the control light λ_c is tuned from the blue detuning side to the red detuning side of λ_{r0} , and the resonant wavelength $\delta\lambda_r$ increases with λ_c . When $\lambda_c = 1603.23$ nm, the resonant wavelength shift $\delta\lambda_{r-\max} = 1.62$ nm is obtained, which is labeled as point P. This critical point P indicates the position of “pull-back”, where the maximum resonance shift is observed. Beyond this point, i.e., as shown in the curve of $\lambda_c = 1603.27$ nm, the resonant wavelength drops to its initial value. In Fig. 4.24(b), the wavelength λ_c of the control light is reversely tuned from the red detuning side to the blue detuning side of λ_{r0} . The resonant wavelength λ_r is approximately maintained at its initial position when $\lambda_c \leq 1602.20$ nm; then the obvious resonance shift, $\delta\lambda_r = 0.54$ nm, is observed, until λ_c is decreased to 1602.19 nm. Beyond this point, the resonance is blue-tuned when λ_c is further decreased.

Figure 4.24: The transmission spectra when the wavelength of the control light λ_c is: (a) red-tuned; (b) blue-tuned.

The results of the simulation and experiment are compared in Fig. 4.25. When the control wavelength λ_c is red and blue tuned, two different groups of resonance shift positions are obtained based on the experiments, which correspond to two groups of stable deflection positions (curves C and curve A as shown in Fig. 4.10). The unstable points (curve B as shown in Fig. 4.10) are not able to be

observed in the experiments. In order to achieve the “pull-back” position, λ_c should be increased to track the red shift of the resonant wavelength. The “pull-back” effect occurs at $\Delta = 1.51$ nm, where the maximum resonance shift $\delta\lambda_{r-\max} = 1.62$ nm.

Figure 4.25: The nonlinear opto-mechanical wavelength tuning controlled by tuning the wavelength of the control light, where the experiments match the simulation well.

According to the simulation of the opto-mechanical wavelength tuning coefficient $\partial\lambda_r / \partial x = 2.3 \times 10^{-2} \exp(1.35 \times 10^{-2} x)$, the corresponding maximum deflection of the arc is 43.1 nm. The positioning resolution of the arc is 0.28 nm, which is obtained with the 0.01-nm wavelength tuning step of the control light. A higher resolution is expected by using a tunable laser with a smaller tuning step. The experimental results are repeatable with a random range of ± 0.05 nm for “pull-back” wavelength λ_c .

4.3.2 Wavelength tuning in the opto-mechanical laser system

The lasing wavelength tuning of the opto-mechanical laser is controlled by the deflection of the free-standing arc of Ring 1. The light which generates the optical gradient force is provided by the tunable laser system itself.

Figure 4.26: The experimental results of the transmission spectrum of the coupled ring structure. The resonance of the fixed ring and the free-standing ring merges at λ_1 , and is differentiated slightly at λ_2 and λ_3 .

The coupled ring resonators serve as the reflective filter in the tunable laser system. Before the measurement of the lasing spectrum, the transmission spectrum of the couple ring resonator structure is studied and shown in Fig. 4.26. A broadband light is coupled in and out of the bus waveguide through the two tapered optical fibers, and the transmission spectrum is detected by an optical spectrum analyzer. The broadband light source covers the range from 1500 to 1610 nm. At $\lambda_3 = 1541.20$ nm, the left resonance-dip comes from Ring 1 (free-standing ring), while the right resonance-dip comes from Ring 2. The detuning between the two resonance-dips is 0.11 nm. A smaller detuning of 0.06 nm is observed at $\lambda_2 =$

1538.30 nm. The resonance-dips of both rings almost merge at $\lambda_1 = 1535.48$. The position of the merged dip stands for the position of the merged peak in the reflection spectrum, which is considered as the lasing wavelength. Once the free-standing waveguide deflects, the dips of Ring 1 are red-shifted while the dips of Ring 2 are kept constant. Therefore, the merged position moves from λ_1 to λ_2 , and then to λ_3 . Consequently, the lasing wavelength is changed from λ_1 to λ_2 and λ_3 , correspondingly.

Figure 4.27: The experimental results of a series of single-mode lasing wavelength under different gain currents.

The lasing wavelength tuning of the opto-mechanical tunable laser is measured. In order to provide different levels of light power, the current of the gain diode is tuned. As a result, the higher the gain current, a higher light intensity is provided inside the tunable laser cavity.

Figure 4.27 shows the single-mode lasing spectrum under different gain currents. When the gain diode works at 235 mA, a single-mode lasing at $\lambda_1 = 1535.48$ nm is observed. Subsequently, $\lambda_2 = 1538.35$ nm and $\lambda_3 = 1541.25$ nm lase

at 245 mA and 260 mA, respectively. The spacing between two adjacent lasing wavelengths is 2.9 nm and the output power increases from -4 to 0 dBm. When the pumping current of the laser diode is increased to 290 mA and 330 mA, the lasing wavelength is tuned to $\lambda_4 = 1524.3$ nm and $\lambda_5 = 1526.7$ nm, and the lasing power is increased to 0.8 dBm and 1.5 dBm, respectively. The achievable SMSR is kept around 30 dB during the opto-mechanical wavelength tuning. Under a constant gain-current, the lasing wavelength is kept stable with negligible wavelength shift due to the high mechanical damping of the free-standing arc. The tolerance for the gain-current fluctuation is ± 5 mA.

Figure 4.28: The process of the single-mode wavelength tuning of the opto-mechanical tunable laser.

When stable lasing is achieved, the wavelength difference between the resonance of the actuated ring and the lasing wavelength is approximately zero. The lasing wavelength changes nonlinearly when the intro-cavity optical power is increased. The coupled ring structure has a 30-nm FSR due to the Vernier effect, thus there are two FSRs within the 3-dB gain spectrum of the laser diode (~ 1510 to

1560 nm). As a result, the tuning of the lasing wavelength is non-monotonic due to the mode competition, and the tuning process is shown in Fig. 4.28, where λ_1 to λ_5 is obtained in the experiments. The acquired tuning range is 24 nm (3000 GHz), which corresponds to a 14-nm displacement of the free-standing arc. Thus the opto-mechanical tuning coefficient is 214 GHz/nm.

Figure 4.29: Experimental results of switch time of opto-mechanical effect. The rise and fall time are 0.90 μs and 0.88 μs , respectively.

Although the gain chip adopted in this design is identical with that applied in the electrically controlled tunable laser (Chapter 3), the tuning range is degraded due to the opto-mechanical tuning mechanism. The wavelength tuning range could be extended through two approaches: (i) to reduce the threshold current of the tunable laser by improving the alignment accuracy of hybrid integration, or by reducing the optical loss in the silicon photonic circuits. (ii) to increase the opto-mechanical tuning efficiency of the free-standing arc, which is achieved by enlarging the length of the free-standing arc or by reducing the vertical gap between the free-standing arc and the dielectric substrate.

