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**NANYANG
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UNIVERSITY**

SINGAPORE

ON-CHIP SPECTROMETER:

DESIGN, FABRICATION AND EXPERIMENT

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**SCHOOL OF ELECTRICAL AND ELECTRONIC
ENGINEERING**

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**ON-CHIP SPECTROMETER:
DESIGN, FABRICATION AND EXPERIMENT**

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School of Electrical and Electronic Engineering

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

2019

STATEMENT OF ORIGINALITY

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

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.....

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Liu Ai-Qun

AUTHORSHIP ATTRIBUTION STATEMENT

This thesis contains material from 2 papers published in the following peer-reviewed journal(s) / from papers accepted at conferences in which I am listed as an author.

Chapter 3 is published as S. N. Zheng, Y. Y. Chen, H. Cai, Y. D. Gu, Z. C. Yang, Y. L. Hao, D. L. Kwong, and A. Q. Liu, "High-resolution and Large Tunable Range Nanophotonic Spectrometer Using a Microring Resonator." *Conference on Lasers and Electro-Optics (CLEO)* 2018, San Jose, U.S.A. (Oral)

The contributions of the co-authors are as follows:

- Prof. A. Q. Liu provided the initial project direction.
- I conceived the idea and concept.
- I prepared the manuscript drafts. The manuscript was revised by Y. Y. Chen and Prof. A. Q. Liu.
- I designed the study and performed all the laboratory work at the School of Electrical and Electronic Engineering. I also analysed the data.
- I fabricated the device.
- Dr Cai Hong, Dr Y. D. Gu and Prof D. L. Kwong assisted in the fabrication of devices.
- Prof Z. C. Yang and Prof Y. L. Hao assisted in discussions and paper writing.

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9th April 2018

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SUMMARY

This doctorate thesis focuses on the design, fabrication and experimental characterization of novel on-chip spectrometers. Specifically, two different types of on-chip spectrometer have been designed, fabricated and experimentally demonstrated. Fabrication processes based on nano-silicon-photonics (NSP) fabrication technology are developed.

The first part of the thesis reports an on-chip spectrometer called pre-dispersed spectrometer with both high resolution and large bandwidth using thermally tunable microring resonator (MRR) array with an arrayed waveguide grating (AWG) before the MRR array. The AWG functions as a fixed filter to pre-disperse the input spectrum while the following tunable MRRs retrieve the corresponding dispersed spectra with high resolution. By adoption of AWG before the tunable MRR array, the working spectral band can be broadened while maintaining final resolution of the spectrometer due to that the resonance wavelength of MRR can be finely tuned. Besides, the tunable MRR array has much higher fabrication tolerance and is more compact compared to the approaches using the stationary microring resonators array. The pre-dispersed spectrometer achieves high resolution (0.1 nm) and large bandwidth (27 nm) within only 9 channels in a compact size of $3 \times 3 \text{ mm}^2$. The model of MRR thermal tuning exploiting thermo-optic (TO) effect is built and theoretically analysed. Heater optimization and thermal isolation trenches are implemented to improve the heating efficiency.

The second part of the thesis focuses on the development of a microring resonator-assisted Fourier-transform (RAFT) spectrometer. In this design, Fourier-transform (FT) spectrometer is realized with a thermally tunable photonic Mach-

Zehnder interferometer (MZI). A microring resonator with high quality factor is cascaded before the Mach-Zehnder interferometer to pre-filter the input spectrum while the MZI is exploited to reconstruct the pre-filtered spectra. The proposed RAFT spectrometer has both high resolution (0.47 nm) and very large bandwidth (90 nm) due to the large transparency window of Mach-Zehnder interferometer and high quality factor (Q) of microring resonator. It has a small footprint of 2.2 mm². The model of MZI thermal tuning exploiting TO effect is built and theoretically analysed. Low-loss Si rib waveguide is designed, fabricated and experimentally tested to reduce insertion loss and improve resolution. A low loss rate of 0.1 dB/m is experimentally tested. Thermal isolation trenches are implemented and experimentally tested to reduce thermal consumption and thermal crosstalk.

The third part of the thesis focuses on the development of core fabrication technology of nano-silicon-photonics fabrication technology, including silicon strip waveguide, inverse taper fibre-chip coupler, rib waveguides, directional couplers, and titanium nitride (TiN) heaters and thermal isolation trenches. Si₃N₄ strip waveguide, microring resonator, and directional coupler are also designed and fabricated. The fabrication processes are developed. The problems encountered in optical lithography are discussed. The fabrication processes of a waveguide-coupled Ge-on-SOI photodetector (PD) are also presented. The dark current is 4.4 nA at 0 bias. The responsivity is 0.81 A/W at 1538.5 nm. A spectrometer using a thermally tunable MRR integrated with a Ge-on-SOI PD is designed and experimentally demonstrated.

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NOMENCLATURE

MRR	microring resonator
FSR	free spectral range
FWHM	full width at half maximum
Q	quality factor
TO	thermo-optic
TOC	thermo-optic coefficient
CMOS	complementary metal-oxide-semiconductor
SOI	silicon on insulator
Si	silicon
Ge	germanium
Al	Aluminium
Si₃N₄	silicon nitride
TiN	titanium nitride
SiO₂	silicon dioxide
CVD	chemical vapor deposition
PECVD	plasma-enhanced chemical vapor deposition
FTS	Fourier-transform spectrometer
OPD	optical path difference
SNR	signal-to-noise ration
OPL	optical path length
RAFT	microring resonator-assisted Fourier-transform
MZI	Mach-Zehnder interferometer
MEMS	micro-electromechanical systems

PIC	photonic integrated circuit
NSP	nano-silicon-photonic
FFT	fast Fourier transform
SNR	signal-to-noise ratio
AWG	arrayed waveguide grating
PCG	planar concave gratings
SWIFTS	stationary-wave integrated Fourier-transform spectrometer
DFT	digital Fourier transform
SHS	spatial heterodyne spectrometer
IR	infrared
NIR	near infrared
MIR	mid-infrared
VIS	visible
SEM	scanning electron microscope
TEM	transmission electron microscope

CHAPTER 1

INTRODUCTION

1.1 Motivations

This PhD research topic is motivated by the potential impact of the integrated photonic technology in developing on-chip spectrometers.

Integrated photonic or integrated optics platform has the advantage of high compactness, low cost, and high robustness, compared to the benchtop optics. Free space optics requires various components such as lenses, prisms, mirrors, beam splitters, attenuators, gratings, optical detectors, and so on. To make the whole optical system work well, each component needs good alignment in the optical transmission space. Besides, free-space optical components are expensive and bulky. The emergence of optical fibre makes the delivery of optical signal much more convenient and makes the long-distance transmission possible. Integrated optics targets to make the optical system on a single chip called photonic integrated circuits (PICs), eliminating the assembly and alignment processes and the unstableness due to environment fluctuations. Besides, the trend of data transmission and processing carried by optical signals instead of electric signals makes the integrated optics more promising to be applied in the data communication and computation areas [1]. Many possibilities have been investigated in integrated photonic platform such as LEDs, lasers, various counterparts of conventional optical components, photodetectors, and so on. The rapid development in fabrication technology has made the structure size down to submicron-meter. The so-called nanotechnology has opened new physical areas such as nano-photonics.

Photonic nano-waveguides or nanowires are basic components in the PICs. Lightwave is basically a kind of electromagnetic wave. It propagates in waveguides by total internal reflection. Nanotechnology based on silicon-on-insulator (SOI) has made the waveguide structure size to be several hundred nano-meters so that the waveguide can only transmit fundamental mode, which enables better manipulation, delivery of optical signals in PICs and better performance of various optical components. Microring resonator can enormously increase the light intensity propagating in it. It has such a high finesse that it can be exploited as a filter with very fine pass bandwidth and low loss. Thermo-optic effect (TO effect) can be harnessed to tune the refractive index of a material. It is used in applications such as temperature sensor, phase shifter, and modulator.

Optical spectrometer is an important apparatus to measure the properties of light and has been one of the most important instruments for spectrum analysis in a wide range of applications such as substance identification, biological and chemical analysis, environment monitoring, remote sensing in satellites and so on. The visible wavelength (VIS) range is mostly utilized to characterize the fluorescence or absorption of many types of fluorophores, photoluminescent markers, LEDs, and photovoltaics. The absorption bands in the near-infrared (NIR) range (0.7-2.5 μm) are relatively broad due to overtones and combination bands. The NIR range is often used to detect food, pharmaceuticals, polymers, petrochemical products, aqueous solutions, etc. The mid-infrared (MIR) range (2.5-5 μm) is useful for atmospheric sensing, material identification, chemical and biomolecule sensing, etc, due to strong fundamental vibration bands. The optical spectrometer has been made smaller and smaller for more convenience and lower cost [2-5] as it is critical to bring the chemical/biological sensing, spectroscopy, and spectral imaging into robust, compact

and cost-effective devices. Hence, on-chip spectrometer has been a hot research topic with the development of devices requiring spectrum analysis such as wavelength monitoring [6-8], photonic sensors and on-chip spectroscopy [9-16] based on photonic integrated circuits. It has the advantages of low cost, high compactness, high robustness and high ability for integration to enable portable sensing instruments and integrated spectroscopy systems. The maturity in building the PIC in optical telecommunication band enables the various state-of-the-art integrated spectrometers. The increasing need for wavelength monitoring in optical communication networks also boosts the development of integrated spectrometers. The fast development in various material platforms, such as silicon, silicon nitride, germanium, aluminium nitride, etc, dramatically extends the spectral range, which promises broad sensing and spectroscopic applications ranging from VIS to IR range. As a result, scientists have been trying different approaches to realize optical spectrometer on a single chip. The maturity of nano-silicon-photonic fabrication technology and availability of foundries has enabled the integration of large scale photonic devices on a single chip [17]. And actually, the nano-silicon-photonic fabrication line has been perfectly applied in integrated photonic devices fabrication. However, low performance issues such as narrow bandwidth and low SNR are encountered when scaling down optical spectrometers. Some approaches adopted dispersive ways like array waveguide gratings (AWG) [18-21], planar concave gratings (PCG) [13, 18, 21, 22] which are quite similar with the conventional grating-based counterparts. Some exploited the characteristics of photonic devices to fabricate tiny structures to disperse light such as photonic crystals (PCs) [8, 23-25] and photonic random structures [26]. And there are also other approaches such as stationary microring resonators (SMRR) array [27], speckle pattern reconstruction by spiral waveguides [28] and digital planar

holography (DPH) [29, 30]. The trade-off between resolution and bandwidth as well as low signal-to-noise ratio (SNR) due to dispersion limit their application. Cascaded configurations are adopted to realize both high resolution and large bandwidth [13, 31]. Conventional Fourier-transform (FT) spectrometer using Michelson interferometer is known for high resolution, broadband and high SNR, which is suitable for infrared (IR) applications [32]. On-chip FT spectrometers are also demonstrated such as FT spectrometer based on micro-electromechanical systems (MEMS) technology [33-36], stationary-wave integrated FT spectrometer (SWIFT) [37, 38], spatial heterodyne spectrometers (SHS) [16, 39-44], thermally tunable MZI [45, 46], co-propagative FT (CPFT) spectrometer [47] and digital Fourier-transform (DFT) spectrometer [48, 49]. The similar trade-off between channel count and SNR is encountered in most FT methods. For thermally tunable MZI, challenges lie in improvement of MZI arm length and refractive index modification.

1.2 Objectives

The objective of this thesis is to explore and investigate potential applications of photonic devices based on integrated photonic circuits platform. Specifically, applications in developing an on-chip spectrometer are investigated. The first objective is to innovate high-resolution and large-bandwidth on-chip spectrometers for on-chip spectrum analysis applications such as wavelength monitoring in optical networks, integrated photonic sensing, on-chip spectroscopy and environmental monitoring, etc. Besides, fabrication processes based the nano-silicon-photonic fabrication technology are also to be developed, including fabrication of nano-waveguides, inverse taper fibre-chip coupler, directional couplers, heaters, metal wires, Ge-on-SOI photodetectors, trenches, etc.

In this PhD thesis, two different types of on-chip spectrometers will be developed.

The first approach for on-chip spectrometer takes advantage of arrayed waveguide grating and tunable microring resonator to realize a pre-dispersed spectrometer to achieve sub-nanometer resolution and large bandwidth (~ 100 nm). A TMRR array is cascaded with the AWG in a way that each output waveguide of the AWG is connected to a tunable MRR. And there is an integrated Ge-on-SOI photodetector in the drop port of each MRR. An arrayed waveguide grating firstly pre-disperses the input spectrum to several separated spectral bands into the corresponding TMRRs cascaded in each output channel of the AWG. Thermo-optic effect is exploited to tune the resonance wavelength of the microring resonator to realize a continuously tunable filter with ultra-narrow bandpass due to high finesse of the resonance peaks of the MRR. Tunable MRR has higher fabrication tolerance and is more compact compared to the stationary MRR array[27].

The second approach demonstrates a microring resonator-assisted Fourier-transform (RAFT) spectrometer to achieve sub-nanometer resolution and large bandwidth (~ 100 nm). The RAFT spectrometer employs a thermally tunable Mach-Zehnder interferometer configuration as a temporal tuning Fourier-transform spectrometer. The tunable MZI has large transparency window and presents no trade-off between resolution and bandwidth. Thus, it can resolve the trade-off between resolution and bandwidth, which is inherent in dispersion approaches. To reduce optical path length and temperature change while maintaining the resolution, a thermally tunable MRR is cascaded before the FTS with the drop port of MRR as input of the tunable MZI. The MRR pre-filters the input spectrum to a spectrum with sparsely spaced wavelength components. This spectrum can be easily differentiated

by the tunable MZI. The MRR can be tuned to change the filtered spectrum. All the filtered spectra are recovered by the tunable MZI and combined to reconstruct the input spectrum. Since MRR presents high quality factor, it can be tuned with an ultra-fine value. Hence, by time serializing the tunable MRR, the full input spectrum can be continuously filtered by the MRR. Thus, the resolution is dramatically enhanced by the MRR far beyond the Rayleigh criterion of the tunable MZI. Therefore, high resolution can be achieved without compromising the bandwidth. Besides, only one detector is required for one single device, which promises high SNR and small footprint.

The proposed on-chip spectrometers will have high potential to be applied in spectral analysis applications such as handheld spectrometers [2], image spectrometry [38], integrated sensing systems [12, 13] and on-chip spectroscopy [14, 50].

The fabrication processes using technology compatible with the technology of complementary metal-oxide-semiconductor (CMOS) will be developed such as nano-silicon-photonic waveguides, inverse taper fibre-chip coupler, directional couplers, heaters, thermal isolation trenches and waveguide-coupled Ge-on-SOI photodetector.

1.3 Major Contributions

The major contributions of this research include various aspects of theoretical analysis, design, fabrication and experiments of two types of nanophotonic spectrometers.

- (a) A tunable microring resonator filter coupling with two waveguides is designed. The tuning through thermo-optic effect is analyzed theoretically

and the model of microring resonator thermal tuning is built.

- (b) The influences of heater's dimensions and isolation trenches on heating efficiency and temperature response are theoretically analyzed and experimentally tested.
- (c) Pre-dispersed spectrometer with an arrayed waveguide grating, tunable microring resonator array, and Ge-on-SOI photodetector array is designed, fabricated and experimentally tested. High resolution of 0.1 nm and large bandwidth of 27 nm are achieved in 9 detection channels.
- (d) The advantages of tunable microring resonator over stationary microring resonator are experimentally tested. The tunable microring resonator is more compact than stationary microring resonator array. Resonance wavelength of the tunable microring resonator is easier to control.
- (e) Thermal tuning of tunable MZI through thermo-optic effect as a Fourier-transform spectrometer is analyzed theoretically and the model of MZI thermal tuning is built. A microring resonator with high quality factor $Q \sim 9,661$ is adopted. Thermal consumption of MRR and MZI are 1.23 mW/nm and 11.185 mW/ π , respectively. High resolution (0.47 nm) and large bandwidth (90 nm) are experimentally achieved in one single detection channel.
- (f) Thermal tuning with TO effect of Si with high efficiency (1.23 mW/nm for MRR and 2 mW/ π for MZI) and large range (19 nm for MRR and more than 80 periods for MZI) are achieved. High response speed is also achieved (~ 10 kHz).
- (g) Si_3N_4 waveguide with relatively low loss and Si_3N_4 MRR with high quality factor are fabricated and experimentally tested to develop a Si_3N_4 platform

potential for applications in near-infrared (NIR) range.

- (h) Low loss Si rib waveguide is designed, fabricated and experimentally tested. The fabrication processes of strip waveguide, rib waveguides, TiN heater, thermal isolation trenches and Ge-on-SOI photodetectors are developed based on SOI wafers.
- (i) Experiments were carried out to characterize the performance of the spectrometer devices.
- (j) High resolution 0.1 nm and large tunable range of ~19 nm are realized with a single tunable MRR integrated with a Ge-on-SOI photodetector. The thermal consumption is ~3.8 mW/nm.

1.4 Organisation

This thesis report consists of six chapters.

Chapter 1 introduces the motivations, objectives and major contributions of this project as presented in this chapter. The motivations section explains why and how the PhD research is carried out. The objective part presents the main focus of this thesis. Innovations, important outcomes and main work are described in the contribution section.

Chapter 2 firstly gives reviews on guided waves including guide waves, low-loss waveguide, photonic microring resonator and Mach-Zehnder interferometer. Three refractive index modification methods on photonic chip are reviewed including electric field effect, plasma effect and thermo-optic effect. Basic concepts of optical spectrometers are introduced. Various state-of-the-art on-chip spectrometers are reviewed and discussed. Finally, integrated photodetectors on Si PICs are introduced.

Chapter 3 gives the detailed description on theoretical analysis and

experimental demonstration of a pre-dispersed spectrometer with an arrayed waveguide grating, tunable microring resonator array and Ge-on-SOI photodetector array. Theoretical mode of microring resonator thermal tuning is analyzed including heat transfer analysis, heater optimization, etc. And the theoretical model is built. Experiments are carried out and results are discussed. Experimental results show the advantages of tunable MRR over stationary MRR array.

Chapter 4 gives detailed description of the theoretical analysis and experimental demonstration of a microring resonator-assisted Fourier-transform spectrometer. The thermal tuning of the Mach-Zehnder interferometer is analyzed and the theoretical model is built. Experimental results are presented and discussed. The approaches of improving the performance including isolation trenches and waveguide loss implementation are discussed and demonstrated.

Chapter 5 presents the fabrication processes based on nano-silicon-photonic fabrication technology. Nano-silicon-photonic processes for stripe waveguide, rib waveguides, inverse taper fibre-chip coupler, and directional couplers are presented. Si_3N_4 waveguide with lower loss and microring resonator with higher quality factor are designed, fabricated and experimentally tested to provide promising platform in the NIR range. Fabrication processes of TiN heater and thermal isolation trenches are presented. Fabrication processes of waveguide coupled Ge-on-SOI photodetector are developed and presented. The experimental results of an on-chip spectrometer using a tunable microring resonator integrated with a Ge-on-SOI photodetector are presented and discussed.