The opto-mechanical tunable laser is a self-feedback system. The intra-cavity light at a certain frequency provides optical force which bends the free-standing arc and adjusts the resonance, and the resonance shifting provides feedback to the lasing frequency. The lasing wavelength (frequency) tuning is due to the changing in the gain ability of different frequencies caused by the arc deflection. The equivalence between the intro-cavity optical power and the mechanical displacement of the free-standing arc is broken when the gain current is changed, and then re-built at a new gain level. As a result, the lasing wavelength is tunable through the opto-mechanical effect. The thermal-optic effect is possible to be applied for wavelength tuning along with the opto-mechanical effect. To enable temperature tuning, it requires the metal lines to be patterned upon the silicon dioxide cladding, working as micro heaters. However, the silicon dioxide cladding underneath the metal lines may be etched off during the HF vapor release process, thus the micro heater is possibly disabled. Therefore, special treatments, such as protecting the metal layer with thin Si_3N_4 film, are required during the chip fabrication.

The response speeds of the opto-mechanical effect are measured, as shown in Fig. 4.29. The modulation frequency is set to 200 kHz. The rise and fall time are 0.9 μ s and 0.88 μ s, respectively. The rise and fall time are comparable, at the same level of the thermal-optic switching speed. The opto-mechanical response is determined mainly by the intrinsic spring constant of the free-standing waveguide. A higher tuning speed is expected by optimizing the design of the free-standing waveguide, such as shortening the length of the clam-clam beam, or patterning the photonic waveguides using other materials like Si_3N_4 with higher rigidity.

4.4 Summary

This chapter focuses on the theory, fabrication and experiments of the opto-mechanical tunable laser based on the NSP integrated circuits. The theoretical analysis explores the mechanism of opto-mechanical wavelength of the single-ring nano-actuator and the external cavity tunable laser. The gain diode and the NSP circuits are integrated on a SOI chip with a volume of $3\text{ mm} \times 0.7\text{ mm} \times 0.7\text{ mm}$. In the experiments, a 24-nm tuning range is obtained through deflecting the free-standing arc using optical force which is provided by the intra-cavity optical energy. The deflection of the arc is 14 nm, which corresponds to an opto-mechanical tuning coefficient of 214 GHz/nm. The output power is dependent on the current of the gain diode. The SMSR is 30 dB, and the tuning speed is approximately 1 μs . The innovation of the opto-mechanical tunable laser is summarized as:

- (a) The opto-mechanical nano-actuator is demonstrated for wavelength tuning. The theory for nonlinear opto-mechanical tuning is setup by the force analysis. A “pull-back” phenomenon is proposed for the first time and shown in the experiments. The concept of the opto-mechanical wavelength tuning is utilized in designing a tunable laser. The tuning of lasing wavelength is realized by controlling the deflection of the free-standing waveguide actuated by the optical gradient force.
- (b) This is the first effort to develop a tunable laser whose lasing wavelength is tuned by all-optical method, instead of electrical methods. In contrast to the electrical wavelength tuning, the opto-mechanical tuning is potentially able to avoid the problems thus as electrical circuit designs and thermal dissipation issues. Although the 24-nm tuning range and 30-dB SMSR are not as good as the electrically controlled tunable laser presented in Chapter

3, the performance of the opto-mechanical tunable lasers could be improved with a larger opto-mechanical tuning coefficient, which is achievable by refining the design of the free-standing arc, or precisely controlling the HF etching process.

CHAPTER 5

RING CAVITY TUNABLE LASER

This chapter presents the design, fabrication and experiments of a ring cavity tunable laser using NSP circuits. The ring cavity consists of a semiconductor optical amplifier (SOA) chip, a closed main-loop, a U-shape sub-loop and two separated micro ring resonators. The unidirectional operation of the ring laser is made possible by using the specially designed NSP sub-loop. In this chapter, firstly, the schematic and working principle are introduced, followed by the numerical simulations for the ring laser parameters; then the fabrication and fabrication results are presented; finally, the experimental results such as the unidirectional operation effect, the spectrum purity and the wavelength tuning are discussed in details.

5.1 Design of the ring cavity tunable laser

The primary advantage of the ring external cavity configuration is the increased suppression of diode cavity resonances by reducing the reflections on both facets. When the unidirectional operation is achieved, the standing-wave interference pattern does not occur in the laser gain medium, and consequently the spatial hole burning is limited. In this way, stable single frequency emission can be obtained. In this design, the NSP circuits are utilized to construct all the functional elements required in a ring laser, i.e., filters, couplers, isolators, etc.

5.1.1 Schematic of the ring cavity tunable laser

Figure 5.1: Schematic illustration of the ring cavity tunable laser with NSP circuits: the sub-loop enables the unidirectional propagation, and the resonant wavelength of the two ring resonators is thermally tuned.

The schematic of the ring cavity tunable laser based on the NSP circuits is illustrated in Fig. 5.1. The tunable laser is constructed on a SOI platform, which

consists of a SOA chip to provide gain, and an external cavity based on NSP integrated circuits to select and tune the output wavelength. Both facets of the SOA chip are anti-reflection coated with a reflectivity of $< 0.1\%$. The output waveguide is tilted by 12° to avoid the facet reflection to the gain medium. The external photonic circuits, including a closed main-loop, a U-shape sub-loop and two ring resonators, are formed by silicon waveguides of 450 nm in width and 220 nm in height. The two ring resonators, with radii of 60 μm and 62 μm respectively, work as the wavelength filters, to ensure an above 40 nm single-mode tuning range based on the Vernier effect. The lasing wavelength is tuned by changing the refractive index of the ring resonator, by applying the thermal-optic effect. Light is coupled out from the closed loop with a waveguide splitter. The gap between the parallel waveguides is 300 nm and the coupling length is 10 μm , and $\sim 10\%$ optical power is coupled out from the closed ring cavity. Both the clockwise (CW) and the counterclockwise (CCW) waves are able to be coupled out, and the CCW is the preferred direction.

An attractive approach to achieve an efficient single-frequency operation is realized by eliminating the spatial hole burning effect in the gain medium via unidirectional configurations. Traditional optical isolators are separated elements, and have intrinsic limitations when integrated with the photonics waveguide circuits. In this design, the U-shape sub-loop serves as an optical isolator for the unidirectional operation, utilizing the merit of flexibility of NSP circuits. The special advantages of this NSP sub-loop design are not only the flexible integration with other NSP circuits, but also the capability for easy fabrication.

5.1.2 Design of the Y-junction

To realize the isolation function of NSP circuits, the U-shape sub-loop converts part of the CW wave to the CCW wave. The Y-junction structure, which connects the U-shape sub-loop with the main-loop, serves as an optical splitter and a combiner as well. The U-shape sub-loop consists of at least two Y-junctions. The amount of Y-junctions shared by the main-loop and the sub-loop is N , where $N = 0, 2, 3, \dots, m$ ($N = 1$ is impossible). In Fig. 5.1, three Y-junctions are shared by both the main-loop and the sub-loop, thus $N = 3$.

Figure 5.2: Schematic of the Y-junction, which serves as the optical splitter and combiner.

As shown in Fig. 5.2, the Y-branch waveguide structure works as a 1×2 optical splitter and a 2×1 combiner. C-O-A is the section in the main-loop, while O-B is the section in the sub-loop. The Y-junction is wavelength independent, thus is suitable for the widely tuned laser. The splitting and combining effects of the Y-junction structure are studied using the beam propagation method (BPM), and only TE polarization propagation wave is considered.

Assume the optical power in the combined waveguide is normalized to 1, $P_{S2} = x$ is coupled to the sub-loop, while $P_{S1} = 1-x$ remains in the main-loop. The power split ratio is thus $(1-x)/x$ when the Y-junction serves as a splitter. Consequently, the CW wave is partially coupled to the U-shape sub-loop via the Y-junction splitter; then, the partially coupled wave is combined back to the main-loop and converted to the CCW wave by the Y-junction combiner. On the contrary, the CCW wave is designed to be never coupled out by the Y-junctions, which will be detailed in the consequent paragraphs.

Figure 5.3: The optical combining effect of the Y-junction. The combined power is dependent on the power ratio in the two branches of the Y-junction.

For the Y-junction combiner, a unique design is made to reduce the loss during combining the light in these two branches. The waveguides in the sections of CO and OB are the single-mode waveguide with a 450-nm width. The waveguide in the section of OA allows the propagation of the multiple modes. Its length is 300 μm and its width increases from 450 nm to 2000 nm and then decreases to 450 nm again. The optical combining effect of the Y-junction is shown in Fig. 5.3. The x -

axis represents for the optical power ratio between the two branches BO and AO, and the y-axis stands for the combined power. When the power ratio increases from 0 to 1, the combined power varies from 0.69 to 0.985. The peak value 0.985 occurs when the power ratio between the two branches is around 0.5. This result indicates that a certain optical loss happens when the light passes through the Y-junction combiner.

5.1.3 Analysis of unidirectional operation

The number of N affects the optical isolation effect of the U-shape sub-loop. Initially, the CCW and the CW waves obtain identical gain in the SOA, which is normalized to 1 for simplicity. As a result, the optical powers emitted from the two facets of the SOA are identical. After one round-trip in the ring cavity, the power of the CCW and CW waves is changed due to the difference in light paths. The gain coefficient of the CW wave is expressed as $g_{CW} = (1-x)^n$, when $N = n$. The gain coefficient of the CCW wave g_{CCW} is much more complex, which is derived as following.

When $N = 2$, the gain coefficient of the CCW wave g_{CCW} is expressed as

$$g_{CCW}|_{N=2} = \beta^2 + x\beta^2 + x(1-x)\beta, \quad (5.1a)$$

where $\beta = \beta(2, x)$ is the average value of the pass-through coefficient of the Y-junction combiners when $N = 2$, $1-\beta$ indicates the optical loss at the Y-junction combiners, x is the portion split to the sub-loop at the Y-junction splitter. Consequently, the intra-cavity gain coefficient ratio between the CCW and CW waves is expressed as

$$\left. \frac{g_{CCW}}{g_{CW}} \right|_{N=2} = \frac{\beta^2 + x\beta^2 + x(1-x)\beta}{(1-x)^2}. \quad (5.1b)$$

When $N = 3$,

$$g_{CCW}|_{N=3} = (1+x+x(1-x))\beta^3 + x(1-x)^3\beta^2 + x^2(1-x)^2\beta, \quad (5.2a)$$

$$\left. \frac{g_{CCW}}{g_{CW}} \right|_{N=3} = \frac{(1+x+x(1-x))\beta^3 + x(1-x)^3\beta^2 + x^2(1-x)^2\beta}{(1-x)^3}. \quad (5.2b)$$

Similarly, when $N = n$, the equations are derived as

$$\begin{aligned} g_{CCW}|_{N=n} &= \beta^n + x(1-x)^{n-2}\beta^2 + x(1-x)\beta^{n-1} \\ &\quad + x^2\beta^2[(1-x)^{n-3}\beta + (1-x)^{n-4}\beta^2 + \dots + (1-x)^0\beta^{n-2}] \\ &\quad + x\beta[(1-x)^{n-1}\beta^1 + (1-x)^{n-2}\beta^2 + \dots + (1-x)^2\beta^{n-2}], \end{aligned} \quad (5.3a)$$

$$\begin{aligned} \left. \frac{g_{CCW}}{g_{CW}} \right|_{N=n} &= \frac{\beta^n + x(1-x)^{n-2}\beta^2 + x(1-x)\beta^{n-1}}{(1-x)^n} \\ &\quad + \frac{x^2\beta^2[(1-x)^{n-3}\beta + (1-x)^{n-4}\beta^2 + \dots + (1-x)^0\beta^{n-2}]}{(1-x)^n} \\ &\quad + \frac{x\beta[(1-x)^{n-1}\beta^1 + (1-x)^{n-2}\beta^2 + \dots + (1-x)^2\beta^{n-2}]}{(1-x)^n}, \end{aligned} \quad (5.3b)$$

which are further simplified as

$$\begin{aligned} g_{CCW}|_{N=n} &= \beta^n + x(1-x)\beta^{n-1} + x(1-x)^{n-2}\beta^2 \\ &\quad + \frac{[x^2(1-x)^{n-2}\beta^3 + x(1-x)^n\beta^2] \cdot [1 - (1-x)^{2-n}\beta^{n-2}]}{(1-x-\beta)}, \end{aligned} \quad (5.4a)$$

$$\begin{aligned} \left. \frac{g_{CCW}}{g_{CW}} \right|_{N=n} &= \frac{\beta^n + x(1-x)\beta^{n-1} + x(1-x)^{n-2}\beta^2}{(1-x)^n} \\ &\quad + \frac{[x^2(1-x)^{n-2}\beta^3 + x(1-x)^n\beta^2] \cdot [1 - (1-x)^{2-n}\beta^{n-2}]}{(1-x)^n(1-x-\beta)}, \end{aligned} \quad (5.4b)$$

where $\beta = \beta(n, x)$ is the average value of the pass-through coefficient of the Y-junction combiners when $N = n$.

Figure 5.4 shows the simulation results based on Eq. 5.4 (a) and (b). It

shows the normalized gain coefficient value of the CCW wave g_{ccw} and the gain coefficient ratio between the counter-directional waves g_{ccw}/g_{cw} , after one round trip in the ring cavity. Both g_{ccw} and g_{ccw}/g_{cw} are dependent on the amount of N . After a single round-trip, the gain coefficient ratio in the counter-directions increases from 1 to above 30 when N is increased from 0 to 6 ($N = 1$ is not achievable). This indicates the ability for unidirectional operation is enhanced when N is increased. However, the increase of N also increases the optical loss for the CCW wave in the main-loop, because the CCW wave experiences a certain loss $1-\beta$ when passing through every Y-junction, as indicated in Fig. 5.3. Considering the value of g_{ccw} , it has a maximum value of 1.64 at $N = 3$. In other words, the CCW light achieves the highest gain in a single round-trip as the Y-junctions number is $N = 3$, corresponding to the lowest threshold current of the laser system.

Figure 5.4: The normalized gain coefficient g_{ccw} and the gain coefficient ratio g_{ccw}/g_{cw} between the counter-directional waves, and both of them are dependent on the Y-junctions number N .

5.2 Simulation of the ring cavity tunable laser

This section studies the properties of the ring cavity tunable laser theoretically.