Chapter 6 draws conclusions and gives recommendations.

CHAPTER 2

LITERATURE SURVEY

2.1 Guided Waves

Photonic waveguide is the basic component in the PIC platform. It not only plays a role in transmitting light wave in a structure with dimensions from hundreds of nanometres to several micrometres, but also critical to the development of many photonic devices, such as bus couplers, branches, wavelength filters [51], wavelength or mode (de)-multiplexers [52-54], modulators [55-57], switches [58], phase shifters [59], etc. Photonic waveguide also offers an efficient approach for nonlinear optics, due to the high confinement of optical field. The emergence of PIC platform with the development of nano-fabrication technology paves the way to compact waveguide system for nonlinear optics for applications in integrated light sources [60-63]. There are many types of optical waveguides such as planar waveguide (also called slab waveguide), strip waveguide, rib waveguide, optical fibre and so on [64]. Hence, photonic waveguide is critical to bring bulky optical components onto a photonic integrated circuit (PIC), a highly integrated platform due to its ultra-small geometrical structures to enable compact, robust and low cost photonic system [65].

2.1.1 Low-loss Waveguide

The important characteristic of a waveguide is the optical attenuation or loss that a light wave experiences when it propagates along the waveguide. The propagation loss must be reduced for practical application in PICs. The losses of a waveguide are induced by many mechanisms, including absorption, scattering and

radiation loss [1, 66].

In semiconductors, the absorption is due to interband (or band edge absorption) and free carrier absorption. Both can induce significant loss. The interband absorption occurs when the photon energy is larger than the bandgap energy of the waveguide material. Hence, light with longer wavelengths should be adopted to propagate in the corresponding material to avoid interband absorption. Free carrier absorption also called intraband absorption, occurs when a photon loses its energy to excite an electron or hole from an already existing state to another normally different higher state in the same band.

The scattering loss is induced by volume scattering and surface scattering. The former is due to imperfections acting as scattering centres within the volume of the waveguide, including voids, contaminant atoms and crystalline defects. Surface scattering is more dramatic since the optical field especially high-order modes can interact strongly with the waveguide surfaces or interfaces with cladding materials. And normally the surfaces or interfaces are not smooth. In planar waveguide circuits, the scattering losses due to sidewall roughness are more significant due to imperfect etching processes [67]. Normally higher index contrast between the core and the cladding will induce more scattering losses [67, 68]. Hence, the scattering loss can be reduced by improving material quality, optimizing etching processes for smooth surfaces [69, 70], adopting materials with a lower refractive index as the core material and using high-aspect-ratio waveguides.

Optical loss can also be induced by radiation effect which occurs when photons propagating in a waveguide transmit into the surrounding material and are no longer guided. Hence, for a certain well confined mode, the change of the cut-off conditions will induce the loss of confined energy into the surrounding material, such

as bending with small bending radius [71], tapering, and size variety, etc. The poorly confined high-order mode is more likely to be radiated into the surrounding material. The lower-order optical modes may be transformed to higher-order modes due to nonuniformity of the waveguide. Nevertheless, the bending or curving of waveguides dominates in inducing radiation loss.

Many approaches have been attempted to achieve low-loss waveguides. A low-loss (0.3 dB/cm) silicon waveguide is developed in [72], where thermo-oxidation is exploited to define the waveguide profile without physical etching, thus resulting in a smooth interface between the waveguide and the SiO₂ cladding. The modal profile of the fundamental TE mode is shown in Fig. 2.1(a). The approach of adopting rib waveguide has been tried to reduce waveguide losses [73, 74]. Shallow ridge is made to reduce interaction of the optical field with rough sidewalls, achieving a low loss of 0.274 dB/cm [73]. The modal profile is shown in Fig. 2.1(b). A high-aspect-ratio Si₃N₄ waveguide with an ultra-low loss of 0.1 dB/cm is demonstrated [75]. Figure 2.1(c) shows the profile of the fundamental TE mode. The upper and lower claddings are made of thermally grown SiO₂. The width of the waveguide is 13 μm and the thickness of the core is only 40 nm. With high aspect ratio cross section, most electric field is exposed to the thick cladding and there is only a very small portion of electric field interacting with rough etched sidewalls. The claddings are very thick (up to 15 μm) to avoid interaction with the interface between cladding and air. And the low impurities further reduce the optical losses. Delay lines made of low refractive index material Silica is developed on a Si chip, achieving a ultra-low loss rate 0.08 dB/m [76]. Etched Silica surface has higher quality and the optical mode is designed to have less interference with rough sidewalls.

Figure 2.1: Fundamental quasi-TE modal profile of (a) the etchless Si waveguide, (b) the shallow-ridge Si waveguide and (c) the high-aspect-ratio Si_3N_4 waveguide.

Many photonic devices require nanowire waveguide since nanowire is single mode waveguide which is easier to be harnessed. Loss rate of the state-of-the-art Si nanowire is ~ 1 dB/cm. The Si_3N_4 material has lower refractive index than Si, thus it is preferred for lower loss. Low-loss Si_3N_4 nanowires have been developed in the NIR range with a loss rate < 1 dB/cm from 532-900 nm [77]. Different methods have been tried to further reduce the loss of Si_3N_4 waveguide such as the double strip structure with a loss rate of 0.2 dB/cm [78], rectangular cross section filled with and

encapsulated by silicon dioxide (SiO_2) with a loss rate ≤ 0.1 dB/cm [79] and strip waveguide specially fabricated by etching SiO_2 trench before deposition with a 0.4 dB/cm loss at $1.55 \mu\text{m}$ [80]. The low-loss waveguide can be applied in on-chip routing which requires a waveguide length of up to dozens of centimetres [74, 81]. Ultra-low-loss waveguide can also enable realization of on-chip delay lines which require a length up to several metres [76, 82].

2.1.2 Photonic Microring Resonator

Optical microcavities are important basic components in modern optics [83]. They are widely applied as optical filters and means for accurate measurement, laser devices, nonlinear optics, etc. The optical microcavities include Fabry-Perot cavity, photonic crystal and whispery gallery mode ring resonator and so on. The schematic configuration of an add-drop microring resonator (MRR) is shown in Fig. 2.2(a). It is composed of two unidirectional waveguides and an MRR. If the second waveguide is removed, it is called an all-pass MRR [84]. MRR has the characteristics of an optical filter according to the filter characteristic as shown in Fig. 2.2(b) and (c). Transmission spectra from throughput and drop port are denoted with solid and dash line, respectively. The wavelength position where the dips or peaks appear ($\lambda_1, \lambda_2, \lambda_3 \dots$) is the resonance wavelength. FSR is called free spectral range, which represents the wavelength or frequency difference between two adjacent resonance wavelengths or frequencies and $\delta\lambda$ is the full width at half maximum (FWHM) of the resonance line shape. Only the light at the resonance wavelength of the MRR (λ_2) will resonate in the MRR. The resonating light intensity will be enhanced dramatically and then coupled into another waveguide and output from the drop port. The remaining light (off-resonance wavelengths, λ_1) will be output from the throughput port. Light can also be added through the add port. If the wavelength overlaps with the resonance

wavelength (λ_a), the light will finally be output from the throughput port. Normally in a purely passive MRR, the loss coefficient α is a fixed value ($0 < \alpha < 1$). Hence, the way to achieve minimum or maximum transmission from throughput or drop port is to change the coupling coefficients of the two unidirectional couplers, t_1, t_2 [84].

Figure 2.2: (a) Schematic of an add-drop MRR. Filter Characteristic of (b) an all-pass MRR and (c) an add-drop MRR.

The dispersion of the propagation constant can be expressed as

$$\frac{\partial \beta}{\partial \lambda} = -\frac{k}{\lambda} n_g \quad (2.1)$$

where n_g is group refractive index, and is expressed as

$$n_g = n_{eff} - \lambda \frac{\partial n_{eff}}{\partial \lambda} \quad (2.2)$$

Thus, the free spectral range (FSR) is

$$FSR = \Delta \lambda = \frac{\lambda^2}{n_g L} \quad (2.3)$$

The quality factor Q standing for the sharpness of the resonance, is expressed as

$$Q = \frac{\lambda}{\delta \lambda} \quad (2.4)$$

The effective index of the MRR will change with different surrounding substances and concentrations of the substances. Hence, MRR can enable very high sensitivity on sensing applications such as refractive index sensor [85], gas sensor [12, 86-88] and biochemical detection [9, 89, 90] due to its high-Q characteristic. Optical MRR can also be used as an optomechanical device to enhance interaction between light and mechanics to realize the amplification of radio-frequency signals [91, 92], motion amplification and cooling [93], and actuation [94, 95]. A wide-range tunable laser is developed in with double coupled resonators [96]. Microring resonators can also be used for filters [97-99] and nonlinear applications [100, 101].

2.1.3 Mach-Zehnder Interferometer

The Mach-Zehnder Interferometer (MZI) is extensively used in the PIC platform such as filters [102], modulators [103], and switches [104], etc. The schematic of an MZI is shown in Fig. 2.3. The input light is split by the splitter to two beams into arm 1 and arm 2. If the splitter is a 50/50 beam splitter, the light intensities

in arm 1 and arm 2 are equal. After propagating in the arms, the two beams will recombine at the output waveguide through the waveguide combiner.

Figure 2.3: Schematic of a Mach-Zehnder Interferometer.

Suppose the electric fields of the propagating mode in arm 1 and arm 2 are E_1 and E_2 , respectively, and the amplitude of both electric fields is E_0 , the transfer function of the MZI is expressed as

$$S_T = S_0 \{E_0^2 [1 + \cos(\Delta\phi)]\} \quad (2.5)$$

where $S_T = S_0(E_1 + E_2)^2$ is the intensity at the output waveguide. The phase difference between the two beams $\Delta\phi$ is either due to the different propagating constants between the two arms or imbalance arm length. Thus, the output intensity changes cosinusoidally with the phase difference. The maximum intensity occurs when $\Delta\phi$ equals to $2m\pi$, while the minimum intensity occurs when $\Delta\phi$ equals to $2(m+1)\pi$, where m is an integer. Thus, the transmitted light intensity can be changed from the minimum to the maximum value by changing the phase difference via manipulating propagation constant or arm length.

2.2 Refractive Index Tuning

Optical tuning is required in integrated optical systems. The refractive index is a complex number expressed as $N = n + i\kappa$. The real part n is the refractive index indicating the phase velocity and the imaginary part κ is the extinction coefficient

which describes how easily it can be penetrated by a beam of light. In integrated optics, there are three main ways to tune the refractive index of a material, namely by electric field effect, carrier injection or depletion effect and thermo-optic effect.

The change in the real refractive index Δn due to applied electric field is called electrorefraction, while the change in imaginary part of the refractive index $\Delta \alpha$ is called electroabsorption [105]. The primary electric field effects to cause electrorefraction and electroabsorption are the Pockels effect, the Kerr effect, and the Franz-Keldysh effect. Pockels effect also known as the linear electro-optic effect causes a change in real refractive index Δn , which is proportional to electric field E . The change depends on the angle between the direction of the applied electric field and the crystal axes. Thus, the effect is polarization dependent. There is almost no Pockels effect in silicon concerning the geometry of the silicon crystal structure. Hence, it is not an option for optical tuning in silicon. To utilize the largest electro-optic coefficient of a certain material, the electric field is applied to align with one of the principal axes. The Kerr effect is the second order electric effect. The real refractive index change is proportional to the square of the applied electric field. The Kerr effect is not polarization dependent. The Kerr effect in silicon as a function of applied electric field, at 300K and $\lambda = 1.3\mu\text{m}$ is shown in Fig. 4.23 in [105]. The refractive index changes from 10^{-8} to 10^{-4} when electric field is changed from 10^4 to 10^6 V/cm. Hence, the Kerr effect is rather weak in Si and is hard to be harnessed. The Franz-Keldysh effect induces both electrorefraction and electroabsorption. But it mainly causes the electroabsorption. The energy band of the semiconductor is distorted by the electric field, resulting in the change of absorption properties, particularly at the wavelengths close to the band gap. Figure 4.24 in [105] shows the Franz-Keldysh effect in silicon at 300 K and for $\lambda = 1.07 \mu\text{m}$ and $\lambda = 1.09 \mu\text{m}$. The

refractive index changes from 10^{-6} to 10^{-4} when electric field changes from 4×10^4 to 4×10^5 V/cm.

Free carriers in a material will affect both the real and imaginary refractive indices. The Drude model shows that the carrier density influences the plasma frequency, and thus affects the refractive index [17]. It is called the plasma effect. According to Drude-Lorenz equation [105], for carrier injection concentration of $5 \times 10^{17} \text{ cm}^{-3}$ for both electrons and holes, the changes of refractive indices in Si at 1550 nm are $\Delta n = 1.67 \times 10^{-3}$ and $\Delta \alpha = 7.25$. The refractive index change is in the order of 10^{-3} . However, the additional loss due to carrier injection is 7.25 cm^{-1} , which corresponds to a loss rate of 31.465 dB/cm. Thus, the refractive index modification by carrier injection or depletion in Si will induce large loss.

Thermo-optic (TO) effect is that the refractive index of a material will change as a function of its temperature T . The thermo-optic coefficient (TOC) depends on the temperature T and wavelength λ of light propagating in the material [106], thus refractive index n can be expressed as $n(\lambda, T)$ [106]. The advantage of strong TO effect in silicon (TOC $\approx 1.84 \times 10^{-4}/\text{K}$) is frequently exploited to implement refractive index tuning in various components in integrated photonic circuits such as temperature sensor [107, 108], modulator [56] and phase shifters [109-111].

Since the electric field effect is too weak in Si, the carrier injection and thermo-optic effect are widely exploited on Si photonic platform. Thermo-optic effect allows larger refractive index modification than carrier injection. However, the tuning speed using carrier injection (GHz level) is much faster than that using thermo-optic effect (kHz level).

2.3 Spectrometers

An optical spectrometer is an apparatus to measure properties of light to get the spectrum. Its applications range from material identification, environmental sensing, food and beverage safety, health monitoring to remote sensing in satellites, etc. There are three types of spectrometers based on working principle, the dispersive, filter-based and Fourier-transform (FT) spectrometer. The fast development of nanophotonic fabrication technologies reduces the structure size to nanometers. Many miniaturized spectrometers have been demonstrated, which typically have the advantages of robustness, cost-effectiveness, and compatibility to integrate with photonic integrated circuits, etc. There are many promising applications such as on-chip sensing and spectroscopy [14, 112, 113], food and beverage quality control and environment monitoring [114], etc.

2.3.1 Fundamental Concepts of Spectrometers

The conventional dispersive spectrometer utilizes optical gratings [5, 115] to disperse light by frequency. The schematic of the Hamamatsu mini-spectrometer using reflective gratings is shown in Fig. 2.4(a). Light is coupled to the device through an optical fibre. After collimation, the light will be focused to the reflective gratings. The dispersion angle is wavelength dependent. After dispersed and focused, light components will be detected by the image sensor. The schematic working principle of a diffractive grating is shown in Fig. 2.4(b). The dispersion characteristic of the grating is due to interference of light. To create constructive interference, the optical path difference (OPD) of the two incident beams to adjacent slits is expressed as

$$\text{OPD} = d(\sin i - \sin \theta) = m\lambda \quad (2.6)$$

where m is an integer standing for the diffraction order, d the grating period, i the

incident angle of the light beam and θ the dispersive angle. Then we can obtain the spread of spectrum of order m between wavelength λ and $\Delta\lambda$

$$D = \frac{d\theta}{d\lambda} = \frac{-m}{d \cos \theta} = \frac{\sin \theta - \sin i}{\lambda \cos \theta} \quad (2.7)$$

Thus, the spread of spectrum D of order m depends on the incident wavelength. The resolving power indicating the smallest resolvable wavelength difference is given by

$$R = \frac{\lambda}{\Delta\lambda} = mN \quad (2.8)$$

where N is the slit number of the grating.

Figure 2.4: (a) Schematic of the Hamamatsu mini-spectrometer TF series C14486GA.

(b) Schematic working principle of a diffractive grating.

Figure 2.5: Axsun's MEMS-based spectrometer exploiting a tunable Fabry-Perot filter taken from [4].

A spectrometer exploiting Fabry-Perot tunable filter based on micro-electromechanical systems (MEMS) fabrication technology is developed by Axsun Technologies [4]. It is a tunable Fabry-Perot cavity with the schematic shown in Fig. 2.5. The upper mirror can be tuned by electrostatic force to change the cavity gap to tune the filtered output wavelength.

The schematic of a conventional Fourier-transform spectrometer using a Michelson interferometer [116] is shown in Fig. 2.6. The mirror in one arm is stationary for reference and the other is movable to generate OPD between the two arms. The OPD equals to $x_2 - x_1$. The two beams will interfere after recombining in the beam splitter. As a result, there will be a time-varying signal in the output of the photodetector, i.e. interferograms. By applying Fourier transform (FT) to this signal, the input spectrum is retrieved [32]. The interferograms with different input spectra are shown in Fig. 2.7. The resolution $\delta\sigma$ is given by $1/\Delta L$. The parameter $\sigma = 1/\lambda$ is wavenumber and ΔL is the maximum OPD. Hence, the resolution depends on the maximum travel range of the movable mirror. The FT spectrometer has many advantages over other conventional optical spectrometers. The multiplex advantage

and throughput advantage enable shorter detection time and higher SNR. The stray light is negligible and the resolution (in wavenumber) is constant throughout the detected spectral range. Since the interference length should be less than the coherent length of the light source to obtain better and more interferograms, the maximum OPD ΔL or resolution is limited by the coherent length. The typical light sources used include incoherent sources such as incandescent light bulb and silicon carbide rod, and coherent sources such as He-Ne laser and laser diode. The coherent length equals to $c/n\Delta f$, where c is the speed of light, n is refractive index in the material and Δf is the bandwidth. Incoherent sources have a short coherent length (tens of micrometres), while coherent sources have a much longer coherent length (tens of centimetres). Hence, coherent source is required for high resolution applications.

Figure 2.6: Schematic of a conventional Fourier-transform spectrometer using a Michelson interferometer.

Figure 2.7: Interferograms with different input spectra. (a) One infinitesimally narrow line. (b) Two infinitesimally narrow lines with equal intensity. (c) Lorentzian shape spectrum centred at the mean of the lines in (b).