5.2.1 Properties of the single-mode wavelength selection

In this design, there are two separated ring resonators with a slight radii difference, working as the wavelength filters due to the Vernier Effect. The wavelength selection is determined by these two separated ring resonators, and the filter functions for Ring 1 and Ring 2 are expressed as

$$\frac{E_{out1}}{E_{in1}}(\lambda) = \frac{-\kappa^2 e^{\frac{-\alpha L_1}{2}} e^{\frac{-j\beta L_1}{2}}}{1 - t^2 e^{-\alpha L_1} e^{-j\beta L_1}}, \quad (5.5a)$$

$$\frac{E_{out2}}{E_{in2}}(\lambda) = \frac{-\kappa^2 e^{\frac{-\alpha L_2}{2}} e^{\frac{-j\beta L_2}{2}}}{1 - t^2 e^{-\alpha L_2} e^{-j\beta L_2}}, \quad (5.5b)$$

where α is the power absorption coefficient in the guided waveguide, $\beta = 2\pi n_{\text{eff}}/\lambda$ is the propagation constant, $L_i = 2\pi R_i$ ($i = 1, 2$) is the round trip length of the two ring resonators, r is the cross-coupling coefficient, and κ is the self-coupling coefficient. Therefore, κ^2 and r^2 are the power splitting ratios of the coupler, and $\kappa^2 + r^2 = 1$. The electrical field after passing the two ring resonators is expressed as

$$\frac{E_D}{E_{in}} = \frac{\kappa^4 e^{\frac{-\alpha(L_1+L_2)}{2}} e^{\frac{-j\beta(L_1+L_2)}{2}}}{(1 - t^2 e^{-\alpha L_1} e^{-j\beta L_1})(1 - t^2 e^{-\alpha L_2} e^{-j\beta L_2})}. \quad (5.6)$$

(a)

(b)

Figure 5.5: The transmission spectrum of the wavelength filtering effect: (a) the FSR of the double-ring filter is 51 nm, (b) the FSR of Ring 1 is 1.6 nm.

The mode spacing of the ring cavity tunable laser is determined by the total cavity length, which is expressed as:

$$\Delta\lambda_{\text{mode}} = \frac{\lambda^2}{nL_{\text{tot}}} = \frac{\lambda^2}{n_{\text{int}}L_{\text{int}} + n_{\text{eff}}[L_{e1} + L_{e2}]} . \quad (5.7)$$

where L_{int} is the physical length of the SOA, n_{int} the effective refractive index of the active waveguide, L_m is the physical length of the bus waveguides in the external NSP circuits, n_{eff} the effective refractive index of the nano-silicon waveguide. L_{e1} , L_{e2} is the effective waveguide length of ring resonator 1 and 2 respectively, which can be expressed as

$$L_{ei} = 2\pi r_i \left(0.5 + \frac{1 - \kappa^2}{\kappa^2}\right), \quad i = 1, 2. \quad (5.8)$$

According to the principle of wavelength selection in the external cavity tunable laser, the mode spacing of the tunable laser is constant since cavity length change induced by the effective index change can be neglected, when the peak wavelength of the filter is tuned.

The transmission spectrum is determined by both of the two resonators. Fig. 5.5 shows the transmission spectrum when $\kappa^2 = 0.1$. Due to the Vernier effect, the free spectrum range of the double-ring-filter is 51 nm, as shown in Fig. 5.5 (a). It ensures a 51-nm single-mode operation range without mode hopping. The maximum transmission at 1560.02 nm has a peak value of -1.9 dB, which is 6.2 dB higher than its adjacent side modes. Compared with the coupled ring structure, the loss margin between the main and the side modes is larger, and thus higher SMSR is expected for the lasing spectrum. The optical spectrum of Ring 1 ranging from 1550 nm to 1570 nm is shown in Fig. 5(b), where the FSR of Ring 1 is 1.6 nm.

In order to achieving a stable and pure single-mode operation, the relationship between the full width at half maximum (FWHM) of the filter spectrum and the longitude mode spacing is required to satisfy [2]

$$\frac{1}{2} FWHM \leq \Delta\lambda_{\text{mode}}. \quad (5.9)$$

For the add-drop ring resonator, the FWHM at the resonance is expressed as

$$FWHM = \frac{(1 - ar^2)\lambda^2}{\pi n_g L r \sqrt{a_r}}. \quad (5.10)$$

where a_r is the single-pass amplitude transmission, and is expressed as $a_r^2 = \exp(-\alpha L)$, where α is optical absorption coefficient, and L is the circumference of the ring resonator.

Figure 5.6: The calculation of the FWHM of the filter and the longitude mode spacing of the ring cavity $\Delta\lambda_{\text{mode}}$, dependent on the coupling coefficient κ^2 of the ring resonator and the physical length of the bus waveguides in the ring cavity L_m .

The FWHM of the filter spectrum and the longitude mode spacing of the ring cavity $\Delta\lambda_{\text{mode}}$ are shown in Fig. 5.6. The black curve stands for the value of the half FWHM. It is obvious that the condition shown in Eq. 5.9 is harder to be satisfied for longer L_m . The conventional ring cavity tunable laser usually has a cavity length of above 100 mm, thus the pure single-mode operation is hard to be obtained. However, the operation of pure single-mode can be easily achieved with such a waveguide-based laser, benefitting from the compact size of the NSP

circuits. For example, Eq. 5.9 can be satisfied as long as $\kappa^2 < 0.3$ as $L_m = 5$ mm. It is an important advantage of the ring cavity tunable laser proposed with this design.

The quality factor (Q -factor), indicating the sharpness of the resonance at the central wavelength, is expressed as

$$Q = \frac{\lambda}{FWHM_i} = \frac{\pi n_g L_i r \sqrt{a_r}}{(1 - a_r r^2) \lambda}. \quad (5.11)$$

Figure 5.7: The Q -factor of the ring resonator, determined by the optical transmission loss of the waveguide and the radius of the ring resonator.

It is crucial to reduce the round trip loss in the cavity and to increase the Q -factor. The propagation loss is diminished through adopting a high quality SOI wafer and optimizing the fabrication processes. Higher Q -factor can be obtained with larger L and smaller a_r . However, the accumulated propagation loss increases with increasing the cavity length, since a_r increases with L . Fig. 5.7 shows the relationship between the Q -factor and the radius of the ring resonator when $\kappa^2 = 0.15$.

Figure 5.8: The quality factor of the ring resonator, as well as the normalized optical transmission, as a function of the power coupling coefficient κ^2 .

The quality factor of the ring resonator and the normalized optical transmission, as a function of κ^2 , are shown in Fig. 5.8. The solid lines and the dash lines stand for the conditions when the optical transmission loss in the waveguide is 1.5 dB/cm and 10 dB/cm respectively. The Q -factor decreases with κ^2 , while the value of the normalized optical transmission increases with κ^2 . At the conditions of $\kappa^2 = 0.1$ and the optical transmission loss is 1.5 dB/cm, the Q -factor is 1.3×10^4 and the transmission power is 88%, both of which are suitable to serve as a wavelength filter in an external cavity tunable laser.

5.2.2 Parameters of the ring cavity laser

The external feedback in a ring cavity is characterized by a wavelength dependent coupling strength $C_{ccw}(\lambda)$, which presents the fraction of the field amplitude from the left facet that is coupled into right facet of the SOA in the CCW direction. For this ring cavity tunable laser, with the intra-cavity U-shape sub-loop

which works as an optical isolator, the nonreciprocal coupling strength can be achieved, that is, $C_{CCW}(\lambda) \gg C_{CW}(\lambda)$, and

$$C_{CCW}(\lambda) = C_{m1}C_{m2}C_p t_{r1}t_{r2}t_w g_{CCW}, \quad (5.12)$$

$$C_{CW}(\lambda) = C_{m1}C_{m2}C_p t_{r1}t_{r2}t_w (1-x)^n, \quad (5.13)$$

where C_{m1} and C_{m2} are the coupling coefficient between the internal cavity and the photonic external cavity at two facets, respectively; C_p is the power ratio remaining in the main ring cavity at the output coupler, t_{r1} and t_{r2} are the transmission coefficient when considering the optical loss in two ring resonators, and t_w is the total loss in the guiding waveguide of the ring cavity. The maximum value is achieved at the resonance of the ring resonator. All other elements are wavelength independent, and considered as constant in this specially designed cavity.

The large loss margin $\Delta\alpha$ between the main and side modes is necessary for a high SMSR.

$$\Delta\alpha = \frac{1}{L_{\text{int}}} \ln\left(\frac{T_0}{T_1}\right), \quad (5.14)$$

where T_0 and T_1 are the transmission of the ring resonator for the main and the first side modes. Assuming the main mode is located at the ring resonance wavelength, a loss margin of 6 dB is high enough to obtain a 40-dB SMSR with a 25-mW intracavity optical power.

Figure 5.9: The loss margin $\Delta\alpha$ between the main mode and side mode, as a function of the power coupling coefficient κ^2 .

As shown in Fig. 5.9, the loss margin $\Delta\alpha$ decreases exponentially with the power coupling coefficient κ^2 . Supposed that κ^2 increases from 0.01 to 0.4, the loss margin decreases from 25 dB to 1.5 dB. Although the largest margin loss is expected to be obtained when κ^2 is approaching to 0, the transmission power after passing the ring resonator is also approaching to 0. Such a situation is thus not acceptable due to the huge optical loss. The optimized value of κ^2 is chosen by considering the tradeoff between the margin loss (correspond to SMSR), the Q -factor value, and the transmission power. For an optimized laser performance, the value of κ^2 is set to 0.05 to 0.15.

Figure 5.10: SMSR varies with the bus-to-waveguide power coupling coefficient κ^2 under different mirror coupling efficiency C_m , where the total power in the cavity is 25 mW.

Figure 5.11: Linewidth of the output laser varies with the bus-to-waveguide power coupling coefficient κ^2 under different mirror coupling efficiency C_m , where the total power in the cavity is 25 mW.

The value of the SMSR is determined by the mirror coupling efficiency C_m and the bus-to-ring power coupling coefficient κ^2 . The simulation results as the total intra-cavity power is 25 mW are shown in Fig. 5.10. The mirror coupling efficiency C_m , in terms of the percentage of the optical power remaining in the ring cavity main-loop after passing the 2×2 waveguide coupler, is a key parameter that affects the SMSR. A higher SMSR requires a smaller C_m . As the value of κ^2 varying between 0.02 and 0.13, the SMSR can be kept above 50 dB when C_m is 0.1.

The value of the linewidth, in terms of C_m and κ^2 , is shown in Fig. 5.11. The narrower laser linewidth is obtained with smaller κ^2 , because a smaller κ^2 corresponds to a longer effective external cavity length as the light travels a longer time in the ring resonators. The linewidth is controlled to be <100 kHz supposed the condition $\kappa^2 < 0.2$ is satisfied.

5.3 Fabrication and Packaging

The fabrication process flow of the ring cavity tunable laser has been illustrated in Chapter 3. There are still some special treatments to be mentioned. The wavelength tuning is controlled by using the electrical method, and only the thermal-optic effect is adopted for simplicity. The nano-silicon waveguide is patterned to the channel shape rather than the rib-waveguide, thus the additional optical loss caused by the refractive index discontinuity at the channel-rib interface is avoided. The active waveguide of the SOA chip is bent with 12.5° in order to avoid the reflection at the left facet. The nano-silicon waveguide is therefore designed to an arc with an identical angle to match the optical modes at the coupling region.

Figure 5.12: The SEM graph of the ring cavity tunable laser, which integrates the SOA chip and the NSP circuits.

(a)

(b)

Figure 5.13: The zoom-in SEM graphs of (a) the region where the active waveguide is coupled with the passive waveguide; (b) Ring 2 with metal micro heater and electrical pads on top of the upper cladding SiO_2 .

The overview of the SEM graph of the ring cavity tunable laser, which integrates the SOA chip and the NSP circuits, is shown in Fig. 5.12. The SOI chip has dimension of $3 \text{ mm} \times 1.5 \text{ mm} \times 0.7 \text{ mm}$, and the SOA chip has a dimension of $650 \text{ } \mu\text{m} \times 250 \text{ } \mu\text{m} \times 100 \text{ } \mu\text{m}$. The metal pads and electrodes, which are used for

electrical connection, are highlighted with the yellow color. The integrated ring cavity tunable laser presented in Fig. 5.12 includes 3 Y-junctions in the main-loop. The overall optical waveguide length (without the two ring resonators) is 4.5 mm. The radii for Ring 1 and Ring 2 are 60 μm and 62 μm , respectively. Both the CW and CCW waves are coupled out of the main-loop of the ring cavity, via the 2×2 waveguide coupler. The coupling gap is 250 nm and the radius of the arc is 120 μm , both of which determine the coupling coefficient to be 0.1. It means that 10% optical power is coupled out of the cavity, while 90% of the optical power remains in the ring cavity.

Figure 5.13(a) presents the zoom-in view of the region where the active waveguide is coupled with the passive waveguide. The active waveguide, parallel with the nano-silicon waveguide, lies at the bottom of the flipped chip. The tapered nano-silicon waveguide is clad by SiO_2 , and the width for the SiO_2 cladding is 6 μm . The gap between the facet of the active waveguide and the tapered nano-silicon waveguide is approximately 5 μm , which is enough to control the optical loss within 2 dB (supposed the perfect alignment in both the vertical and lateral directions). After the hybrid packaging process, the vertical misalignment can be controlled to 100 nm due to the specially developed etching process for the designed cavity, and the lateral misalignment is estimated to be smaller than 300 nm. The zoom-in view of Ring 2 is shown in Fig. 5.13(b), with metal lines and electrical pads on top of the upper cladding SiO_2 . The ring resonator under the SiO_2 cladding is highlighted with a green color. The metal lines, which serve as heaters, have a width of 1.8 μm and a line-line gap of 1.8 μm .

5.4 Experimental results and discussion

This section presents and discusses the experimental results of ring cavity tunable laser. The experiments are carried out in three consecutive steps: the unidirectional operation effect of different sub-loop designs is measured and compared; followed by measuring the single mode properties and the spectrum purity as applying the device with the optimized sub-loop design; the widely wavelength tuning capability is demonstrated at last.

During the lasing experiment, the packaged tunable laser is placed on a sub-mount, connecting with a thermoelectric cooler, and the working temperature is kept constant at 25 °C. The emitted light is collected using a lens fiber, and measured by the optical spectrum analyzer. The SOA has a typical 3-dB bandwidth of 65 nm, a small signal gain of 17 dB at peak wavelength, and a saturation output power of 10 dBm. When the SOA current is 170 mA, the gain spectrum of the SOA is centered at 1520 nm, with a 3-dB spectrum range of 1495 - 1558 nm.