2.3.2 On-chip Dispersive Spectrometers

In dispersive methods, the input spectrum is spatially demultiplexed according to wavelength or frequency. The filter-based spectrometer adopts filtering elements to direct light into different channels according to wavelength or frequency. Hence, the filter-based type is included in the dispersive type here. On-chip dispersive spectrometer includes arrayed waveguide gratings (AWG) [18-21, 117-121], planar concave grating (PCG) [18, 21, 122], photonic crystals (PCs) [23-25, 123-125], stationary microring resonator (SMRR) array [27], random structures [26, 126] and digital planar holography (DPH) [29, 30]. There is inherent trade-off between

resolution and channel count. Hence, large channel count is required to achieve high resolution and wide bandwidth.

Arrayed waveguide grating (AWG) also called waveguide grating routers (WGR) or phased arrays (PHASAR), has long been used as (de)multiplexer in fibre-optic communications. In recent years, AWG has been a critical component in integrated photonic systems [17, 105, 127], with applications ranging from (de)multiplexers, add-drop filters [128] to $N \times M$ wavelength routing. It has also been adopted as on-chip spectrometers [18, 19, 21, 31, 117, 119, 121]. Figure 2.8 shows the schematic working principle of the AWG [129]. There are two star-couplers also called free propagation region (FPR). One is input FPR and the other output FPR. When the input light coming from the input waveguides (left) reaches to object plane of the first FPR, the light will diffract into the waveguides array. The length increment between adjacent waveguides equals to an integer of the centre wavelength λ_c . After propagating through the second FPR, the input light can be recovered in the image plan by constructive interference between multiple beams, with light at central wavelength λ_c in the centre. When the input light $\lambda_1 \neq \lambda_c$, the position in the image plan will shift by a certain value along the focal line. As a result, the input light with different wavelength components can be dispersed into corresponding output waveguides. If the light is input from the waveguides in the right side. All wavelength components will combine in the waveguide in the left side after transmitting through the first FPR.

The length difference between adjacent arrayed waveguides ΔL is

$$\Delta L = m \frac{\lambda_c}{n_{eff}} \quad (2.9)$$

where m is an integer namely the order of the waveguide array, λ_c is the central wavelength and n_{eff} is the effective index of the optical mode in the arrayed

waveguides. The schematic response of the AWG in the image plane is shown in Fig. 2.9(a).

Figure 2.8: Schematic working principle of an AWG taken from [129].

The optical field will fall on the same position at $2\pi m$ phase difference. This shows the periodic characteristic of the AWG. The schematic spectral response of output waveguide channels is shown in Fig. 2.9(b). The period in the frequency domain is called free spectral range (FSR). The condition is that the frequency shift Δf_{FSR} causes the phase difference to be 2π . Hence,

$$\frac{2\pi\Delta f_{FSR}}{c} n_g \Delta L = 2\pi \quad (2.10)$$

where n_g is the group index of the optical mode in the arrayed waveguides. Thus, the FSR is

$$\Delta f_{FSR} = \frac{c}{n_g \Delta L} = \frac{f_c}{m'} \quad (2.11)$$

where $m' = (n_g / n_{eff})m$. To function as a spectrometer, the bandwidth equals to the FSR Δf_{FSR} . The resolution equals to channel spacing Δf , which is expressed as $\Delta f_{FSR}/M$, where M is channel count, namely the number of output waveguides. Hence, the resolution is inversely proportional to channel count.

Figure 2.9: (a) Schematic response of the AWG in the image plane. (b) Schematic spectral response of output waveguide channels.

Planar concave grating (PCG) is similar to the grating based free-space counterpart. A lot of work have been done in NIR [13, 122] and mid-infrared (MIR) ranges [18, 21]. The schematic view of PCG from [21] is shown in Fig. 2.10. The area in blue is etched and the area in red is the Si area. The input light diffracts in the input aperture and propagates in the FPR. Grating structures are fabricated along the Rowland circle. The light rays reflected by each grating facets have different optical path delays. The adjacent optical paths have equal optical delay length ΔL . Hence, they will interfere at the output waveguides. Thus, the operating principle of a PCG is similar to that of an AWG. The optical delay length ΔL determines the FSR.

Figure 2.10: Schematic view of a planar concave grating taken from [21].

The super prism phenomenon of photonic crystals (PCs) with strong dispersion [130] can also be utilized to realize disperse light [23, 24]. Photonic crystals have properties and compatibility with PIC. Hence the PCs can be utilized as a spectrometer within a small footprint. The schematic of a PCs spectrometer from [23] is shown in Fig. 2.11, where light experiences only in plane propagation. A spectrometer demonstrates a resolution of 1.2 nm in 10 nm bandwidth on the Si_3N_4 on SiO_2 platform near 655 nm in [24]. A resolution larger than 5 nm in 50 nm bandwidth on SOI platform near 1550 nm is also demonstrated. PCs based on-chip spectrometers where light has in plane input and out of plane output are also demonstrated [25, 123, 125]. Though the PCs structure has compact size, the resolution is moderate, and the bandwidth is limited. Besides, the requirement of off-chip detection for PCs delivering out of plane output light reduces robustness and compactness.

Figure 2.11: Schematic working principle of PCs-based spectrometer taken from [23].

The schematic working principle of a spectrometer with stationary MRR (SMRR) array is shown in Fig. 2.12(a) from [27]. Figure 2.12(b) shows the spectrum reconstruction processes. The MRRs have an ultra-small radius increment, each for different wavelengths. The wanted wavelengths will be directed into the scatterer array and then into off-chip detector array or CCD array. The scatterer array can be replaced with on-chip waveguide-coupled detector array in real applications. The resolution depends on the resonance wavelength difference or radius difference between adjacent MRR. The bandwidth equals to the FSR of the MRR. Thus, to achieve large bandwidth, the radius should be as small as possible. To achieve high resolution, the adjacent MRR radius difference should be as small as possible. Hence, the MRR is fabricated by e-beam lithography to achieve ultra-small feature size and to precisely control the MRR radius to change the resonance wavelength of each MRR. A resolution of 0.6 nm in 56 nm spectral range is achieved in 84 detection channels. Whereas the small radius change ($\sim 1 \mu\text{m}$) is hard to be realized using mass production technology, namely fabrication technology using optical lithography. Besides, large channel count is required to achieve high resolution, reducing compactness and SNR.

Figure 2.12: On-chip spectrometer with SMRR array taken from [27].(a) Schematic working principle. (b) Spectrum reconstruction processes.

Random structures are exploited to demonstrate an on-chip spectrometer. The scanning electron microscope (SEM) image of the fabricated spectrometer from [26] is shown in Fig. 2.13. Light are scattered in the random media. The fins with photonic crystal structures act as channels to direct wanted diffused light into corresponding detection channels. Thereafter, the light will be scattered off-plane by the waveguide ridge along the semi-circle and detected by a microscope. In real application, on-chip integrated photodetectors will be used. The multiple scattering in the random structure increases the optical path, which enables fine spectral resolution. A high resolution of 0.75 nm in 25-nm bandwidth centred at 1512.5 nm is achieved with 25- μm -radius structure. The bandwidth $\Delta\lambda$ is expressed as

$$\Delta\lambda = 2M\delta\lambda \quad (2.12)$$

where M is detection channel count and $\delta\lambda$ is resolution. Hence, large channel count is required to achieve practical resolution and bandwidth. However, the channel count is limited in the small footprint. Even though the implementation of paralleled

structures is proposed to extend working bandwidth, the limit of bandwidth in each structure leads to large number of structures. For example, 4 structures are required to achieve 100 nm bandwidth. The total detection channel count will be 100. This will cause increased footprint and low SNR.

Figure 2.13: SEM image of the fabricated spectrometer using random structures taken from [26].

The schematic of an integrated digital planar holography (DPH) spectrometer from [29] is shown in Fig. 2.14. Input light is split by a directional coupler according to the bandwidth requirement. The split beams are directed to the DPH structures and reflected. Therefore, the light is demultiplexed. The demultiplexed light is directed into corresponding detection channels according to the wavelengths. However, large footprint (2 cm^2) and low SNR due to large channel count limit its application.

Figure 2.14: Schematic of an integrated DPH spectrometer taken from [29].

Methods of cascading dispersive elements to achieve high resolution as well as large bandwidth are developed such as cascaded tunable microring resonator (TMRR) and PCG [13], and cascaded AWG and SMRR array [31]. They are limited either by trade-off between SNR and bandwidth or fabrication variation.

Cascaded tunable MRR and PCG is shown in Fig. 2.15, achieving 0.1 nm resolution and 10 nm bandwidth in 100 detection channels [13]. The resolution depends on the linewidth of MRR resonance peak and the bandwidth equals to the FSR of the PCG. The FSR of MRR and the channel spacing of PCG should be well aligned during thermal tuning both MRR and PCG for time-multiplexing. This is quite challenging because the fabrication variation of the nano-silicon-photonic technology will induce phase error in both MRR and PCG. Hence, it puts stringent requirements on the designing and thermal tuning of both MRR and PCG.

Cascaded AWG and SMRR array is shown in Fig. 2.16 [31]. A high resolution of 0.1 nm in 10 nm spectral range with 100 detection channels is achieved. Similarly, the resolution depends on the linewidth of MRR resonance peak and the bandwidth is the FSR of the AWG. The light is pre-dispersed by the AWG. The pre-dispersed spectra will transmit into corresponding channels, where there are 10 SMRRs filters. The wavelength components will be filtered by each SMRR and read out by the

following detectors. Like spectrometer using only SMRR array, the resonance wavelength is very hard to control due to fabrication variation. Besides, the large detection channel count reduces the SNR and increases the footprint.

Figure 2.15: Micrograph of the cascaded spectrometer with tunable MRR and PCG from [13].

Figure 2.16: Schematic of the cascaded spectrometer with AWG and stationary MRR array from [31].

2.3.3 On-chip Fourier-transform Spectrometers

Fourier-transform spectrometer can overcome the limitation of resolution and channel count trade-off in dispersive approaches to achieve high resolution and high SNR. On-chip FT spectrometers are demonstrated such as FT spectrometer using

MEMS technology (MEMS FTS) [33, 35, 36], stationary-wave integrated Fourier-transform (SWIFT) [37, 38], spatial heterodyne spectrometers (SHS) [39-42, 131], tunable MZI [45, 46], co-propagative FT (CPFT) spectrometer [47], and digital Fourier-transform (DFT) spectrometer [48, 132]. However, trade-off between resolution and detection channel count still exists in approaches detecting spatial interferograms. Other methods are limited either by limited optical path difference (OPD) or undersampling.

The FT spectrometer based on MEMS technology using a Michelson interferometer configuration [33-36] is shown in Fig. 2.17. MEMS electrostatic comb driver actuators are adopted to scan the optical path length (OPL). The advanced MEMS technologies have enabled many advanced microspectrometers [5, 133]. An MEMS FT spectrometer is commercialized by Si ware with practical resolution (16 nm) and bandwidth ($> 1 \mu\text{m}$) with a compact size (7 mm^2). A large travel range of 1 mm is obtained. The resolution depends on the travel range of the comb driver. Compared to spectrometers based on PIC, the MEMS FTS suffers from unstableness of the comb driver and limited travel range. The requirements of off-chip light sources and detectors also reduces its robustness.

Figure 2.17: SEM image of a MEMS-based FT spectrometer taken from [36].

Many works have been done to realize the FT spectrometer onto a nano-silicon-phonic chip. Stationary-wave integrated Fourier-transform (SWIFT) spectrometer is demonstrated with a 4-nm spectral resolution and 96 nm bandwidth centred on 1500 nm [37] as shown in Fig. 2.18. The two counter-propagating waves interfere and form a standing wave namely the spatial interferogram along the waveguide. Near field optical probes with gold nanowires are implemented along the waveguide and interacts with the evanescent wave to directly detect light intensity. The gold nanowires are deposited on the top surface of the Si waveguide. Far field imaging is required to detect the scatter light from the near field probes. There are no movable or tuning parts in the highly compact spectrometer chip (0.1 mm^2). However, off-chip far field imaging will add to its size and weight and reduces its robustness. The finite nanowires may cause under-sampling, resulting in lower resolution.

Figure 2.18: Different configurations of SWIFT spectrometer taken from [37].

Spatial heterodyne spectrometers (SHS) are demonstrated, which are suitable for on-chip detection [16, 39-43, 134, 135]. Stationary Mach-Zehnder interferometer array is employed as shown in Fig. 2.19. The light is input by the multi-aperture or

multiple beam splitters into each MZI. It has N Mach-Zehnder interferometers. There is an OPD increment ΔL between adjacent MZIs. The first MZI has zero OPD and the N th MZI has an OPD of $N\Delta L$. The minimum MZI quantity is given by [39]

$$N_{\min} = 2 \frac{\Delta\lambda}{\delta\lambda} \quad (2.13)$$

where $\Delta\lambda$ is the bandwidth and $\delta\lambda$ is the resolution. Thus, there is trade-off between MZI counts (or bandwidth) and resolution. Hence, to achieve a 1-nm resolution at 50-nm bandwidth, 100 MZIs are required. The splitting of input light through multi-aperture or multiple beam splitters further reduces the SNR.

Figure 2.19: Optical micrograph of the SHS spectrometer taken from [41].

The typical configuration of the FT spectrometer mirroring the conventional structure is a thermally tunable MZI [45, 46] as shown in Fig. 2.20. Interferogram is continuously sampled while continuously changing the OPD between the two arms of the MZI in the time-domain. Only one detection channel is required. Hence, it can deliver large bandwidth and high SNR, compared to those probing spatial interferograms. A resolution of 3.05 nm has been demonstrated with arm length of 30.407 mm and maximum temperature excursion of 54 K [46].

The resolution $\delta\sigma$ depends on the maximum OPD and is expressed as

$$\delta\sigma = \frac{1}{OPD} \approx \frac{1}{\alpha\Delta TL} \quad (2.14)$$

where α is the thermo-optic coefficient of the waveguide, ΔT is the maximum temperature change and L is the MZI arm length. Thus, to further improve the resolution, long arm length and large temperature excursion is required. However, there is a limit in arm length concerning the optical loss (1-2 dB/cm) in the Si photonic chip. Higher temperature change will induce larger thermal expansion and increase power consumption.

Figure 2.20: Schematic of the tunable Mach-Zehnder interferometer taken from [46].

Co-propagative FT (CPFT) spectrometer using one stationary MZI is also demonstrated [47] as shown in Fig. 2.21. The two arms are designed to allow propagation of different optical modes to generate phase delay along the propagation direction. Grating structures are implemented between the two arms to reflect the spatial interferogram off-plane through evanescent wave probing. A resolution of 6 nm is achieved in a bandwidth larger than 100 nm centred at 850 nm within compact size (0.1 mm²) on the Si₃N₄ on SiO₂ platform.

The resolution $\delta\lambda$ can be expressed as [47]

$$\delta\lambda \approx 1.207 \frac{\lambda^2}{\Delta n_{eff} L} \quad (2.15)$$

where λ is central wavelength and L is the interferogram length. Hence, the resolution is easy to improve with longer sampling length. The interferogram period Λ should satisfy

$$\Lambda = \frac{\lambda}{\Delta n_{eff}} \quad (2.16)$$

where Δn_{eff} is the effective index difference between two optical modes. However, the requirement of off-chip detection reduces the compactness and robustness. Besides, probing weak evanescent wave and large detection channel count will reduce the SNR.

Figure 2.21: Schematic of the co-propagative stationary FTS taken from [47].

Digital Fourier-transform (DFT) spectrometer adopting multiple switches in MZI arms to manipulate optical path difference is developed and demonstrated [48, 49, 132]. The switches are tuned through thermo-optic effect. The DFT spectrometer detects discrete temporal interferogram by controlling the switches in the time-domain as shown in Fig. 2.22.

The spectral channel count is expressed as

$$N = 2^j \quad (2.17)$$

where j is the count of the switches. The resolution $\delta\lambda$ is expressed as

$$\delta\lambda = \frac{\lambda^2}{(2^j - 1)n_g \Delta L} \quad (2.18)$$

where n_g is the group index of the designed waveguide and ΔL is length difference of the two arms between adjacent switches. Hence, both spectral channel count and resolution scale up with the switch count. A high resolution of 0.2 nm with 6 switches is achieved. The finite switches will induce undersampling, reducing the resolution.

Figure 2.22: Diagram illustrating the structure of a DFT spectrometer from [132].

As a result, it remains challenging to develop an on-chip spectrometer, achieving high resolution, large bandwidth, and high SNR. The specifications of various methods to realize a spectrometer are summarized in Table 2.1.

Table 2.1: Specifications of various methods to achieve a spectrometer.

Principle	$\delta\lambda$ /nm	Range / μm	BW /nm	Finesse	Channel	Size / mm^2
Free space grating [*]	5	0.95-1.7	750	150	-	5.76e^4
Free space FTS ^{**}	1	0.9-2.6	3700	3700	1	2.3e^6
MEMS FTS ^{***}	16	1.35-2.5	1150	71.88	1	7
AWG ^[19]	0.2	1.54-1.55	10	50	50	64
PCG ^[18]	3.2	1.537-1.563	25.6	8	8	0.56
PCs ^[24]	1.2	0.65-0.66	10	8.33	8	9.1×10^{-3}
SMRR array ^[27]	0.6	1.55-1.606	56	93.33	84	1
Random structure ^[26]	0.75	1.5-1.525	25	33.33	25	1.96e^{-3}
DPH ^[29]	0.15	0.63-0.694, 0.766-0.85	148	986.67	926	200
TMRR and PCG ^[13]	0.1	1.483-1.493	10	100	100	2
AWG & SMRR array ^[31]	0.1	0.653-0.66	10	100	100	>1
SWIFT ^[37]	4	1.452-1.548	96	24	79	<1
SHS ^[41]	0.04	1.55-1.55075	0.75	18.75	32	7.5
Tunable MZI ^[46]	3.05	1.499-1.595	100	32.79	1	20
CPFT ^[47]	6	0.8-0.9	100	16.67	-	0.1
DFT ^[49]	0.2	1.55-1.57	20	100	1	-

^{*} Hamamatsu mini-spectrometer TF series C14486GA. ^{**} ARCoptix FT-NIR 0.9-2.6.

^{***} NeoSpectra Micro – SWS62231 Spectral Sensor.

2.4 Integrated Photodetectors

A photodetector is an optoelectronic device to convert light or photon signals to electric signals and used for detection of optical signals. Integrated photodetectors are of great use in photonic integrated circuits. Data transmission at a bit rate of 10 Gb/s over a long distance makes photonics integration a more easier approach to implement than electrical interconnect [136]. They can also be applied to enable compact and cost-effective photonic sensing and spectroscopy system [11, 14, 137, 138]. For a semiconductor photodetector, the internal photoelectric effect occurs when the incident photon energy is no less than the bandgap of the absorbing material. A semiconductor photodiode light detection circuit is shown in Fig. 2.23(a). The photodiode is reverse-biased. When it senses the light, electron and hole pairs are generated, and swept across the absorbing material with the application of external voltage, resulting in a photocurrent I_p proportional to the incident intensity. The schematic of photo-sensing of a PN junction with zero bias is shown in Fig. 2.23(b). The absorption of a photon excites an electron in P side from valence band to conduction band, resulting in the generation of an electron-hole pair. If there is an external reverse biased voltage, under the influence of the electric field, these carriers will move through the material and result in a current in the external circuit.