5.4.1 Effect of the unidirectional operation

The effect of unidirectional operation under different U-shape sub-loop designs is tested, and the different P-I curves under different Y-junctions numbers are also included. The effects of the U-shape sub-loops are manifested in several aspects: (a) to affect the threshold current of the CCW and CW waves; (b) to determine the output power of the CCW and CW waves; (c) to determine the output power ration between the CCW and the CW waves. (d) to affect the slop efficiency of the P-I curve of the laser. During the experiments, the output of both the CW and CCW directions are monitored by an optical spectrum analyzer.

Figure 5.14: The output power versus the SOA current for the CCW wave when the Y-junction number is $N = 0$ (no sub-loop).

Figure 5.15: The output power versus the SOA current for the CCW and the CW propagating waves when the Y-junction number is $N = 2$.

Figure 5.16: The output power versus the SOA current for the CCW and the CW propagating waves when the Y-junction number is $N = 3$.

Figure 5.17: The output power versus the SOA current for the CCW and the CW propagating waves when the Y-junction number is $N = 4$.

During the absence of any U-shape sub-loop, the ring cavity laser works in a bi-directional manner, and both directions has similar performance with slight

differences and can be fitted with an identical curve. The P-I experimental curve of the CCW wave is shown in Fig. 5.14. The threshold current is 245 mA, and is saturated in both directions at 310 mA, and the corresponding saturation power P equals to 185 mW. A slope efficiency of 4.3- μ W/mA is in the stimulation region. In the saturation region, the output power increases slightly with the increase of the SOA pumping current.

To obtain unidirectional operation, the CW wave is partially converted to the CCW wave via the U-shape sub-loop. The experimental results of P-I curves in the counter-directions are shown in Fig. 5.15 - 5.17, where the number N of the Y-junctions is 2, 3 and 4 consecutively. For the CW light, the threshold current is 258, 282, 290 mA, and the saturation power is 162, 142, 90 μ W, consecutively. For the CCW wave, the threshold current is 223, 210, and 233 mA, and the saturation power is 585, 960, 920 μ W, when $N = 2, 3$ and 4 consecutively.

It is obvious that the CCW wave is enhanced while the CW wave is suppressed using the U-shape sub-loop. This unidirectional effect is enhanced by the increases of N : the saturation power ratio between the CCW and CW waves is 3.61, 6.83, 9.38, consecutively when $N = 2, 3$ and 4. The CCW is the preferred light propagation direction with the merits of lower threshold current, higher saturation output power, and large slop efficiency. At higher SOA current, the lasing power saturation occurs due to the reduction of the net gain for the single-mode lasing. In addition, the mode-competition results in the power saturation and the broadening of the laser linewidth at high operating powers.

Figure 5.18: Comparison of the P-I curves of CCW wave when $N = 0, 2, 3, 4$.

The comparison of P-I curves of the CCW wave at different Y-junction numbers is plotted in Fig. 5.18. The four curves stands for $N = 0, 2, 3, 4$. The ring laser is under bi-directional operation at $N = 0$, and unidirectional operation at $N \geq 2$. For the CCW wave, the lowest threshold and the highest output power, and the highest slope efficiency occurs as $N = 3$, which is explained by the simulation results shown in Fig. 5.4: the round trip gain of the CCW wave obtains its maximum value when $N = 3$, corresponding to the lowest intra-cavity optical loss.

5.4.2 Single-mode properties at $N = 3$

Based on the discussion above, the optimized Y-junction number is $N = 3$ for the ring cavity tunable laser, considering the output power, threshold current and slope efficiency. Consequently, the following experiments are operated with the design of $N = 3$.

Figure 5.19: The optical spectra of the CCW and CW output at different SOA currents ($N = 3$): (a) 280 mA, (b) 310 mA and (c) 360mA.

The unidirectional effect, as well as the single-mode spectrum purity of the CCW wave, is dependent on the SOA current. A series of CCW and CW lasing spectra, are observed as the SOA current is set to 280 mA, 310 mA and 360 mA, and these three spectra are shown in Fig. 5.19.

Assume the CCW light works at its saturation status with the maximal output power and the highest SMSR, simultaneously the CW light works below its threshold, this situation is considered as ideal unidirectional effect. Fig. 5.19(a) shows the lasing spectrum from 1500 to 1550 nm when the SOA current is 280 mA. The CCW wave works at the single-mode status: the lasing wavelength is 1524.82 nm with a 945 μ W peak power and a 50.5 dB SMSR. The CW wave is not stimulated. The counter-propagation wave suppression ratio (CWSR), P_{ccw}/P_{cw} , is 55.5 dB, which means that the ideal unidirectional operation is achieved.

Figure 5.20: Experiments of the CWSR, P_{ccw}/P_{cw} , as the function of the SOA current.

When the SOA current is increased to 310 mA, both the CCW and CW waves are working at the single-mode status, as shown in Fig. 5.19(b). The CWSR

between the CCW and CW waves decreases to 8 dB. When the SOA current is increased to 360 mA, the optical spectrums are as shown in Fig. 5.19(c). The high-level gain in the laser cavity allows the stimulation of the side modes after the saturation of the main mode, for both the CCW and the CW wave. The CWSR between the CCW and CW waves is 7.5 dB, and the SMSR for both the CCW and CW waves is heavily degraded.

The CWSR, P_{ccw}/P_{cw} , is a function of the SOA current, as shown in Fig. 5.20. The corresponding SOA current working range is from 225 to 280 mA, when the CWSR > 40 dB is chosen as the criterion for the unidirectional operation. The CWSR is decreased to 7.5 dB when the SOA current is increased above 310 mA. Specifically, the CWSR is kept at its maximal value of 55 dB, when the CCW wave works in saturation status and the CW wave is under threshold, where the SOA current range is 255 ~ 270 mA.

Figure 5.21: Based on the single-mode performance, the working status of the ring cavity tunable laser is divided into 4 periods, as noted with P₁-P₄.

Taking the CCW wave for illustration only, the working status of the ring cavity laser has four periods according to the single-mode CCW wave spectrum, as shown in Fig. 5.21. In period 1 (200 ~ 209 mA), the CCW wave are operated under threshold. In period 2 (210 ~ 254 mA), the CCW wave works in the stimulated status, with a slop efficiency of 16.2 $\mu\text{W}/\text{mA}$, and the SMSR of the CCW wave increases with SOA current. In period 3 (255 mA ~ 330 mA), the CCW wave works in the saturation status, and the SMSR is kept at above 50 dB. In period 4 (> 330 mA), the CCW wave is operated far above the threshold current, thus the side modes are stimulated besides the main mode due to the extra-high gain level, and the SMSR is decreased to below 50 dB accordingly as well. Considering both the output power and the SMSR performance, the laser shows best performance in period 3, during which the lasing wavelength shows the best spectral purity. According to Fig. 5.20 and Fig. 5.21, the optimized range for the SOA current is 255~280 mA, during which the satisfied unidirectional operation, the high output power, and the high SMSR are realized.

The linewidth is tested using the heterodyne beating method, and the results are shown in Fig. 22. The heterodyne beating method has the advantages of simple setup, with the absence of long-distance optical fiber and the acoustic modulator. However, it requires that the two beating lasers have comparable output power, and the linewidth of the reference laser is smaller or comparable with that of the laser under testing.

The ring laser is operated at 280 mA, and the CCW light is coupled to a 3-dB coupler, and a commercial tunable laser (Ando AQ4321) worked at 1528.82 nm serves as the reference light. The two beams are combined and sent to the photo-detector and then to the electrical spectrum analyzer. The pump current is supplied

by a source measure unit (Keithley 236), which provides stable current performance and reduces the electrical noise due to current fluctuation. In addition, the working temperature of the gain chip is precisely controlled at 25 °C during the experiments, thus the Gaussian contribution to the laser linewidth is significantly limited. The laser lineshape is considered as approximately Lorentzian for simplicity of analysis.

Figure 5.22: Linewidth measurement of the CCW wave lased at 1524.82-nm, a laser with a narrow linewidth is chosen as the reference.

The beating linewidth is equal to the sum of the linewidths of both lasers, i.e., $\Delta\nu = \Delta\nu_i + \Delta\nu_c$, where $\Delta\nu_i$ is the linewidth of the laser under testing, and $\Delta\nu_c$ is the linewidth of the commercial reference laser. The observed linewidth from the spectrum analyzer is $\Delta\nu = 280$ kHz, while the linewidth of the reference laser is $\Delta\nu_c = 100$ kHz, thus the linewidth of the ring cavity tunable laser under testing is 180 kHz.

5.4.3 Wavelength tuning properties

Figure 5.23: The combined optical spectra of a series of single-mode output with a tuning range from 1501.82 nm to 1557.21 nm.

After demonstration of the unidirectional effect and single mode properties, the wavelength tuning properties of the ring laser are measured. The wavelength tuning experiments are conducted within the optimized current range (255-280 mA). A series of spectra for single mode CCW output are obtained by applying the thermal voltage to the micro heater on Ring 2.

The combined optical spectra for wavelength tuning are shown in Fig. 5.23. The acquired wavelength covers the range from 1501.82 nm to 1557.21 nm, with a 55.4 nm tuning range and a frequency space of 1.62 nm. The output power is kept above -2 dBm as the wavelength ranging from 1504 nm to 1540 nm, but is degraded obviously when the wavelength is larger than 1540 nm, due to the lowered gain level. The wavelength between 1554 nm and 1557.2 nm is missed during the wavelength tuning, because the gain level at this wavelength is much lower than at

the central wavelength. As a result, the lasing at this wavelength is easily inhibited due to the mode competition.

Figure 5.24: The relationship between the output wavelength and the thermal optical voltage.

The wavelength tuning process is shown in Fig. 5.24. The lasing wavelength increases from 1548.94 nm to 1557.21 nm, when the thermal voltage is increased from 0.79 to 0.98 V; the wavelength increases from 1501.825 nm to 1548.94 nm, when the thermal voltage is increased from 1.03 V to 1.725 V. The identical output wavelength at 1548.94 is obtained at both 0.79 and 1.725 V, thus one entire tuning period is acquired. This 55.4-nm wavelength tuning period corresponds to the free spectrum range of the double-ring-resonator filter.

The wavelength tuning of the presented tunable laser is discontinuous when Ring 1 works as a reference filter and the effective refractive index of Ring 2 is tuned through thermal-optic effect. The quasi-continuous wavelength tuning could be achieved when both ring resonators are thermally tuned. In this way, most

wavelengths are obtainable within the gain spectrum. The tuning of both ring resonators is more complex, which requires precise control and cooperation of two power supplies.

Figure 5.25: The SMSR versus the output wavelength of the CCW wave.

The performance of the SMSR at different output wavelengths is shown in Fig. 5.25. The SMSR of the CCW wave is dependent on the gain profile of the SOA. The SMSR is above 50 dB when the wavelength is tuned from 1508 nm to 1537 nm, but decreases to below 50 dB when the wavelength is tuned outside this range. The reason is that the gain profile of the SOA is approximately parabolic, and the center wavelength is 1525 nm. Benefitting from the large gain difference brought by the two separated ring resonators, the SMSR is still kept above 44-dB even at the edges of the gain spectrum.

In the experiments, the single-mode lasing shows excellent spectral purity (180 kHz linewidth, and 50 dB SMSR). Two contributions give rise of such an attractive performance. The first contribution is the ring cavity configuration that

both facets of the SOA chip are connected with the NSP circuits and the propagation wave is controlled by the external filters on both sides of the SOA, the lasing spectrum is thus purified. The second contribution is the separated ring resonator filters that are able to generate a larger loss margin between the main and the side mode, compared with the coupled ring structure. The mode space of the ring cavity is thus comparable with the FWHM of the filter, and the lasing spectrum of the single mode output is thus narrowed and stabilized.

5.5 Summary

This chapter focuses on the design, simulation, fabrication and experiments of the ring cavity tunable laser based on NSP circuits. The theoretical analysis explores the mechanism of the unidirectional operation, as well as the tunable laser specifications. The ring cavity tunable laser is fabricated and integrated on a single chip with a dimension of $3\text{mm} \times 1.5\text{ mm} \times 0.7\text{ mm}$. The experimental results consists of three consecutive steps: firstly, the effect of different sub-loop designs is compared, and $N = 3$ is chosen as the optimized design; next, the excellent unidirectional operation and the single mode performance are experimentally demonstrated (55-dB CWSR, 180-kHz linewidth, and above 50-dB SMSR); finally, the 55.4-nm wavelength tuning range are demonstrated by applying the thermal-optic effect. The innovations of the ring cavity tunable laser are summarized as follows,

- (a) This is the first effort demonstrated to develop a monolithic ring cavity tunable laser based on waveguide-based photonic circuits. In contrast to the fiber ring lasers and the free-space ring lasers [19, 20], this ring cavity tunable laser is monolithically integrated based on the NSP circuits, which is highly compact. The cavity length is shortened from meter-scale to mm-scale, which enables the compatibility between the longitudinal mode spacing and the bandwidth of the ring resonance. Therefore, the lasing spectrum of this tunable laser is of high purity and high stability.
- (b) A novel U-shape sub-loop is designed to enforce the unidirectional operation in the ring cavity laser. The unidirectional effect of different sub-loops is evaluated theoretically and then verified experimentally. It gets rid of the

dependence on the separated magnetic-optic isolators, as well as the complex hybrid integration.

- (c) The principle analysis of the ring cavity tunable laser based on the NSP circuits is demonstrated. This chapter also investigates the dependence of the laser performance on the parameters of the NSP elements, such as the waveguide transmission loss, the coupling coefficient and radii of the ring resonators, and the physical length of the NSP.

CHAPTER 6

CONCLUSIONS

6.1 Conclusions

Three different schemes of monolithic external cavity tunable laser based on nano-silicon-photonic integrated circuits have been developed. The contents of this thesis cover mainly the theoretical analysis and experiments for the electrically controlled and opto-mechanical tunable laser (linear cavity), and the ring cavity tunable laser. The major conclusions are listed below.