Figure 2.23: (a) Schematic of a semiconductor photodiode light detection circuit. (b) Schematic of photo-sensing of a PN junction.

The commonly used photodiode types are p-i-n type, metal-semiconductor-metal (MSM) type and avalanche type. The p-i-n type enables lower junction capacitance and more freedom to change the thickness of depletion region compared to a simple p-n type. In a normal-incidence p-i-n photodetector, thicker absorbing region allows higher quantum efficiency, while increases the carrier transit time, degrading the bandwidth. The capacitance can be reduced to improve the bandwidth by adopting small active area. The capacitance can also be reduced by adopting thicker absorbing region, which in turn increases the carrier transit time. In an MSM photodiode, carriers are prevented from entering the semiconductors, which enables lower dark current, leading to higher sensitivity. The capacitance is also lower. The responsivity is dramatically degraded by the electrode fingers. Hence, thick absorbing region is required and space between electrodes needs to be enlarged. However, this increases transit time and reduces bandwidth. Hence, both types encounter the trade-

off between quantum efficiency and bandwidth. Thus, there should be compromise between various parameters (quantum efficiency, bandwidth, SNR, etc) in photodiode design. The avalanche photodiode (APD) has much higher sensitivity due to the internal gain mechanism in the structure. One photon can generate multiple electron-hole pairs, which produces dramatically higher sensitivity.

Waveguide photodiode structure using side illuminating is developed to overcome the trade-off between quantum efficiency and bandwidth. The absorber can be made thinner to reduce transit times. Thus, to achieve larger bandwidth without sacrificing the responsivity. Waveguide-coupled photodiode allows more uniform absorption along the absorber length. Hence, the waveguide-coupled structure has been widely used in the PICs.

Conventional optical components in data communication system are typically III/V compound materials such as GaAs and InP due to high absorption efficiency, high drift carrier velocities, and good material quality [139]. With the fast development of silicon photonics, germanium has been a preferable material since it can be grown on silicon. The development of selective-area epitaxial growth of high-quality Ge on Si has enabled the waveguide-coupled Ge-on-SOI with high performance photodiodes on SOI platform. There are roughly two types of integrated photodiodes on Si photonic integrated platform, namely germanium-based and hybrid III/V-silicon [140]. Integration of photodetectors made of III/V materials on Si chip is difficult. The III/V layer stack is usually bonded to SOI wafer but can also be epitaxially grown on Si [139, 141]. Any III/V material that can be grown on InP can be used in hybrid III/V-Si PICs. However, the multiple epitaxy processes of III/V materials are complicated, and the bonding technology is not good enough to make good alignment between Si waveguides and hybrid PDs. Germanium is a good

absorbing material in the NIR wavelength band including the entire 1310 nm window and C and L bands. Germanium is especially attracted due to its good compatibility with nano-silicon-photonic fabrication line compared to the III/V materials. Selective area growth by chemical vapor deposition is the common way to integrate Ge waveguide-coupled photodiodes into the Si PICs. Figure 2.24(a) shows the schematic of a typical vertical configuration of waveguide coupled Ge-on-SOI photodiode. Figure 2.24(b) shows the schematic of a typical configuration of hybrid III/V-Si waveguide coupled photodiode.

Figure 2.24: (a) Schematic of a typical vertical waveguide coupled Ge-on-SOI photodiode. (b) Schematic of a typical hybrid III/V-Si waveguide coupled photodiode.

2.5 Summary

In this chapter, basic concepts of low-loss waveguides, photonic microring resonator, Mach-Zehnder interferometer, refractive index modification in photonic chip are introduced. Three refractive index modification methods are introduced

including electric field effect, plasma effect and thermo-optic effect. Among the three, the latter two are widely harnessed on Si photonic platform. Thermo-optic effect can achieve larger refractive index excursion than carrier injection or depletion on Si photonic chip, while the tuning speed using carrier injection or depletion (GHz) is much faster than that of thermo-optic effect (kHz). The fundamental concepts of spectrometers are presented. The state-of-the-art on-chip spectrometers are reviewed and discussed. Integrated photodetectors on Si photonic platform are also introduced.

CHAPTER 3

PRE-DISPERSED SPECTROMETERS

This chapter presents the design, fabrication and experimental demonstration of a pre-dispersed spectrometer with an arrayed waveguide grating (AWG) and thermally tunable microring resonator (MRR) array integrated with Ge-on-SOI photodetector (PD) array. The AWG pre-disperses the input spectrum to separated spectral bands. And the tunable MRR array retrieves the spectral bands with high resolution. The original input spectrum is retrieved by combining the retrieved spectra from each channel. The final resolution depends on the linewidth (sub-nanometre) of the MRR resonance peak. The bandwidth equals to the free spectral range (FSR) of the AWG, which can be as large as 100 nm. Hence, the proposed pre-dispersed spectrometer can achieve high resolution as well as large bandwidth using only a few channels.

The thermal tuning of the waveguide effective index exploiting thermo-optic (TO) effect is theoretically analysed concerning waveguide dispersion, thermo-optic nonlinearity and thermal expansion. The resonance wavelength tuning model of an microring resonator is built and theoretically analysed. The relation that resonance wavelength is proportional to heating power is theoretically and experimentally obtained. Heating efficiency and temperature response using a titanium nitride (TiN) heater are theoretically analyzed concerning heater dimensions, microring resonator dimensions, and thermal isolation trenches implementation. The fabricated pre-dispersed spectrometer is experimentally tested. The advantage of tunable microring resonator over stationary microring resonator are theoretically analysed and experimentally tested. The experimental results are presented and discussed.

3.1 Design of a Pre-dispersed Spectrometer

The schematic of the pre-dispersed spectrometer is shown in Fig. 3.1(a). It consists of an arrayed waveguide grating, tunable MRR array, and integrated Ge-on-SOI photodetector array. The waveguides and heaters are spaced with SiO₂ cladding. The light to be analyzed is input into the spectrometer chip through an inverse taper fibre-chip coupler. In each channel, the output waveguide of AWG is connected to a thermally tunable MRR and a PD is connected to the drop port of each MRR. Bond pads are used to wire bond the spectrometer chip to external PCB board for electric connections to supply electric signal to heaters, power photodetectors and read out electric signal from the photodetectors. Figure 3.1(b) shows the working principle. The working spectral bands of MRRs match the transmission spectra of the AWG. The working spectral bandwidth of the MRR equals to the FWHM of the transmission peak in each channel. The AWG is exploited to pre-disperse the input spectrum to several separated spectral bands into corresponding channels (Ch 1, Ch 2, ..., Ch n). The number of channel n equals to the amount of AWG output waveguides. Each tunable MRR functions as a high-resolution tunable filter due to its ultra-narrow linewidth of the resonance peak. In Ch n , the pre-dispersed spectrum transmits into the tunable MRR and detected by the PD. Hence, the pre-dispersed spectrum can be reconstructed with the tunable MRR. The same reconstruction process applies to all channels. Since each MRR works in a certain spectral band aligned with the transmission spectra of the AWG, the full initial input spectrum can be retrieved by combining the reconstructed spectra by the tunable MRR array. Microheaters are employed to separately tuning the corresponding MRRs by independently controlling the applied voltages. The output signal will be separately detected by photodetectors and read out through bond pads. The final resolution depends on the linewidth of

MRR resonance peak, which is sub-nanometer level. With multiple channels, the spectral range can be extended. The bandwidth equals to the FSR of the AWG, which can be as large as 100 nm. Hence, the pre-dispersed spectrometer is promising to achieve high resolution (sub-nanometer) and large bandwidth (100 nm) with only a few detection channels.

Figure 3.1: (a) Schematic of a pre-dispersed spectrometer with an AWG, tunable MRR array and integrated PD array. (b) Working principle of the pre-dispersed spectrometer. Working bands of MRRs should match the AWG transmission spectra.

3.2 Theoretical Analysis

The schematic of a thermally tunable MRR is shown in Fig. 3.2(a). It consists of two waveguides, a microring resonator, a microheater and an integrated photodetector (PD). Thermal tuning is exploited here to generate large refractive index change due to the large thermo-optic coefficient of Si. Direct current (DC) voltage can be applied on metal pads to power the heater. Electric signal from the PD can be read out through the metal pads. The 2D schematic of the thermally tunable microring resonator is shown in Fig. 3.2(b). The waveguides for coupling light in and out of the MRR namely waveguide 1 and waveguide 2 are designed to be nanowire strip waveguides for the best transmission of the fundamental quasi transverse electric (quasi-TE) mode. Input light is coupled into the tunable MRR from the input port. Wavelength components will resonate in the MRR if the wavelengths equal to the resonance wavelengths of the MRR. Due to the coupling between the MRR and waveguide 2, they will finally transmit into the drop port and detected by the PD. Other off-resonance wavelength components will transmit through the waveguide 1 into the throughput port. The resonance wavelength λ_r can be tuned by modifying the refractive index of the MRR with the microheater above it. Hence, the resonance wavelength will be tuned by changing the electric power applied on the heater.

The working principle of a tunable MRR as a tunable filter is shown in Fig. 3.3. Figure 3.3(a) shows the schematic of the input spectrum. The resonance wavelength is red-shifted while increasing the electric power P applied on the heater as shown in Fig. 3.3(b). Lines with different colors denote different tuning states of the MRR ($\lambda_1, \lambda_2, \dots, \lambda_n$). Figure 3.3(c) shows the reconstruction process. The PD detects a time-varying electric signal (denoted by back dashed line) while tuning the power P . Electric power P_n corresponds to the position where the resonance

wavelength is λ_n . Thus, by detecting the output power while tuning the applied heating power P on the heater, the input spectrum of the tunable MRR can be reconstructed.

Figure 3.2: (a) 3D Schematic of a thermally tunable microring resonator integrated with a Ge-on-SOI photodetector. (b) 2D schematic of the thermally tunable microring resonator.

Figure 3.3: Working principle of a tunable MRR as a tunable filter. (a) Schematic of the input spectrum. (b) MRR resonance wavelength thermal tuning. (c) The input spectrum reconstruction process.

3.2.1 Light Propagating in an MRR

When light is resonating in the MRR, the phase delay θ of the light in the ring is expressed as

$$\theta = 4\pi^2 n_{\text{eff}} \frac{r}{\lambda_r} = 2m\pi \quad (3.1)$$

where m is an integer.

Hence, the resonance wavelength λ_r is expressed as

$$\lambda_r = \frac{2\pi r}{m} n_{eff} \quad (3.2)$$

Figure 3.4 shows the simulation results of transmission characteristic of an MRR. The fundamental quasi-TE mode is harnessed for the MRR. Hence, the waveguides are designed to mainly transmit the quasi-TE mode. The core and cladding materials are silicon and silica, respectively. The average radius is 5 μm ; the waveguide core width is 450 nm; the waveguide core height is 220 nm; the gap between straight waveguide and the MRR is 200 nm. The simulation grid size is 40 nm in x , y , and z directions. The simulated free spectral range (FSR) is around 18 nm. Weak resonance peaks are detected from the add port. This is due to the light reflection in the MRR. The light reflection may cause resonance mode splitting.

Figure 3.4: Simulated transmission spectra of an MRR from (a) throughput port, (b) drop port and (c) add port.

3.2.2 Resonant Wavelength Tuning through TO Effect

DC voltage is applied on TiN heater to generate joule heating to thermally tune the MRR. Figure 3.5 shows the schematic cross section of the MRR with TiN

heater above. The SiO₂ cladding thickness between heater and the MRR is 1 μm to avoid excess loss through optical absorption by the heater. The static temperature T of MRR is proportional to the heating power P according to Green's function [142]. Thermal isolation trenches can reduce heat dissipation from TiN heater to Si substrate and the surrounding SiO₂. Hence, isolation trenches are adopted to improve heating efficiency. The schematic top view of an MRR with TiN heater above without isolation trenches is shown in Fig. 3.6(a). The schematic top view of an MRR with TiN heater above with isolation trenches is shown in Fig. 3.6(b). The 3D view of simulated static temperature distribution in the tunable MRR without isolation trenches is shown in Fig. 3.7(a). The total heating power on TiN heater is 2.8 mW. Ambient temperature is set as 297.15 K. The average radius of the MRR in the is 3.3 μm ; the dimensions of MRR cross section are $450 \times 220 \text{ nm}^2$; the average radius of the heater is 3.2 μm ; the dimensions of heater cross section are $1 \times 0.15 \text{ }\mu\text{m}^2$; the thickness of SiO₂ cladding sandwiched between MRR and heater is 1 μm ; the gap between trench and MRR is 2 μm . The static temperature distributions in the cross section of MRR without isolation trenches and with isolation trenches applied with the same heating power are shown in Fig. 3.7(b) and (c), respectively. The dimensions of the thermal isolation trenches are shown in Fig. 3.7(c). The maximum temperature is improved with isolation trenches.

Figure 3.5: Schematic cross section of an MRR with TiN heater above.

Figure 3.6: Schematic top views of a tunable MRR with TiN heater above (a) without and (b) with isolation trenches.

Figure 3.7: (a) 3D view of simulated static temperature distribution in the tunable MRR. Simulated static temperature distribution in the cross section of the MRR (b) without isolation trenches, and (c) with isolation trenches.

The simulation result of the relation between the static temperature and the heating power of heater is shown in Fig. 3.8(a), whereby the static temperature T is proportional to heating power P .

Therefore, the static temperature is expressed as

$$\Delta T = k_T P \quad (3.3)$$

where k_T is a constant denoting the heating efficiency. The coefficient k_{T1} with isolation trenches is larger than k_{T2} without isolation trenches. It means that the heating efficiency with isolation trenches is higher than that without isolation trenches, specifically $k_{T1} = 1.6 k_{T2}$ from Fig. 3.8(a). Therefore, the heating efficiency is 1.6 times that without isolation trenches. The simulation result of MRR temporal temperature with constant heating power applied on the heater (2.8 mW on TiN heater) is shown in Fig. 3.8(b). The temperature firstly rises quickly and then reaches a constant value namely static temperature. The temperature rise time it takes for heat to transfer from heater to Si waveguide is about 20 μs without isolation trenches and 38 μs with isolation trenches. Hence, the response with isolation trenches is slower than that without isolation trenches.

Figure 3.8: (a) Simulation result of the relation between static temperature T and heating power P . (b) Temporal temperature of the MRR with constant heating power with and without isolation trenches.

Simulation is performed to investigate the effect of heater width on the heating efficiency k_T . Figure 3.9(a) shows the simulation result of the relation between static temperature and heater width with 2.8 mW total heating power. It shows that the static temperature decreases with increasing heater width from 0.5 μ m to 3 μ m. The temporal temperature at different heater widths without isolation trenches is shown in Fig. 3.9(b). There is no obvious influence on the rise time when changing the heater width.

Figure 3.9: (a) Relation between static temperature and heater width with the same heating power. (b) Dynamic temperature change at different heater widths without trench.

The influence of microring resonator radius on heating efficiency k_T is also theoretically analysed. Figure 3.10 shows the simulation result of the relation between heating efficiency k_T and MRR average radius r . The MRR average value is set from 3 to 20 μm. The heater width is the same for all the MRRs. The heating efficiency data are well fit to the average radius when an exponential curve fitting is used with fitting R-square value of 0.99999. Thus, the heating efficiency can be expressed as

$$a = A_1 e^{-r/l_1} + A_2 e^{-r/l_2} + a_0 \quad (3.4)$$

Hence, the heating efficiency k_T is inversely proportional to MRR average radius r or perimeter.

Figure 3.10: Relation between heating efficiency k_T and MRR average radius r .

Refractive index is wavelength and temperature dependent [106, 143]. The thermo-optic coefficient (TOC) of silicon has a second-order dependent on temperature as shown in Fig. 3.11(a). The thermal expansion coefficient also presents an obvious dependence on temperature [144] as shown in Fig. 3.11(b). The effective index of the fundamental quasi-TE mode depends on both the core and cladding material, namely silicon and silica, respectively. The modal profile of the fundamental quasi-TE mode of the Si strip waveguide with dimension $450 \times 220 \text{ nm}^2$ is shown in Fig. 3.12. Figure 3.13 shows the simulation result that the effective index of the fundamental quasi-TE mode at 1550 nm is proportional to temperature. The effective index is well fit to temperature data with a second-order polynomial curve.

Figure 3.11: (a) Relation between thermo-optic coefficient (TOC) of Si and temperature. (b) Relation between thermal-expansion coefficient and temperature.

Figure 3.12: Modal profile of the fundamental quasi-TE mode of the strip waveguide.

Figure 3.13: Relation between effective index of the quasi-TE mode and temperature.

The calculated parameter values of waveguide dispersion, thermo-optic effect and thermal expansion around $T_0 = 300$ K and $\nu_0 = 193.414$ THz are shown in Table 3.1. The partial derivative is denoted as $\partial n_{eff}/\partial x = \partial_x n$. The dispersion and TOC are obtained for the quasi-TE mode of the waveguide. The refractive index model of SiO₂ is obtained based on the Sellmeier model considering both dispersion and temperature dependent thermo-optic coefficient [143] on the condition that the TOC of SiO₂ is nearly constant. The TOC model of Si is based on [145] considering the temperature range (>300 K), while the dispersion of Si is based on the Sellmeier model [106].

Resonance wavelength of the MRR considering effective index dispersion is expressed as

$$\lambda_r = \lambda_{r0} + \frac{\lambda_{r0}}{n_g} \Delta n_{eff} \quad (3.5)$$

where the resonance wavelength λ_r of MRR is proportional to effective index change Δn_{eff} . Hence, the resonance wavelength is proportional to temperature excursion ΔT or heating power P .

Table 3.1: Parameter values of waveguide dispersion, thermo-optic effect and thermal expansion.