- (a) The concept of designing a tunable laser using nano-silicon-photonic circuits has many special merits. First, the effective cavity length of the laser cavity ranges in $1 \sim 10$ mm, thus the longitude mode space is comparable with the FWHM of the ring-resonator filter ($0.05 \sim 0.2$ nm). This property provides distinctive advantage for high stability of the single-mode lasing, as well as high spectrum purity. Second, the ring resonators not only provide the functions such as wavelength selection, but also extend the effective cavity length within a smaller space, which ensures the high compactness of the design. Last but not least, the advanced fabrication process ensures only 2 dB/cm optical loss for the nano-silicon-photonic waveguide. The silicon platform makes it possible for wavelength tuning using multiple schemes, such as the opto-electrical approach (including thermal-optic and free-carrier effects) and the opto-mechanical approach.

- (b) In the theoretical study of the electrically controlled tunable lasers, the optical feedback model and the theoretical explanation of the single-mode wavelength selection have been developed. The mechanism between the reflective filtering properties of the coupled ring structure and the specifications of the tunable laser such as tuning range, SMSR and output power have been theoretically elucidated in detail.
- (c) In the experimental investigation of the electrically controlled tunable laser, two electrical tuning schemes, utilizing the thermal-optic and the free-carrier effect respectively, are adopted for tuning the effective refractive index of the ring waveguides. As a result, the experiments demonstrate an over 40-nm tuning range with 2-pm tuning accuracy, and 40-dB SMSR at 1-mW output power. The conflicts between tuning range, tuning accuracy and SMSR, which is always a challenge in previous works, have been solved.
- (d) The external cavity tunable laser has been formed by integrating the NSP circuits with the bare gain chip on to a single chip, which has a dimension of $3\text{mm} \times 1\text{ mm} \times 0.7\text{ mm}$. The fabrication processes have been developed using silicon photonics and the MEMS technology. The packaging processes for gain and NSP waveguides integration have been specially developed, and the 100-nm and 300-nm alignment accuracy in vertical and lateral direction, has been achieved respectively, superior to the μm -level accuracy in other reported works.
- (e) In the theoretical study of the opto-mechanical tunable lasers, the resonant wavelength tuning schemes of both a silicon ring resonator and the coupled ring resonators have been theoretically demonstrated. A novel physical

phenomenon named ‘pull-back’ nonlinearity in a nano-actuator is proposed by analyzing the force equilibrium and the system stability.

- (f) For the first time, the opto-mechanical effect has been applied for wavelength tuning in an external cavity tunable laser. In the experiments, it has demonstrated a maximum deflection of 43.1 nm with a 0.28 nm tuning step for the single ring resonator, and a 24-nm tuning range for the tunable laser. Unlike the conventional electrically controlled wavelength tuning, it is able to tune the lasing wavelength through the all-optical scheme, getting rid of the dependence on the electrical circuits and avoiding the thermal issues.
- (g) An integrated ring cavity tunable laser, for the first time, has been theoretically and experimentally demonstrated based on the NSP circuits. Specially, all the optical functions required in a ring cavity tunable laser, are realized through employing the nano-silicon-waveguide circuits, to replace the passive elements such as optical lens, mirrors, prisms, couplers and isolators as needed in conventional ring lasers.
- (h) In the theoretical investigation of the ring cavity tunable lasers, a planar U-shape sub-loop which serves as a planar optical isolator is proposed and optimized. The design of the sub-loop makes it possible for unidirectional light propagation in the ring laser, and the numbers of Y-junctions in the sub-loop is optimized to $N = 3$. Compared with the conventional optical isolators that are separated elements with huge volume, the proposed sub-loop is part of the NSP circuits which is compact and fully integrated.
- (i) In the experimental study, a working device of the ring cavity tunable laser has been fabricated and integrated on a SOI chip with a dimension of 3 mm $\times$ 1.5mm $\times$ 0.7 mm. Multiple valuable specifications of the device have been

measured: firstly, it has demonstrated a 55-dB counter-propagation wave suppression ratio, which indicated the ideal unidirectional operation; second, it shows 50-dB SMSR and 180-kHz linewidth, which shows a perfect spectrum purity; finally, a 55.4-nm wavelength tuning range with 1.62 nm channel space is obtained.

The theoretical analysis and experiments results of the three integrated tunable lasers have demonstrated that the NSP circuits and elements are able to improve the laser specifications, such as running range, tuning accuracy, SMSR, linewidth, stability, and integration potential. The application of NSP circuits avoids the large beam divergence in the free-space environment, and provides the potential for novel tunable laser configurations with high integration capability and promising performance. To further improve the performance of the external cavity tunable lasers based on NSP circuits, several future works with relevant recommendations are described in the following section.

6.2 Recommendations

Recommendations for future research are summarized as follows

- (a) Silicon is a promising material for NSP based tunable lasers, not only for its low optical transmission loss, but also for its compatibility for multiple refractive index tuning schemes. Three schemes, the thermal-optic, the free-carrier injection, and the opto-mechanical, have been employed and discussed in this thesis. Besides, the refractive index of nano-silicon waveguide is possible to be tuned with the nano-electrical-mechanical system (NEMS) technology, which is expected to carry out in future works.
- (b) The electrically controlled tunable laser can be further improved in following aspects: getting higher thermal-optic tuning efficiency and prolonging the lifetime of the micro heaters by optimizing the pattern of the micro heater, eliminating the thermal issue due to free-carrier injection by re-designing the configuration of the P-I-N junction.
- (c) In the opto-mechanical tunable laser, the optical force is a novel method to be first utilized in a tunable laser. Although the principle for the static opto-mechanical effect has been demonstrated, the dynamic physical scheme that the laser cavity interacts with the opto-mechanical cavity has not been fully demonstrated. Further investigation is required to understand the dynamical working principle.
- (d) Although the opto-mechanical tunable laser has been successfully demonstrated, the specification such as the tuning range and the SMSR, are not comparable with electrically controlled laser, and thus there is a plenty of space to be improved. A novel design is worth being investigated for better utilization of the opto-mechanical effect, with either new designs of

the NSP circuits, or alternative material to enhance the opto-mechanical tuning coefficient.

- (e) In the ring cavity tunable laser, a U-shape sub-loop serving as an optical isolator is designed, in order to realize the unidirectional operation. To further enhance the unidirectional effect, it requires novel planar optical circuits or the optimization of current optical circuits. For instance, the numbers of the Y-junctions N determines the unidirectional effect, and the round trip gain ratio reaches 8 dB when $N = 3$. Actually, if the optical loss at the Y-junction could be further reduced, the enhanced unidirectional effect is expected at larger N , and the round trip gain ratio is expected to be above 20 dB.
- (f) In all these three demonstrated integrated tunable lasers, the III-V gain diodes are hybrid bonded onto the single SOI chip. The coupling coefficient between the active and the passive waveguides, dependent on the alignment accuracy, is a key parameter that affects the laser performance. The achievable coupling coefficient is ~50%, with misalignment limitation of 100 nm and 300 nm in the vertical and lateral directions as present in this thesis. A higher coupling coefficient is expected by optimizing the NSP circuit design or the bonding processes, thus higher output power and higher SMSR are expected benefiting from the reduced coupling loss.

AUTHOR'S PUBLICATIONS

Journal Papers

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4. M. Ren, H. Cai, Y. D. Gu, L. K. Chin, K. Radhakrishnan, H. D. Sun, D. L. Kwong and A. Q. Liu, "A ring-cavity tunable laser integrated and controlled by nano-silicon-photonics circuits," *Laser Photonics Rev.*, submitted.

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