Parameter	Value	Unit	Parameter	Value	Unit
$n_{eff} _{\nu_0}$	2.23	-	$\partial_{T^2}n$	2.5×10^{-7}	K^{-2}
$\partial_{\nu}n$	1.1×10^{-2}	THz^{-1}	$\partial_{\nu, T^2}n$	-4.6×10^{-9}	$K^{-2} THz^{-1}$
$\partial_{\nu^2}n$	4.8×10^{-6}	THz^{-2}	$\partial_{\nu^2, T^2}n$	1.7×10^{-9}	$K^{-2} THz^{-2}$
$\partial_{\nu^3}n$	-2.3×10^{-6}	THz^{-3}	$\partial_{\nu^3, T^2}n$	7.0×10^{-10}	$K^{-2} THz^{-3}$
Parameter	Value	Unit	Parameter	Value	Unit
$\partial_T n$	1.9×10^{-4}	K^{-1}	α_1	2.5×10^{-6}	K^{-1}
$\partial_{\nu, T}n$	3.5×10^{-7}	$K^{-1} THz^{-1}$	α_2	8.5×10^{-9}	K^{-1}
$\partial_{\nu^2, T}n$	-6.4×10^{-8}	$K^{-1} THz^{-2}$	α_3	-2.3×10^{-11}	K^{-1}
$\partial_{\nu^3, T}n$	-2.0×10^{-8}	$K^{-1} THz^{-3}$			

3.2.3 Spectral Range Extension with MRR Array

For a single tunable MRR, to work as a spectrometer, the working bandwidth equals to the FSR of the MRR. Since FSR is inversely proportional to the average radius, large FSR can be obtained with a smaller MRR. However, low resolution and high loss are encountered when reducing the radius. Hence, to extend the spectral range, tunable MRR array is adopted. To implement the tunable MRR array, pre-dispersion is required. Here, an arrayed waveguide grating is exploited to perform the pre-dispersion. The channel counts N of an AWG is expressed as

$$N = \frac{FSR}{\Delta\lambda_{ch}} \quad (3.6)$$

where FSR is free spectral range and $\Delta\lambda_{ch}$ is channel spacing. Thus, to achieve practical resolution using one single AWG, the channel count will be too large due to the trade-off between resolution $\Delta\lambda_{ch}$ and channel count N . Therefore, tunable MRR array with the pre-dispersion by an AWG makes it possible to achieve high resolution without resorting to large channel count.

A broadband light is firstly coupled through an input waveguide into the AWG, through which the light is pre-dispersed to several separated spectral bands. Thus, the input spectrum $I_{in}(\lambda)$ is decomposed to several separated spectral bands $I_1(\lambda)$, $I_2(\lambda)$, ..., $I_N(\lambda)$, where N is the total number of output channels. The intensity is shaped by an envelope $f_n(\lambda)$, where n is an integer ($0 < n \leq N$). Thus, the decomposed spectral band into channel n is expressed as

$$I_n(\lambda) = f_n(\lambda)I_{in}(\lambda) \quad (3.7)$$

The pre-dispersed spectral bands will thereafter transmit into the MRR array and detected by the PD array accordingly. The working bands of MRRs match the transmission spectra of the AWG. The tunable MRR in each channel works as a high-resolution tunable filter to reconstruct the spectral band in channel n . The output light intensity detected by the PD $I_o(\lambda)$ in channel n can be expressed as

$$I_o(\lambda) = \mu_n(\lambda)f_n(\lambda)T_n(\lambda)I_{in}(\lambda) \quad (3.8)$$

where $\mu_n(\lambda)$ is the coefficient due to loss and dispersion during transmission, $T_n(\lambda)$ is the transmission factor of the MRR in channel n and λ is within the spectral band of the MRR. As a result, the input spectrum $I_{in}(\lambda)$ in the working band of channel n is expressed as

$$I_{in}(\lambda) = \frac{1}{\mu_n(\lambda)f_n(\lambda)T_n(\lambda)}I_o(\lambda) \quad (3.9)$$

The factor $1/(\mu_n(\lambda)f_n(\lambda)T_n(\lambda))$ can be obtained by proper calibration with a tunable laser

source. Thus, the input spectrum $I_{in}(\lambda)$ within the working band of the MRR in channel n is reconstructed. The same reconstruction processes apply to all channels. Therefore, the original input spectrum $I_{in}(\lambda)$ can be retrieved by combining all the reconstructed spectra from all channels. Hence, the resolution of the pre-dispersed spectrometer depends on the MRR resonance linewidth instead of the AWG channel spacing. And the bandwidth equals to the FSR of the AWG, which can be as large as 100 nm through optimized design.

3.3 Experimental Results and Discussions

The pre-dispersed spectrometer is fabricated using the nano-silicon photonic fabrication technology. After fabricating the Si waveguides structures, several implantation processes and Ge epitaxy are performed for fabrication of the waveguide-coupled photodetector. Subsequently, a 1 μm -thick upper silicon dioxide (SiO_2) cladding layer is deposited and then a thin layer of titanium nitride (TiN) is formed to act as the resistive layer for heaters. An aluminium (Al) thin film is then patterned for electrical connection to power the heaters and photodetectors. The detailed fabrication processes are presented in Chapter 5.

The optical micrograph of an integrated pre-dispersed spectrometer is shown in Fig. 3.14. It consists an arrayed waveguide grating, tunable microring resonator array and Ge-on-SOI photodetector array. The AWG has 9 output waveguides. Each output channel has an integrated Ge-on-SOI photodetector in the drop port of the MRR. Bond pads are for wire bonding the chip to a printed circuit board (PCB) to apply electric signal to the heaters of the tunable MRRs, power and detect electric signal from the PDs. The SEM image of a microring resonator is shown in Fig. 3.15. The optical micrograph of an AWG is shown in Fig. 3.16 with 5 input waveguides

and 9 output waveguides, two free propagation regions (FPR) and an array of 19 waveguides. The input waveguide in the center of the FPR 1 is used as the input in the demonstration of the pre-dispersed spectrometer. Rib waveguides are designed for waveguide array so that the fabrication tolerance has less influence on the effective index. On the other hand, the waveguide with rib has less optical loss than that of the strip waveguide. The SEM image of the FPR 2 is shown in Fig. 3.17. Figure 3.18 shows the optical micrograph of a Ge-on-SOI photodetector. The pre-dispersed spectrometer chip is wire-bonded to a PCB for testing as shown in Fig. 3.19.

Figure 3.14: Optical micrograph of the integrated pre-dispersed spectrometer with tunable MRR array cascaded with an AWG and integrated with PD array.

Figure 3.15: SEM image of a microring resonator without SiO₂ cladding.

Figure 3.16: Optical micrograph of an arrayed waveguide grating. FPR: free propagation region.

Figure 3.17: SEM image of the FPR 2 of an arrayed waveguide grating.

Figure 3.18: Optical micrograph of a Ge-on-SOI photodetector.

Figure 3.19: The device with spectrometer chip wire-bonded to a PCB for testing.

3.3.1 Experimental Setup

The experimental setup for characterization of the pre-dispersed spectrometer is shown in Fig. 3.20. Two tunable laser sources (TLS-1: Santec TSL-510 and TLS-2 (ANDO AQ4321D) are used. Since the resonance of light in MRR requires interferences of light and the OPD of MRR is hundreds of micrometres, coherent sources such as LED and lasers are required for the pre-dispersed spectrometer in real applications. Polarization beam splitter (PBS) and polarization controller (PC) are used to ensure the input light into the pre-dispersed spectrometer is TE-polarized. Device under test (DUT) namely the pre-dispersed spectrometer chip with a thermoelectric cooler (TEC) under it is mounted on the holder of the XYZ stage for fibre-chip coupling. The temperature is controlled by a controller (CTL). A digital-to-analog converter (DAC) is used to convert digital signal to analog signal containing voltage information. An off-chip PD (Thorlabs, PDA-10CS-EC) is used to detect the output light intensity from output channels. Microcontroller is adopted to supply power to the MRR heaters and process electric signal from the PD. The optical loss rate of the fabricated waveguide with $450 \times 220 \text{ nm}^2$ dimensions for the

fundamental quasi-TE mode in the targeted wavelength range is 1-2 dB/cm. The optical loss of the inverse taper fibre-chip coupler is 3 dB.

Figure 3.20: Experimental setup for characterization of the AWG pre-dispersed spectrometer.

3.3.2 MRR and AWG Characterization

The MRR characterization is experimental tested. A broadband light source (Amonics C+L Band ASE broadband light source) is used to perform MRR characterization. An optical spectrum analyser (OSA, Yokogawa AQ6370D) is used to view the output spectra from the throughput port of the MRRs. The detailed transmission spectrum from channel 1 with ASE source input showing the resonance dips of the MRR is shown in Fig. 3.21(a). The average radius of the MRR is $\sim 33.9 \mu\text{m}$. The FSR of the MRR is 2.676 nm at 1555.496 nm. The linewidth of the resonance peaks from drop port of MRR is 0.07655 nm with quality factor of $\sim 20,531$ at 1571.668 nm.

The relation between the resonance wavelength and the electric power on MRR heater in channel 3 is shown in Fig. 3.21(b). The experimental resonance wavelength data can be well fit to the heating power with a linear equation. Hence, we assume a linear relation between resonance wavelength and heating power. The power consumption is 0.07 nm/mW. The maximum temperature excursion is estimated to be 20.938 K. Thus, the heating efficiency is $\sim 558 \text{ K/W}$.

Figure 3.21: (a) Transmission spectrum from channel 1 with ASE source input. (b) Relation between resonance wavelength and electric power on MRR heater in channel 3. The error bars denote standard deviation.

Figure 3.22 shows the resonance wavelengths of 7 microring resonators at resonating order m and $m-1$ with identical designed values. The designed average radius $r = 33.9 \mu\text{m}$. The resonance wavelength at the same resonating order is different for each MRR with a maximum shift of $\sim 1.2 \text{ nm}$ due to the fabrication

variation. The silicon (core) with SiO₂ (cladding) has a high index contrast. Hence the resonance wavelength of MRR is sensitive to the size change. The resonance wavelength at the same resonating order will vary from one MRR to another. And it cannot be neglected if the designed resonance wavelength tolerance is less than the resonance wavelength tolerance due to the fabrication variation. The electron beam lithography (EBL) can be used to fabricate structures with much smaller feature size and higher tolerance [27]. However, mass production has not been realized using EBL so far. Hence, active tuning is promising in controlling the resonance wavelength of the MRR.

Figure 3.22: Resonance wavelength at resonating order m and $m-1$ of 7 MRRs.

AWG characterization is experimentally tested using ASE source. OSA is used to view the output spectra from the throughput port of the MRRs. The transmission spectra of the 9 channels of the AWG with ASE source input is shown in Fig. 3.23(a). Lines in different colours correspond to different output channels. The FSR of the AWG is ~ 28 nm and the channel spacing is ~ 3 nm. The dips in the spectra are the resonance dips of the MRRs. The detailed transmission spectra of the AWG with ASE source input within one FSR is shown in Fig. 3.23(b). The FSR is 27 nm.

The channel spacing is 3.306 nm and the FWHM is 2.312 nm at 1553.616 nm in channel 4. The crosstalk is -19.3 dB.

Figure 3.23: (a) Transmissions spectra of the 9 channels of AWG with ASE source input. (b) Transmission spectra of the AWG with ASE source input within one FSR.

3.3.3 Characterization of the Pre-dispersed Spectrometer

The experimental setup to characterize the pre-dispersed spectrometer is shown in Fig. 3.20. TLS-1 is used for single wavelength characterization. The

normalized retrieved spectra from 9 channels are shown in Fig. 3.24, where lines in different colors correspond to different input wavelengths. TLS-1 is set with 0.2 nm wavelength increment.

Figure 3.24: Normalized retrieved spectra from the 9 channels with TLS-1 input.

The normalized retrieved spectra from channel 1-9 are shown in Fig. 3.25, Fig. 3.26, Fig. 3.27, Fig. 3.28, Fig. 3.29, Fig. 3.30, Fig. 3.31, Fig. 3.32 and Fig. 3.33, respectively. Lines in different colors correspond to different input wavelengths. There are two peaks in the retrieved spectra shown in Fig. 3.25, Fig. 3.26, Fig. 3.27, Fig. 3.28, Fig. 3.30 and Fig. 3.31. This is caused by the mode splitting due to light reflection in MRR.

TLS-1 and TLS-2 are used simultaneously for double wavelength characterization through an optical coupler. The normalized retrieved spectra with TLS-1 and TLS-2 input simultaneously with varying input power from channel 8 are shown in Fig. 3.34. TLS-1 and TLS-2 are set at 1566 nm and 1566.1 nm, respectively. The two wavelength components with 0.1 nm wavelength separation are differentiated. As a result, high resolution of 0.1 nm is achieved. This 0.1 nm resolution achieves the designed target of sub-nanometers.

Figure 3.25: Normalized retrieved spectra from channel 1 with TLS-1 input. The wavelength increment is set to 0.1 nm.

Figure 3.26: Normalized retrieved spectra from channel 2 with TLS-1 input. The wavelength increment is set to 0.1 nm.

Figure 3.27: Normalized retrieved spectra from channel 3 with TLS-1 input. The wavelength increment is set to 0.2 nm.

Figure 3.28: Normalized retrieved spectra from channel 4 with TLS-1 input. The wavelength increment is set to 0.1 nm.

Figure 3.29: Normalized retrieved spectra from channel 5 with TLS-1 input. The wavelength increment is set to 0.1 nm.

Figure 3.30: Normalized retrieved spectra from channel 6 with TLS-1 input. The wavelength increment is set to 0.1 nm.

Figure 3.31: Normalized retrieved spectra from channel 7 with TLS-1 input. The wavelength increment is set to 0.1 nm.

Figure 3.32: Normalized retrieved spectra from channel 8 with TLS-1 input. The wavelength increment is set to 0.1 nm.

Figure 3.33: Normalized retrieved spectra from channel 9 with TLS-1 input. The wavelength increment is set to 0.1 nm.

Figure 3.34: Normalized retrieved spectra with TLS-1 and TLS-2 (set at 1566 nm and 1566.1 nm, respectively) input simultaneously with varying input power from channel 8.

The experimentally measured working spectral ranges of the 9 channels of the AWG are shown in Table 3.2. The on-chip pre-dispersed spectrometer works from 1542.1 nm to 1569.1 nm, which covers a range of 27 nm. The bandwidth can be increased to 100 nm by optimizing the AWG design. The finesse, i.e. the ratio between bandwidth and resolution, is 270 considering the 0.1 nm resolution and 27 nm bandwidth. The finesse is larger than the state-of-the-art spectrometers listed in Table 2.1. The discontinuity between adjacent channels is due to the slight mismatch of the transmission spectra of the AWG and the MRR. And this can be solved by optimizing the MRR to match the AWG transmission profile better. As shown in Fig. 3.35, the FWHM values of the peaks in transmission spectra of AWG from channel 3 and channel 4 are 2.151 nm and 2.312 nm, respectively. It means that the transmission within the FWHM range is at least 2 folds of the transmission outside the FWHM range. Besides, working within the FWHM region will reduce the crosstalk between adjacent channels. Hence, the MRR should be tuned to cover the range of FWHM of the corresponding channel.

The AWG crosstalk will affect the SNR. Suppose the FSR of the MRR equals to Δ_1 (equal to bandwidth of the MRR working range) as shown in Fig. 3.36(a). The crosstalk ranges are denoted by range A and B. The working resonance position denoted in red in Fig. 3.36(b) is tuned from $\Delta\lambda = 0$ to $\Delta\lambda = \Delta\lambda_N$. When the MRR is tuned to $\Delta\lambda = \Delta\lambda_x$, resonance position on the left of the working resonance position enters crosstalk range A, and resonance position on the right of the working resonance position enters crosstalk range B. The two resonance positions will add noisy power to the detected power from PD. This noise level is increased with decreasing crosstalk value, inducing smaller SNR and dynamic range. Here, the working bandwidth equals to FWHM of the AWG. When the FSR of the MRR equals to Δ_2 , which equals to

bandwidth of working range plus half of crosstalk range, there is only one resonance position, i.e. the working resonance position in the crosstalk range and working range. Hence, when MRR FSR is larger than Δ_2 , the influence of channel crosstalk can be decreased. Hence, the SNR will be improved with larger crosstalk value and/or optimized FSR of MRR. Insertion loss will also reduce the SNR. The insertion loss is ~9 dB considering the loss in polarization beam splitter (3 dB), polarization controller (3 dB) and fibre-chip coupler (3 dB). This loss can be reduced by integrating the PBS and PC on the spectrometer chip.

Table 3.2: Experimentally measured working spectral ranges of the 9 channels of the AWG.

Channel number	Working range (nm)	Channel number	Working range (nm)
Channel 1	1542.1-1544.6	Channel 2	1544.7-1547.1
Channel 3	1549.9-1552	Channel 4	1552.5-1554.9
Channel 5	1555-1556.7	Channel 6	1556.9-1559.3
Channel 7	1561.9-1564.5	Channel 8	1565-1567.5
Channel 9	1566.7-1569.1

Figure 3.35: Transmission spectrum from Ch 3 and Ch 4 with ASE source input.

Figure 3.36: Analysis of AWG crosstalk. (a) Transmission from channel n with ASE source input. (b) Schematic transmission of MRR while tuning the MRR.

3.4 Summary

In this chapter, a pre-dispersed on-chip spectrometer integrated with on-chip Ge-on-SOI photodetector array is designed, fabricated and demonstrated. The spectrometer is realized with an arrayed waveguide grating and thermally tunable microring resonator array. The thermal tuning of the effective index of waveguide fundamental quasi-TE mode is theoretically analysed. The influences of heater width, isolation trenches and MRR perimeter on heating efficiency are theoretically studied. The approaches to improving heating efficiency are proposed and investigated. The model of the thermally tunable MRR is built and theoretical analysed. The model of the pre-dispersed spectrometer is built and theoretically studied.

The pre-dispersed spectrometer is demonstrated by inputting with single laser sources and double laser sources. A high resolution of 0.1 nm and a large bandwidth of 27 nm are achieved with only 9 channels. The MRR thermal tuning power is 0.07 nm/mW. The maximum temperature excursion is estimated to be 20.938 K and the heating efficiency is ~558 K/W. It is very compact with a small footprint of 3×3 mm². It has high potential to innovate a spectrometer for various spectrometric applications such as wavelength monitoring in optical networks, integrated sensing and spectroscopy systems.

CHAPTER 4

MRR-ASSISTED FTS

This chapter presents the design, fabrication and experiment demonstration of a microring resonator-assisted Fourier-transform (RAFT) spectrometer on a single photonic chip. The proposed RAFT spectrometer consists of a tunable microring resonator (MRR) and a tunable Mach-Zehnder interferometer (MZI). The input spectrum is firstly filtered by the MRR to a tuned spectrum with sparsely spaced wavelength components such that the wavelength separation is sufficiently large to be resolved by the tunable MZI. Thereafter, the MRR will be finely tuned to shift the filtered spectrum for the recovery of whole input spectrum. Hence, the final resolution depends on the tuning resolution of the resonance wavelength of the MRR, which is in sub-nanometre level due to the ultra-narrow linewidth of the resonance peak. The resolution is dramatically boosted by the MRR far beyond the classic Rayleigh criterion of the FT spectrometer without resorting to large optical path difference (OPD) of the MZI. It achieves high resolution and large bandwidth in a single channel to realize high SNR.

The thermal tuning of Fourier-transform spectrometer using a tunable Mach-Zehnder interferometer exploiting thermo-optic effect is theoretically analysed. Effective index thermal tuning is theoretically analysed. The thermal tuning model of the MZI is built. The fabricated RAFT spectrometer is experimentally tested. The experimental results are presented and discussed. And the implementations of thermal isolation trenches and low loss Si waveguide to improve the performance of the RAFT spectrometer are also developed and experimentally tested.

4.1 Design of an FTS Enhanced with an MRR

Figure 4.1 shows the schematic of a microring resonator-assisted Fourier-transform spectrometer. It consists of a thermally tunable microring resonator, a thermally tunable Mach-Zehnder interferometer, and a waveguide-coupled photodetector. The MRR is cascaded with the MZI to boost resolution. The average radius of the MRR is $3.2 \mu\text{m}$ to accommodate the resolution of the FT spectrometer. The schematic transmission spectra from throughput port and drop port of MRR are shown in Fig. 4.2. The wavelengths where dips or peaks appear are resonance wavelengths. The wavelength or frequency difference between adjacent dips or peaks is free spectral range (FSR). The schematic input spectrum is shown in Fig. 4.3(a). The light is input to the MRR first and then part of the light transmits to the drop port of the MRR, namely the input of the tunable MZI. There is also part of light that transmits into the throughput port of the MRR. Heater 1 is used to tune the resonance wavelength of the MRR and heater 2 is used to tune the optical path difference (OPD) between the two arms of the MZI. In Fig. 4.3(b) and (c), lines in different colours (styles) denote different tuning states of the MRR. Figure 4.3(b) shows the tuned spectra output from the drop port of MRR where the spectrum is red-shifted when MRR is thermally tuned. The tunable MZI will retrieve each tuned spectrum as shown in Fig. 4.3(c). The MRR will be tuned to finely shift the spectrum ($\Delta\lambda_1, \Delta\lambda_2, \Delta\lambda_3, \dots, \Delta\lambda_n$) as to achieve a high resolution. The tuning resolution depends on the linewidth of MRR resonance peak which is sub-nanometre level. The resonance wavelength shift $\Delta\lambda_r = \Delta\lambda_n$ ($0 \leq \Delta\lambda_n < \text{FSR}$). By combining the retrieved spectra, the original input spectrum can be finally retrieved. The designed resolution of the tunable MZI is tens of nanometres and the designed linewidth of MRR resonance peak is sub-nanometre level. Hence, the final resolution can be significantly boosted. The bandwidth depends

on the components in the transmission paths which can be as large as 100 nm. Therefore, the proposed RAFT spectrometer allows both high resolution (sub-nanometre) and large bandwidth (100 nm) in one detection channel.

Figure 4.1: Schematic of the designed microring resonator-assisted Fourier-transform spectrometer.

Figure 4.2: Schematic transmission spectra from throughput port and drop port of an MRR.

Figure 4.3: (a) Schematic input spectrum. (b) Output tuned spectra from the drop port of MRR at different tuned states of the MRR. The different tuned states are denoted by lines with different colours (styles). (c) Retrieved spectra by the tunable MZI.

4.2 Theoretical Analysis

The fundamental quasi-TE mode of the waveguides in MZI arms is harnessed. Hence, the waveguide dimensions are $450 \times 220 \text{ nm}^2$. We will only consider the thermo-optic tuning induced effect on effective index n_{eff} of the fundamental quasi-TE mode. In practice, some effects should be considered when analysing the thermal tuning of MZI as discussed in Chapter 3. Firstly, the effective index n_{eff} of silicon (Si) waveguide has a strong wavelength dispersion. Secondly, the thermo-optic coefficient (TOC) has a nonlinear behaviour during thermal tuning. The thermal expansion due to temperature excursion also induces waveguide length change ΔL . The fabrication variation will induce effective index difference (δn) and imbalance

(δL) between two arms. The second order of TOC is neglected for temperature excursion of 100 K due to the maximum contribution of 1.2% compared to the first order contribution of 13.5% as shown in Fig. 4.4(a). The third order term of thermal expansion coefficient has a neglectable contribution (maximum 1.7%) for temperature excursion of 100 K compared to lower orders, i.e. 34.2% for the first order and 9.9% for the second order as shown in Fig. 4.4(b).

Figure 4.4: Relation between term contribution and temperature excursion. (a) TOC of silicon. (b) Thermal expansion coefficient.

Hence, the effective index change Δn_{eff} is modified as

$$\Delta n_{eff} = \Delta n_{eff}(v, \Delta T) - \delta n(v) \quad (4.1)$$

where $\Delta T = T - T_0$ with $T_0 = 300$ K. The effective index considering up to the third order around $\nu_0 = 193.414$ THz is expressed as

$$n_{eff}(\nu) = n_{eff}|_{\nu_0} + \partial_{\nu} n \Delta \nu + \frac{1}{2} \partial_{\nu^2} n \Delta \nu^2 + \frac{1}{6} \partial_{\nu^3} n \Delta \nu^3 \quad (4.2)$$

The modified effective index change Δn_{eff} is written as

$$\begin{aligned} \Delta n_{eff}(\nu, \Delta T) = & (\partial_T n + \partial_{\nu, T} n \Delta \nu + \frac{1}{2} \partial_{\nu^2, T} n \Delta \nu^2 + \frac{1}{6} \partial_{\nu^3, T} n \Delta \nu^3) \Delta T \\ & + \frac{1}{2} (\partial_{T^2} n + \partial_{\nu, T^2} n \Delta \nu + \frac{1}{2} \partial_{\nu^2, T^2} n \Delta \nu^2 + \frac{1}{6} \partial_{\nu^3, T^3} n \Delta \nu^3) \Delta T^2 \end{aligned} \quad (4.3)$$

The effective index difference induced by fabrication δn is expressed as

$$\delta n(\nu) = \delta(n_{eff}|_{\nu_0}) + \delta(\partial_{\nu} n) \Delta \nu + \frac{1}{2} \delta(\partial_{\nu^2} n) \Delta \nu^2 + \frac{1}{6} \delta(\partial_{\nu^3} n) \Delta \nu^3 \quad (4.4)$$

The total difference of arm length is expressed as

$$\Delta L = \Delta L(\Delta T) - \delta L \quad (4.5)$$

The modified arm length is expressed as

$$\Delta L(\Delta T) = L(\alpha_1 \Delta T + \alpha_2 \Delta T^2 + \alpha_3 \Delta T^3) \quad (4.6)$$

The input spectrum $I_i(\nu)$ firstly transmits into the MRR. The transmitted spectrum $I_m(\nu)$ output from the drop port is expressed as

$$I_m(\nu) = T(\nu) I_i(\nu) \quad (4.7)$$

where $T(\nu)$ is the transmission factor of the MRR. One arm of the MZI is thermally tuned by heater 2. For an input spectrum with single wavelength $I_m(\nu_0)$ as the input of the tunable MZI, the output intensity of MZI is expressed as

$$I_o(\delta) = 0.5 I_m(\nu_0) (1 + \cos(2\pi \nu_0 \delta / c)) \quad (4.8)$$

where $\delta = \Delta n_{eff} L$ is the optical path difference of the MZI with arm length L . In practice, there are some factors that will influence the signal intensity detected by the detector. The beam splitter is not perfect to give 50% reflection and 50% transmission. Light will experience losses in beam splitters and in waveguides of MZI arms, etc.

As a result, the output intensity is modified as

$$I_o(\delta) = 0.5T(v_0)H(v_0)G(v_0)I_i(v_0)(1 + \cos(2\pi v_0 \delta / c)) \quad (4.9)$$

where $H(v_0)$ and $G(v_0)$ are wavelength dependent correction factors for imperfect beam splitters and optical losses, respectively. The coefficient $0.5T(v_0)H(v_0)G(v_0)$ can be set to $B(v_0)$. Thus, the output intensity is $B(v_0)I_i(v_0)(1 + \cos(2\pi v_0 \delta / c))$, where the modulated portion $B(v_0)I_i(v_0)\cos(2\pi v_0 \delta / c)$ constitutes the interferogram as shown in Fig. 4.5. Thus, taking the modulated portion only, the output intensity for a broadband input spectrum is

$$I_o(\tau) = \int_{-\infty}^{+\infty} B(v)I_i(v)\cos(2\pi v\tau)dv \quad (4.10)$$

where $\tau = \delta/c$. After applying Fourier transform to the above equation, the input spectrum $I_i(\sigma)$ can be obtained as

$$I_i(v) = \frac{2}{B(v)} \int_0^{+\infty} I_o(\tau)\cos(2\pi v\tau)d\tau \quad (4.11)$$

Taking account of waveguide dispersion, temperature dependent TOC and thermal expansion, the phase difference between two arms is simplified to

$$\Delta\phi(v, \tau) = \phi(v) + 2\pi u\Gamma \quad (4.12)$$

with the modified time delay

$$\Gamma \equiv \tau + \gamma_2 \tau^2 \quad (4.13)$$

and modified optical frequency

$$u \equiv v_0 + \Delta v(1 + \xi_1) \quad (4.14)$$

Real time delay τ is linearized as modified time delay Γ to match the phase difference.

The modified optical frequency stretches the original frequency around v_0 by a factor $1 + \xi_1$. According to the definitions of γ_2 and ξ_1 in [46], γ_2 is expressed as

$$\gamma_2 \equiv \frac{c}{L} \frac{n_{eff}|_{v_0} \alpha_2 + \partial_T n \alpha_1 + \frac{1}{2} \partial_{T^2} n}{(n_{eff}|_{v_0} \alpha_1 + \partial_T n)^2} \quad (4.15)$$

and the parameter ξ_1 is expressed as

$$\xi_1 \equiv \frac{v_0(\partial_v n \alpha_1 + \partial_{v,T} n)}{n_{eff}|_{v_0} \alpha_1 + \partial_T n} \quad (4.16)$$

Hence, TOC nonlinearity and thermal expansion broaden and shift the spectrum to higher frequencies. Waveguide dispersion contributes to stretched retrieved spectrum around v_0 [46]. Replace v with u in Eq. 4.11, we obtain

$$I_o(\Gamma) = \frac{1}{1 + \xi_1} \int_{-\infty}^{+\infty} B(u) [I_i(u) \cos(\varphi(u))] \cos(2\pi u \Gamma) du \quad (4.17)$$

Hence, the modified input spectrum is expressed as

$$I_i(u) = \frac{2(1 + \xi_1)}{B(u)} \int_0^{+\infty} I_o(\Gamma) \cos(2\pi u \Gamma) d\Gamma \quad (4.18)$$

Finally, the original input spectrum is retrieved by transforming u to v ,

$$I_i(u) \xrightarrow{v = \frac{u - v_0}{1 + \xi_1} + v_0} I_i(v) \quad (4.19)$$

The calibration of absolute optical frequency v , γ_2 and ξ_1 can be performed by a tunable laser source at different laser frequencies (on resonance and at least three) [46]. The time delay can be written as $\tau = \kappa_\tau P$. The interferogram with a laser source input is

$$I(P, v) = A \cos[2\pi K(v)P(1 + \gamma_w P) + \varphi(v)] \quad (4.20)$$

where $K(v) = \kappa_\tau(1 + \xi_1)\Delta v + \kappa_\tau v_0$ and $\gamma_w = \kappa_\tau \gamma_2$. The coefficient $K(v)$ and γ_w can be obtained by curve-fitting the interferograms with Eq. 4.21, a nonlinear cosine function. $B(u)$ can be obtained through experimental power calibration for each optical frequency. The same retrieval process applies to all MRR thermal tuning states. By scanning the MRR resonance wavelength shift from 0 to FSR, the original

input spectrum will be retrieved by combining all retrieved sparse spectra.

Figure 4.5: Schematic interferogram in MZI output with single wavelength source input.

The simulated relation between OPD and the resolution of the tunable MZI and the heating power on heater 2 is shown in Fig. 4.6. Here we mainly focus on the variation trends of OPD and resolution with changing k_T and L . Considering that the first-order term of TOC contributes far less than the zero-order term, a constant TOC is assumed in the simulation for simplicity. The temperature excursion is fixed at a moderate value of 24.9 K. The conditions with different parameters are shown in Table 4.1. Therefore, the resolution of the tunable MZI can be improved either by increasing the arm length and/or increasing the heating efficiency. The maximum arm length depends on the tolerable optical loss. For waveguide with Si core and SiO₂ cladding adopted here, the loss rate is 1~2 dB/cm, resulting in 10-20 dB loss with 10 cm length. The loss experienced in the device will add to the total insertion loss, leading to low throughput namely low SNR. One efficient way to improve heating efficiency is to fabricate isolation trenches near MZI arms to remove Si substrate to reduce heat dissipation [146]. Another way is to change heater material and put it on

the waveguide rib [146]. The two approaches to improving heating efficiency are also viable for reducing heat consumption of MRR. Without the MRR, to achieve 0.47 nm resolution, the OPD is ~ 102 cm at $k_T = 14.9$ K/W without increasing the maximum temperature excursion, which will induce >100 dB loss.

Figure 4.6: Relation between OPD and heating power and relation between resolution and heating power at (a) fixed arm length L and (b) fixed heating efficiency a .

Table 4.1: Simulation conditions with different parameters.

Conditions	Effective TOC k (/K)	Heating efficiency a (K/W)	Arm length L (cm)
C1	1.95×10^{-4}	14.9	2.46
C2	1.95×10^{-4}	50	2.46
C3	1.95×10^{-4}	100	2.46
C4	1.95×10^{-4}	14.9	5
C5	1.95×10^{-4}	14.9	10

By cascading an MRR before the tunable MZI, the resolution can be dramatically boosted by taking advantage of the high finesse of the MRR resonance peaks. Therefore, high resolution can be achieved at a moderate optical path length and temperature change.

4.3 Experimental Results and Discussions

The microring resonator-assisted Fourier-transform (RAFT) spectrometer is fabricated using the nano-silicon photonic fabrication technology. The fabrication steps are described in Chapter 3. The final step is that the isolation trenches are formed through etching SiO_2 top cladding and Si substrate. The detailed fabricated processes are presented in Chapter 5. The micrograph of the fabricated RAFT spectrometer after Ge epitaxial growth is shown in Fig. 4.7. A tunable microring resonator is cascaded with a tunable Mach-Zehnder interferometer. The output of MZI is split by a 50/50 beam splitter into two parts. Each part has 50% of the input light. One is output through fibre-chip coupler for experimental testing and the other is detected by an integrated PD. Figure 4.8 shows the SEM image of a microring

resonator. Figure 4.9 shows the optical micrograph of a tunable MRR with thermal isolation trenches. Figures 4.10 shows the SEM image of TiN heater 1. Figure 4.11 shows the SEM image of waveguides in the arm of an MZI. Figure 4.12 shows the SEM image of a 50/50 beam splitter in an MZI. The RAFT spectrometer chip is wire-bonded to a PCB board for testing as shown in Fig. 4.13.

Figure 4.7: Optical micrograph of the RAFT spectrometer after Ge epitaxial growth.

Figure 4.8: SEM image of a microring resonator.

Figure 4.9: Optical micrograph of a tunable microring resonator with thermal isolation trenches.

Figure 4.10: SEM image of the TiN heater1.

Figure 4.11: SEM image of waveguides in the arm of a Mach-Zehnder interferometer.

Figure 4.12: SEM image of a 50/50 beam splitter.

Figure 4.13: The device with spectrometer chip wire-bonded to a PCB for testing.

4.3.1 Experimental Setup

Figure 4.14 shows the experimental setup of demonstration of the RAFT spectrometer. TLS-1 and TLS-2 are used for the testing. The working of tunable MZI requires interferences of light beams from both arms and the OPD of the MZI is hundreds of micrometres. Hence, coherent sources such as LED and lasers are required for the RAFT spectrometer in real applications. The PBS and PC will control the light input into the on-chip RAFT spectrometer to be TE polarized. A laptop is used to control the microcontroller to supply DC voltages to heater 1 and heater 2. DACs are used to convert digital signal to analog signal containing voltage information. An operational power amplifier (OPA) is used to amplify the output voltage signal to supply direct current (DC) voltage onto heater 2. The light from the output of the RAFT spectrometer is detected by an off-chip PD. The electric signal from the PD is detected by the microcontroller to be processed by the laptop. DUT with an underlying TEC to make temperature stable is mounted on the holder of the XYZ stage for coupling light into and out of the DUT. Figure 4.15 shows the DUT is mounted on the XYZ stage for fibre alignment. Figure 4.16 shows the electronic

circuit control block with a PCB board controlled by Arduino module.

Figure 4.14: Experimental setup of demonstration of the RAFT spectrometer.

Figure 4.15: Device under test (DUT) mounted on XYZ stage.

Figure 4.16: Electronic circuit control block with an OPA and DACs.

4.3.2 Thermal Tuning of MRR and MZI

Thermal tuning of the tunable MRR is experimentally tested. ASE source is adopted. The light output from the throughput port of the MRR is detected by OSA. The transmission spectrum from throughput port of the MRR is shown in Fig. 4.17. Based on the transmission spectrum, the resonance wavelengths are $\lambda_{on1} = 1528.256$ nm, $\lambda_{on2} = 1555.776$ nm, and $\lambda_{on3} = 1584.296$ nm. The measured FSR is ~ 28 nm. The linewidth is 0.15819 nm when $\lambda_r = 1528.256$ nm. Thus, the quality factor is $\sim 9,661$. The transmission spectra within one FSR from throughput port are shown in Fig. 4.18(a). The resonance wavelength is red-shifted with increasing applied voltage on heater 1. The resistance of MRR heater is ~ 0.547 k Ω . The tuning power consumption is 1.23 mW/nm (~ 34.44 mW/FSR). The maximum estimated temperature change is 188.8 K and the MRR heater efficiency is around 5.5×10^3 K/W. The resonance wavelength of the MRR is proportional to the heating power of MRR heater 1 as

shown in Fig. 4.18(b), which agrees well with the theoretical analysis in Chapter 3. The resonance wavelength is well fit to the heating power with a linear equation. Hence, we assume a linear relation between resonance wavelength and heating power.

When heating MZI only, the resonance wavelength will also be red-shifted due to thermal crosstalk that the heat will be conducted from MZI heater to MRR. A linear relation is also obtained between the resonance wavelength and the heating power on MZI heater 2 as shown in Fig. 4.19. The value of resonance wavelength shift is from 0 to ~1.1 nm. Since there is no obvious influence on MZI by heating MRR from experimental observation, the influence of heating power of MRR heater 1 on MZI is neglected.

Figure 4.17: Transmission spectrum from the throughput port of the MRR with ASE source input detected by OSA.

Figure 4.18: (a) Transmission spectra within one FSR from the throughput port of the MRR with ASE source input detected by OSA at different applied voltages on heater 1. (b) Relation between resonance wavelength and heating power on MRR heater 1.

Figure 4.19: Relation between resonance wavelength shift and heating power on MZI heater 2.

The interferogram can be obtained by detecting the intensity in MZI output while applying a fixed voltage on heater 1 and a sweeping voltage signal on heater 2. The experiment setup is shown in Fig. 4.14. The interferogram with TLS-1 input before temperature compensation is shown in Fig. 4.20(a). The amplitude is quickly decreased because of resonance wavelength shift due to thermal crosstalk. Temperature compensation is performed to reduce influence by the thermal crosstalk. Figure 4.20(b) shows the interferogram after temperature compensation. More interferogram periods are acquired after temperature compensation.

Figure 4.20: Interferograms with TLS-1 input (a) before compensation and (b) after compensation.

4.3.3 Characterization of MRR-assisted FTS

Characterization of the RAFT spectrometer is performed with experimental setup shown in Fig. 4.14. Figure 4.21(a) shows the output interferogram from MZI output port with TLS-1 input (set at on-resonance wavelength 1584.620 nm) with 6 mW input power when MRR tuning state $\Delta\lambda = 3.38$ nm. The features namely the gradually decreasing amplitude and the non-smooth envelope of peaks are due to the

misalignment between chip and optical fibres and are also due to the vibration of the optical fibres as a result of thermal expansion of the chip while heating [46]. There is a phase delay in the interferogram without power applied because the two arms of the MZI are not balanced due to fabrication variation. However, the features and the initial phase delay will affect the intensity but not the frequency position after fast Fourier transform (FFT). And fortunately, the intensity can be retrieved through proper calibration [32]. The misalignment and the vibration will not appear in practical applications as the optical fibres will be permanently fixed to the chip. More than 80 periods are observed with a maximum OPD of approximately 128.354 μm , which corresponds to a theoretical resolution of 77.91 cm^{-1} (19.32 nm at 1584.62 nm). The resistance of the MZI heater 2 is $\sim 1.277 \text{ k}\Omega$. The power consumption of the tunable MZI is approximately 11.185 mW/ π . Figure 4.21(b) shows the FFT result of the interferogram. A single peak appears, of which the position corresponds to the wavelength of TLS-1.

Curve-fitting the interferograms with TLS-1 input is performed to obtain the coefficients of $K(\nu)$ and γ_w . As shown in Fig. 4.22(a), the mean power intensity of the interferogram is subtracted to obtain the black curve. The envelope (red) is obtained by Hilbert transform. Hence, the normalized power intensity is obtained (data points in red) as shown in Fig. 4.22(b). The curve in black is the fitting result. Hence, $K(\nu)$ and γ_w are obtained by linear fitting of at least three data points as shown in Fig. 4.23(a) and (b), respectively. The parameter κ_τ relating heating power to time delay is 0.245 ps/W. The stretching parameter ζ_1 is 0.55. The parameter γ_2 is $8 \times 10^{-3} \text{ ps}^{-1}$. The parameter η_I equals to $(n_{\text{eff}}|_{\nu=0} \alpha_1 + \partial T n) L / c \approx 1.56 \times 10^{-14}$. Hence, the maximum temperature excursion is $\Delta T = \kappa_\tau P_{\text{m-max}} / \eta_I \approx 24.9 \text{ K}$ and the heating efficiency $k_T = \Delta T / P_{\text{m-max}} \approx 13.8 \text{ K/W}$. For temperature excursion of MZI less than 30 K in our

experiment, the first order contribution of TOC is less than 4%. Both the maximum temperature excursion (up to 150°C) and the arm length can be further increased considering optical loss and the material tolerance, to increase OPD, which enables higher resolution of the tunable MZI.

Figure 4.21: (a) The interferogram with TLS-1 input (at on-resonance wavelength 1584.62 nm). (b) FFT result of the interferogram.

Figure 4.22: Calibration with TLS-1. (a) Interferogram (black) after the mean value is subtracted. The envelop (red) obtained by Hilbert transform. (b) Interferogram (red) after normalization. The data are fitted with Eq. 4.20.

Figure 4.23: (a) Parameter $K(\nu)$ from the fitting. (b) Parameter γ_w from the curve-fitting of interferograms with TLS-1 input.

The resonance wavelengths are $\lambda_{on1} = 1528.488$ nm, $\lambda_{on2} = 1556.02$ nm and $\lambda_{on3} = 1584.62$ nm when MRR tuning state $\Delta\lambda = 3.38$ nm. Figure 4.24 shows the retrieved spectra with TLS-1 input (set at the three on-resonance wavelengths when $\Delta\lambda = 3.38$ nm) with 8 mW input power for each wavelength.

Figure 4.24: Retrieved spectra with TLS-1 input (set at the three on-resonance wavelengths when $\Delta\lambda = 3.38$ nm).

Figure 4.25 shows the retrieved spectra with TLS-1 input (set at on-resonance wavelength ($\lambda_{on} = 1528.488$ nm) and three off-resonance wavelengths (λ_{off1} , λ_{off2} , and λ_{off3}), respectively) with 8 mW input power for each wavelength when $\Delta\lambda = 3.38$ nm. The detuned wavelength $d\lambda$ is defined as $\lambda_{off} - \lambda_{on}$. The values of $d\lambda$ are 0.3 nm, 0.47 nm, and 1 nm in Fig. 4.25(a), (b), and (c), respectively. The retrieved power P_{on} of on-resonance wavelength is much larger than that of the detuned off resonance wavelength P_{off} . The power ratio β is defined as P_{on}/P_{off} . The power ratios are larger than 11 dB. Similarly, Fig. 4.26 shows the retrieved spectra with TLS-1 input (set at $\lambda_{on2} = 1556.02$ nm and three off-resonance wavelengths, respectively) with 8 mW input power for each wavelength when $\Delta\lambda = 3.38$ nm. The values of $d\lambda$ are 0.3 nm, 0.47 nm, and 1 nm in Fig. 4.26(a), (b), and (c), respectively. The power ratios β are larger than 16.46 dB when $d\lambda > 0.47$ nm. Figure 4.27 shows the retrieved spectra with TLS-1 input (set at $\lambda_{on3} = 1584.62$ nm and three off-resonance wavelengths, respectively) with 8 mW input power for each wavelength at $\Delta\lambda = 3.38$ nm. The

values of $d\lambda$ are 0.3 nm, 0.47 nm, and 1 nm in Fig. 4.27(a), (b), and (c), respectively. The power ratios β are larger than 10.1 dB when $d\lambda > 0.47$ nm. To effectively block the detuned off-resonance wavelength, $\beta \geq 10$ dB. Therefore, on-resonance wavelength components can effectively suppress the detuned off-resonance wavelength components when $d\lambda > 0.47$ nm with a power ratio $\beta > 10$ dB. Thus, the resolution of the RAFT spectrometer is 0.47 nm. The resolution meets the design target (sub-nanometres). And it could be further improved by optimizing the MRR for finer FWHM or increasing the temperature excursion (~ 100 K) of MZI arm for larger refractive index change without compromising the bandwidth.

Figure 4.28 shows the retrieved spectra with TLS-1 input set at all on-resonance wavelengths when MRR tuning state $\Delta\lambda = 3.38$ nm, 7.38 nm, 11.38 nm, 15.38 nm, 19.38 nm, 23.38 nm, and 27.38 nm, respectively. It is shown that the tunable MZI can retrieve each tuned spectrum output from the drop port of the MRR with single wavelength input when MRR is tuned to cover the FSR of 28 nm.

Figure 4.25: Retrieved spectra with TLS-1 input (set at $\lambda_{on1} = 1528.488$ nm and 3 off-resonance wavelengths, respectively) with detuned wavelength (a) $d\lambda = 0.3$ nm, (b) $d\lambda = 0.47$ nm, and (c) $d\lambda = 1$ nm.

Figure 4.26: Retrieved spectra with TLS-1 input (set at $\lambda_{on2} = 1556.02$ nm and 3 off-resonance wavelengths, respectively) with detuned wavelength (a) $d\lambda = 0.3$ nm, (b) $d\lambda = 0.47$ nm, and (c) $d\lambda = 1$ nm.

Figure 4.27: Retrieved spectra with TLS-1 input (set at $\lambda_{on3} = 1584.62$ nm and 3 off-resonance wavelengths, respectively) with detuned wavelength (a) $d\lambda = 0.3$ nm, (b) $d\lambda = 0.47$ nm, and (c) $d\lambda = 1$ nm.

Figure 4.28: Retrieved spectra with TLS-1 input (set at all on-resonance wavelengths when $\Delta\lambda = 0, 4 \text{ nm}, 8 \text{ nm}, 12 \text{ nm}, 16 \text{ nm}, 20 \text{ nm},$ and 24 nm , respectively).

Figures 4.29 and 4.30 show the retrieved spectra with TLS-1 and TLS-2 input simultaneously with wavelengths set at the adjacent on-resonant wavelengths at different input power values. The tuning state is $\Delta\lambda = 0$. The input on-resonant wavelengths are $\lambda_{on1} = 1525.400 \text{ nm}$ and $\lambda_{on2} = 1552.844 \text{ nm}$ in Fig. 4.29. And the input on-resonant wavelengths are $\lambda_{on2} = 1552.844 \text{ nm}$ and $\lambda_{on3} = 1581.240 \text{ nm}$ in Fig. 4.30. The retrieved power is proportional to the input power. It is shown that the two adjacent on-resonant wavelength components can be easily differentiated and reconstructed by the tunable MZI.

Figure 4.29: Retrieved spectra with TLS-1 and TLS-2 input simultaneously with different input power. TLS-1 is set at on-resonance wavelengths $\lambda_{on1} = 1525.400$ nm and TLS-2 is set at $\lambda_{on2} = 1552.844$ nm.

Figure 4.30: Retrieved spectra with TLS-1 and TLS-2 input simultaneously with different input power. TLS-1 is set at on-resonance wavelengths $\lambda_{on2} = 1552.844$ nm and TLS-2 is set at $\lambda_{on3} = 1581.240$ nm.

A broadband signal measurement is performed to further evaluate the performance of the RAFT spectrometer. A broadband ASE light source (Amonics ALS-CL) covering C and L band is used as the input. The calibration process for broadband source measurement is as follows. The broadband ASE source is used as the input. For the demonstrated RAFT spectrometer, the bandwidth is 90 nm and FSR of the MRR is ~ 28 nm. Hence the number of the retrieved resolution elements is 3 for each tuning state of the MRR. After completing the MRR thermal tuning to cover

one FSR, all the sampled interferograms from input source are obtained. There are two steps to perform wavelength/frequency calibration. The first step is to coarsely determine the frequencies of the sparse spectra by performing FFT to the sampled interferograms. The second step is to finely determine the frequencies according to the tuning state of the MRR. Subsequently, we normalize the retrieved power to the input power for each wavelength to obtain a normalization coefficient matrix A including MRR tuning states, wavelengths and their corresponding transmission coefficients as shown in Fig. 4.31. Hence, for broadband signal input, all the detected sparse spectra are retrieved using the normalization coefficient matrix A and then the retrieved spectra are combined to produce the original input spectrum.

Figure 4.31: Normalization coefficient matrix A including MRR tuning states, wavelengths and their corresponding transmission coefficients.

The retrieved spectrum and input broadband source are shown in the same figure in Fig. 4.32 for comparison. The retrieved spectrum agrees with the input spectrum very well. The small discrepancy is due to misalignment between lensed fibre and inverse-taper waveguide coupler, resonance position variation due to thermal crosstalk and fibre vibration. By packaging the lensed fibre to the input waveguide, the misalignment and fibre vibration would not be present. The thermal crosstalk mainly originates from silicon substrate since the buried oxide layer (BOX) is not thick enough to effectively isolate the heat from the heater above the MZI to Si substrate (the BOX is $2\mu\text{m}$ in the experiment). The residue thermal crosstalk can be mitigated through fabrication and optimization of thermal isolation trenches near

MZI arms. It will also be reduced by making both MRR and MZI fully suspend and/or using thicker BOX. Moreover, it will be well compensated with a feedback control circuit.

Large bandwidth of 90 nm is experimentally demonstrated due to three FSRs are utilized, which meets the broadband design target. The transmission band is as large as 100 nm since working spectral window depends on the transmission band of various components such as waveguides, couplers, beam splitters, etc. The working spectral band can also be largely extended by paralleling several RAFT elements with each working in different spectral range. The finesse of the RAFT spectrometer is 191.49 considering the 0.47 nm resolution and 90 nm bandwidth. The finesse is larger than the state-of-the-art spectrometers listed in Table 2.1. The insertion loss is ~9 dB considering the loss in polarization beam splitter (3 dB), polarization controller (3 dB) and fibre-chip coupler (3 dB). This loss can be reduced by integrating the PBS and PC on the spectrometer chip.

Figure 4.32: Normalized retrieved spectrum (black) with ASE source input (red).

Temperature response of the tunable MZI is experimentally tested. The

experimental setup is shown as Fig. 4.14. TLS-1 is used and set at on-resonance wavelength. The temperature response can be obtained by detecting the response of light intensity in the MZI output port while applying a square voltage signal on MZI heater 1. The temperature response is shown in Fig. 4.33(a). The rise and fall time are 37 μs and 60 μs , respectively.

Temperature response of the tunable MRR is also experimentally tested. The experimental setup is similar to Fig. 4.14, except that the throughput port of the MRR is detected by the PD. TLS-1 is used and set at on-resonance wavelength. The temperature response can be obtained by detecting the response of light intensity in the throughput port of the MRR while applying a square voltage signal on MRR heater 1. The temperature response of the tunable MRR is shown in Fig. 4.33(b). The rise and fall time are 20 μs and 80 μs , respectively. The response time of both the tunable MRR and the tunable MZI are fast (maximum 10 kHz) to enable fast response of the device.

Figure 4.33: (a) Response signal of the tunable MZI with square wave voltage signal on MZI heater 2. (b) Response signal of the tunable MRR with square wave voltage signal on MRR heater 1.

4.3.4 Thermal Isolation Implementation

MRR resonance wavelength is affected by both heater 1 and heater 2. During the experiment, thermal compensation is performed to offset the influence of heater 2 on the MRR. Since the resonance wavelength is proportional to power applied on heater 1 P_r , the resonance wavelength λ_r is expressed as

$$\lambda_r = A_1 + B_1 P_r \quad (4.21)$$

where A_1 and B_1 are constants. The resonance wavelength is also proportional to the heating power on heater 2 P_m ,

Hence, it can also be expressed as

$$\lambda_r = A_2 + B_2 P_m \quad (4.22)$$

where A_2 , and B_2 are constants. The parameter P_r' is defined as

$$P_r' = \frac{A_2 - A_1}{B_1} + \frac{B_2}{B_1} P_m \quad (4.23)$$

where P_r' is the corresponding value applied on heater 1, which causes equal resonance wavelength shift as P_m . The maximum resonance wavelength λ' due to MZI thermal tuning when $P_r = 0$ is expressed as

$$\lambda' = A_2 + B_2 P_{m\max} \quad (4.24)$$

where $P_{m\max}$ is the maximum applied power on heater 2. Suppose the wavelength shift $\Delta\lambda = 0$ (MRR initial tuning state) when the MRR resonance wavelength is shifted to λ' by heater 2. Therefore, the initial value of P_r when $\Delta\lambda = 0$ is expressed as

$$P_0 = \frac{\lambda' - A_1}{B_1} \quad (4.25)$$

On condition that resonance wavelength shift is tuned by heater 1 to $\Delta\lambda$, the value of P_r on heater 1 should be

$$P = \frac{\Delta\lambda}{B_1} + P_0 \quad (4.26)$$

Due to influence of P_m , to make the tuning state stable at $\Delta\lambda$, the value of P_r after compensation should be

$$P_r = P - P_r' = \frac{\Delta\lambda}{B_1} + \frac{B_2}{B_1} (P_{m\max} - P_m) \quad (4.27)$$

As a result, for a given P_m , the resonance wavelength can be stabilized by adjusting P_r . Therefore, more interferogram can be acquired.

To improve heating efficiency and reduce thermal crosstalk, thermal isolation trenches are adopted. Figure 4.34 shows the SEM image of the tunable MRR with

thermal isolation trenches. The SiO_2 cladding is etched away and the underlying Si substrate is partially etched using isotropic etching methods. Thus, the structure is suspended to reduce thermal dissipation to enable higher heating efficiency and lower thermal crosstalk.

Figure 4.34: SEM image of the tunable MRR with thermal isolation trenches.

Figure 4.35(a) shows the tunable MZI structure for thermal isolation trenches testing. Isolation trenches are fabricated near both arms. Dashed isolation trench structures are designed to prevent the waveguides from collapsing. Figure 4.35(b) shows that the power consumption is reduced by more than $4 \text{ mW}/\pi$ with thermal isolation trenches. Besides, power consumption can be dramatically reduced by minimizing the gap between trench edge and waveguide edge on condition that optical losses of the waveguides will not be increased. Smaller gap means that there are less Si substrate remaining in the suspended structures. Power consumption with isolation trenches at gap = $2.5 \text{ }\mu\text{m}$ is 7 folds less than that without isolation trenches. Figure 4.35(c) shows that longer trench length L can also effectively reduce the power consumption on condition that the MZI arm will not collapse. In the experiment, lower power consumption for MZI heater (1.8 W) is required due to shorter tuning

OPL. The power consumption for MZI heater will be further reduced by fabrication of isolation trenches along the waveguides of MZI arms.

Figure 4.35: (a) Isolation trench testing structure using a tunable MZI. (b) Relation between power consumption and gap between isolation trench and waveguide edge. (c) Relation between power consumption and isolation trench length L .

4.3.5 Waveguide Loss Implementation

According to previous analysis, increasing the arm length L of MZI, the resolution of tunable MZI can be improved. The typical loss of the Si single-mode waveguide is 1-2 dB/cm. According to the experimental result, 2.46 cm arm length corresponding to a resolution of $\delta\sigma = 77.91 \text{ cm}^{-1}$ with an optical loss from 2.46 dB to 4.92 dB. If the resolution of the tunable MZI is further increased to 40 cm^{-1} , the arm length L is increased to 4.76 cm, leading to an optical loss of at least 4.76 dB. The optical losses in fiber-chip couplers, beam splitters and waveguides account to the total insertion loss of the RAFT spectrometer. Higher insertion loss causes lower SNR and lower sensitivity. Hence, it is necessary to reduce the waveguide loss to improve the performance.

The electric field intensity profile of the fundamental quasi-TE mode of a silicon rib waveguide is shown in Fig 4.36(a). The rib thickness is 340 nm. The electric field mode is weakly confined, thus the electric field along the rough sidewalls is weak. Besides, the waveguide is partially etched to form a rib waveguide, which further reduces the area of the rough sidewalls. The electric field intensity of the fundamental quasi-TE mode along the sidewalls and the top surface of the rib in magenta in Fig. 4.36(a) is calculated. The simulation results that the electric field intensity changes with ridge width at different rib thicknesses are shown in Fig. 4.36(b). The electric field intensity decreases with increasing ridge width. When rib thickness increases, the electric field intensity firstly increases and then decreases.

Figure 4.36: (a) The electric field intensity profile of the fundamental quasi-TE mode of a silicon rib waveguide. (b) Simulation results of the influence of ridge width and rib thickness on the electric field intensity along the sidewall and the top surface of the rib.

The schematic of the designed rib waveguide is shown in Fig. 4.37(a). The design parameters are also shown. The ridge width is designed as 3 μm . The center-to-center spacing is designed as 5 μm to avoid optical mode overlap between two adjacent waveguides. The rib thickness is designed to be 180 nm. Figure 4.37(b) shows the transmission electron microscope (TEM) image of the cross section of the Si rib waveguide with SiO_2 cladding. Figure 4.38 shows the optical micrograph of

the rib waveguides. Figure 4.39 shows the SEM image of the rib waveguides.

Figure 4.37: (a) Schematic cross section of the designed rib waveguide. (b) TEM image of the cross section of the fabricated rib waveguide.

Figure 4.38: Optical micrograph of the rib waveguides.

Figure 4.39: SEM image of the rib waveguides.

The experiment result for the designed Si low-loss rib waveguide is shown in Fig. 4.40. Three waveguide testing structures with the same dimensions at three different lengths are designed and fabricated due to limited space. The losses are tested and linearly fitted. The average loss is 0.2 dB/cm at 1550 nm. However, ideally, more data points are needed to be certain about the waveguide loss.

Figure 4.40: Experimental test result of the Si low-loss rib waveguide.

4.4 Summary

This chapter presents the design, fabrication and experimental demonstration of a microring resonator-assisted Fourier-transform (RAFT) spectrometer fabricated using SOI wafer based on nano-silicon-photonic fabrication technology. The model of the thermally tunable MZI is built and theoretical analysed. The RAFT spectrometer is demonstrated by inputting with single laser sources and double laser sources. The temperature response is experimentally tested. The approaches to improving heating efficiency and reducing thermal crosstalk are proposed and investigated.

The performance of the on-chip RAFT spectrometer is very promising and viable for both high resolution and broadband applications. The idea that tunable MRR and tunable MZI working collaboratedly resolves the trade-off between resolution and bandwidth intrinsic in dispersive approaches and does not require the large tuning OPL in tunable MZI design. High resolution (0.47 nm) as well as large bandwidth (~90 nm) for a single RAFT spectrometer device is achieved with a compact size of 2.2 mm². The 90 nm bandwidth is experimentally demonstrated. The power consumption of MRR heater is effectively reduced with isolation trenches adopted for MRR. The performance (resolution, insertion loss, SNR, etc) can be further improved to adopt low-loss Si waveguides [72-74] which can enable higher throughput and larger optical path length of the MZI. Further, this design is easy to be extended to middle infrared range since Si has a transparency window up to the mid-IR range.

CHAPTER 5

FABRICATION PROCESSES

This chapter presents the core fabrication technology for on-chip spectrometers, including nano-silicon-photonic fabrication process flow, TiN heater and thermal isolation trenches. The fabrication processes of a waveguide-coupled Ge-on-SOI photodetector are also developed and presented. Experimental results are presented and discussed.

5.1 Fabrication Technology Development

The fabrication process flow based on nano-silicon-photonic technology is shown in Fig. 5.1. The fabrication starts firstly with an 8-inch silicon-on-insulator (SOI) wafer. The thickness of the top Si crystalline layer namely the device layer is 220 nm and the buried SiO₂ dioxide (BOX) layer thickness is 2 μ m to prevent the optical field mode in the top Si layer from penetrating to the Si substrate.

The grating coupler and waveguide structures waveguide are firstly formed by partially etching the Si layer. GC denotes grating coupler; Slot-WG denotes slot waveguide; Ch-waveguide denotes channel waveguide; MOD denotes modulator. Boron and phosphorus are implanted for modulators into P⁺⁺ and N⁺⁺ doing area, respectively. Thick SiO₂ cladding is deposited and planarized through chemical-mechanical planarization (CMP) process. TiN heater is thereafter formed. After depositing another SiO₂ layer, the first viahole for heater and the second viahole for Si layer contact for modulator are opened. Subsequently, Al wires are formed as electric contacts. Thereafter, a thin layer of SiO₂ is deposited. Then bond pads and window are formed. Total SiO₂ cladding in the thermal isolation trench and dicing

trench area is removed. Then, isotropic etching of Si substrate is performed to form thermal isolation trenches to make the targeted structures suspend. Finally, anisotropic etching of Si substrate is performed to form deep dicing trench.

Figure 5.1: The fabrication process flow based on nano-silicon-photonic technology.

5.1.1 Optical Lithography

All device patterns are defined by patterning processes using 248 nm technology. In optical lithography process, there are two main parameters that will determine the quality of profile after development, namely the exposure focus and energy. The patterning of each layer is done with deep ultraviolet UV optical lithography. It includes three steps. The pattern processes include photoresist (PR) coating, optical lithography and develop. The photoresist coating process is to dispense a layer of the PR onto the wafer. The optical lithography process uses the deep UV light to change the properties of the photoresist. The developing process is to etch away the PR exposed or unexposed by UV light. If the exposed area is to be etched, it is called the positive PR. And if the unexposed area is etched away, it is known as the negative PR. Here, all pattern processes use positive PR. After being patterned, the targeted layer is etched with PR as the mask. The various exposure problems are shown in Fig. 5.2. The exposure quality mainly depends on the energy and focus conditions. If the exposure energy is too small, it will not be fully exposed resulting in the feature size smaller than the desired one and if the energy is too strong, the size will become larger. The UV light focal point is supposed to be in the center of the PR. If the focus shifts away from the center, the profile will be rough.

Figure 5.2: Various profiles after exposure.

Figure 5.3: SEM images of (a) a misalignment problem during exposure process and (b) well aligned photoresist for rib and waveguide

Another problem may occur during exposure, which is the misalignment between the light beam and the correct exposure position. The SEM image of a misalignment problem after development is shown in Fig. 5.3(a). The central line 1 (the central line of the waveguide) is supposed to be collinear with central line 2 (the central line of the photoresist for rib). The misalignment occurred during exposure. Once etching is finished, the misalignment will transfer to the rib layer. Figure 5.3(b) shows the SEM image of the well aligned photoresist for rib and waveguide after removing the misaligned photoresist and adjusting the alignment during exposure processes using compensation data. A minimum misalignment of 50 nm is achieved.

5.1.2 NSP Waveguides Formation

Waveguide structures are fabricated using the Si layer. Thus, the optical loss of waveguides should be as small as possible. Therefore, the sidewall of the etched Si waveguide structure should be smooth. For grating couplers and waveguides fabrication, a 70 nm-thick layer of USG SiO₂ is firstly deposited to serve as the hard mask for the RIE etching of Si. USG SiO₂ is undoped silicon glass via low temperature plasma-enhanced chemical vapor deposition (PECVD). Then, lithography is performed for SiO₂ hard mask etch. In the lithography processes, a 90-nm Bottom-Anti-Reflective Coating (BARC) is firstly coated to reduce reflectance from the bottom layer of PR. Smaller line roughness of PR after exposure is achieved with BARC. Then, a layer of PR is coated, followed with exposure and develop processes. Thereafter, hard mask is fully etched, and photoresist is stripped. The nanophotonic structures such as waveguides and grating couplers are formed by partial Si etch with the remaining Si thickness as waveguide rib. Finally, the second lithography for rib etch is performed and the Si layer is fully etched to form waveguide rib structures. Thus, the nano-silicon-photonics structures are formed. The minimum feature size (linewidth or coupling gap) is 200 nm, limited by the exposure wavelength of the lithography technology. The thickness of the Si layer is 220 nm since the standard 220-nm SOI wafer is used. Figure 5.4(a) shows the TEM image of the cross section of the fabricated nanowire Si waveguide. The SEM image of the fabricated waveguide taper coupler presenting a smooth sidewall is shown in Fig. 5.4(b). The SEM image of the fabricated adiabatic taper with rib waveguide is shown in Fig. 5.4(c). The rib width is gradually changing from 0 to a certain value to reduce loss during the optical mode transition between the nanowire waveguide and rib waveguide.

Figure 5.4: TEM image of the cross section of the fabricated Si nanowires. (b) SEM image of the inverse taper coupler. (c) SEM image of the fabricated adiabatic taper with rib waveguide.

5.1.3 Si₃N₄ Waveguide and MRR

There is certain tolerance in the size of the structures due to fabrication variation. Hence, the resonance wavelengths of MRRs with the same designed radius

will not be exactly aligned. Figure 5.5 shows the transparent window of some materials compatible with the nano-silicon-photonic fabrication technology. They cover from ultra-violet (UV) to MIR range. Silicon is a good material for NIR and MIR range and Si_3N_4 can cover from visible range to the MIR range with most applications in VIS [147]. Si has high refractive index ~ 3.5 and high index contrast to cladding material (SiO_2 1.5 or air 1), which makes it most adopted in integrated photonic circuits [17]. Si_3N_4 has lower refractive index ~ 1.9 and much lower thermo-optic coefficient, which enables higher tolerance to fabrication variation and temperature fluctuation. There are various applications in VIS and NIR range including environment monitoring, atmospheric remote sensing, etc. Thus, developing photonic devices on Si_3N_4 platform will bring breakthrough into the wide range of sensing and detection applications.

Figure 5.5: Transparent window of some materials compatible with the nano-silicon-photonic fabrication technology.

The Si_3N_4 thin film is deposited through PECVD process. After deposition, CMP process is performed to planarize and smooth the top surface. The waveguide structures are etched through anisotropic dry etching with PR as the mask. Figure 5.6(a) shows the SEM image of a direction coupler between a straight waveguide and an MRR. Figure 5.6(b) shows the SEM image of the single-mode Si_3N_4 waveguide

array. Figure 5.6(c) shows the SEM image of a fabricated tapered waveguide coupler. Figure 5.6(d) shows the TEM image of the single-mode Si₃N₄ waveguide array. The maximum thickness is 400 nm. The minimum feature size (linewidth or coupling gap) of Si₃N₄ waveguide is 200 nm, limited by the exposure wavelength of the lithography technology. Figure 5.7 shows the loss rate of the single-mode Si₃N₄ waveguide from 1520 nm to 1620 nm. The insert shows the modal profile of the designed single-mode Si₃N₄ waveguide with width 1000 nm and height 400 nm. The effective index of the fundamental quasi-TE mode is $n_{eff} = 1.626$. The minimum loss rate is approximately 0.5 dB/cm at ~1610 nm. The loss rate is less than that of the Si single-mode waveguide (~1 dB/cm).

Figure 5.6: SEM images of (a) direction coupler between a straight waveguide and an MRR, (b) single-mode Si_3N_4 waveguide array, and (c) a tapered waveguide coupler. (d) TEM image of the single-mode Si_3N_4 waveguide array.

Figure 5.7: Loss rate of the designed single-mode Si₃N₄ waveguide. Insert shows the modal profile of the designed Si₃N₄ single-mode waveguide.

Figure 5.8(a) shows the schematic design of the tapered waveguide coupler for chip-fiber coupling. The tapered waveguide width starts from the W_1 from the chip edge and gradually changes to the single-mode waveguide width W_2 . The designed taper widths are 300 nm, 400 nm, 500 nm, and 600 nm for testing, respectively. W_2 is designed to be 1 μm to satisfy the single-mode condition. The thickness of all the Si₃N₄ waveguides is designed to be 400 nm for single-mode condition. The taper length is designed as 200 μm . Figure 5.8(b) shows the coupling losses for different waveguide tapers. The minimum coupling loss occurs when $W_1 = 400$ nm.

Figure 5.8: (a) Schematic of the designed tapered waveguide coupler for chip-fibre coupling. (b) Coupling losses of different designed waveguide tapers.

To test the Si_3N_4 microring resonator, 11 MRR with identical designed dimensions are fabricated. The designed width is 1000 nm; the height is 400 nm; the average radius is $100.5 \mu\text{m}$. Figure 5.9 shows the resonance wavelengths of 11 MRRs at different resonating orders $m-1$, m , and $m+1$. The maximum wavelength shift due to fabrication is $\sim 1.4 \text{ nm}$. It means even though the Si_3N_4 material has smaller fabricated tolerance in terms of low refractive index, the resonance wavelength still cannot be precisely controlled due to fabrication variation.

Figure 5.9: Si_3N_4 MRR resonance wavelength shift due to fabrication variation.

5.1.4 Heater Fabrication

There are many materials which can serve as heater compatible with nano-silicon-photonic fabrication technology. TiN is adopted here considering its high resistivity and compatibility with the nano-silicon-photonic fabrication technology.

TiN layer is deposited through physical vapor deposition (PVD) process. After TiN deposition, a thin Si_3N_4 layer (500 Å) is deposited. The Si_3N_4 layer will protect the TiN layer during the etching process to get a smoother sidewall. Figure 5.10 shows the SEM image of TiN heater. It shows the sidewall is quite smooth. The space between TiN layer and the top surface of Si layer is 1 μm to avoid excess optical loss due to absorption by TiN. The minimum feature size (linewidth and gap) of the TiN heater is 1 μm limited by etching capability. The thickness is 150 nm.

Figure 5.10: SEM image of the TiN heater showing the smooth sidewall.

5.1.5 Thermal Isolation Trenches

The thermal isolation trenches are designed and fabricated to improve heating efficiency thus to reduce power consumption and thermal crosstalk between MRR heater and MZI heater. The fabrication processes of thermal isolation trenches and deep trenches for dicing are shown from step 12 to step 14 in Fig. 5.1.

When all the fabrication steps for devices are completed before fabrication of the dicing trenches, the isolation trenches are formed. The fabrication of the isolation trenches aims to make the waveguides or MRR structures suspend to reduce heat dissipation from the underlying Si substrate and surrounding SiO₂ cladding. After lithography, the total SiO₂ cladding is removed by anisotropic dry etching. Then the Si substrate under the targeted waveguides or MRR structures is partially removed by isotropic etching. Thereafter, the waveguides or MRR structures are suspended with designed SiO₂ beams and the remaining underlying Si substrate as support as shown in Fig. 5.11. Figure 5.11(a) shows the SEM image of the cross section of the tunable MRR with thermal isolation trenches. Figure 5.11(b) shows the SEM image

of the cross section of suspended waveguide structure in an MZI arm with isolation trenches. Since isotropic etching is used for the thermal isolation trench, the aspect ratio equals to 1. The suspended structures with deep isolation trenches will affect the uniformity of the coated photoresist in lithography. The SEM image of the spoiled suspended waveguides structures are shown in Fig. 5.12(a) after deep trenches etching for dicing. As a result, the deep trenches for dicing should be formed at the same time with the isolation trench to avoid additional lithography. Thus, anisotropic etching of Si substrate for deep dicing trench is performed after Si isotropic etch. The SEM image of the cross section of the fibre-chip edge coupling region with thermal isolation trenches is shown in Fig. 5.12(b). The SiO₂ cladding extrudes without collapse after dicing. Thus, the coupling between the tapered fibre and the inverse taper waveguide edge coupler is not harmed by the thermal isolation trenches.

Figure 5.11: SEM images of (a) the cross section of the tunable MRR with thermal isolation trenches and (b) the cross section of suspended waveguide structure in an MZI arm with thermal isolation trenches.

Figure 5.12: SEM images of (a) the spoiled suspended waveguide structures and (b) the cross section of the fibre-chip edge coupling region with thermal isolation trenches.

5.2 Ge-on-SOI Photodetector

The Ge-on-SOI photodetector is fabricated using fabrication technology compatible with the standard nano-silicon-photonic processes. The fabrication process flow is shown in Fig. 5.13. After the Si waveguide structures are fabricated,

P+-type doping using Boron is done to Si substrate. Thereafter, P++-type is performed for contact area of PD. Then, a field SiO₂ layer is deposited and the Ge epitaxy window is open by etching the field SiO₂ to expose the Si substrate. The absorption material Ge is then selectively grown on the substrate of crystalline Si in the Ge window through epitaxy process. The thickness of Ge is 500 nm. Then, SiO₂ upper cladding is removed. N++-type doping is performed to implant phosphorus into the top surface of Ge. A thick layer of SiO₂ cladding is deposited as passivation and CMP is performed to planarize the surface of the wafer. Thereafter, the viahole is opened by etching away all the SiO₂ cladding on the contact area. Then Al wires are formed to contact the doped contact region of PDs. In the deposition of Al, firstly a layer of 50 nm-thick TaN is deposited. Then Al layer is deposited by PECVD process. A thin film of TaN acts as an interlayer to strength the adhesion of Al layer to the wafer.

The false-colored SEM image of the selectively grown Ge after epitaxially processes are shown in Fig. 5.14(a). The optical micrograph of a Ge-on-SOI photodetector is shown in Fig. 5.14(b). The input light from the nanowire is gradually input to the Si substrate beneath the Ge through a taper. Then, the light is evanescently coupled to the absorption layer Ge. The contact 1 and contact 2 are used to supply voltages.

Figure 5.13: Fabrication process flow of Ge-on-SOI photodetector.

Figure 5.14: (a) False-coloured SEM image of the Ge on the Si substrate after epitaxy process. (b) Optical micrograph of a Ge-on-SOI photodetector.

The characteristic of the photodetector is experimentally tested. Figure 5.15(a) shows the I - U curve with input wavelength of 1570 nm. The voltage of scanned from -4 to 2 volts. When the input light power is changed, the current in the inverse biased range changes accordingly and clearly while that in the forward biased range is not clear enough. The dark current is as low as 4.4 nA at 0 bias. Figure 5.15(b) shows the

responsivity at 0 bias. The responsivity can achieve up to 0.81 A/W at 1538.5 nm.

Figure 5.15: (a) I-U curve of the photodetector. (b) Responsivity at 0 bias.

The relevant parameters of different materials including Si waveguides, Si_3N_4 waveguides, TiN heater and Ge, based on the current fabrication processes are shown in Table 5.1.

Table 5.1: Relevant parameters of different materials based on current fabrication processes.

Material	Minimum linewidth	Minimum coupling gap	Thickness
Si	200 nm	200 nm	220 nm
Si ₃ N ₄	200 nm	200 nm	400 nm
TiN	1 μ m	1 μ m	150 nm
Ge	-	-	500 nm

5.3 Spectrometer Integrated with Photodetector

The optical micrograph of the fabricated on-chip spectrometer using a thermally tunable MRR is shown in Fig. 5.16. Voltage is applied on metal pads for TiN microheater to generate joule heating to thermally tune the MRR. The output light from the drop port of the MRR is split by a 50/50 beam splitter to two channels. One channel will be detected by the photodetector. The other channel can be coupled out through fiber-chip coupler for calibration. The SEM image of the directional coupler between the MRR and straight waveguide is shown in Fig. 5.17.

Figure 5.16: Optical micrograph of the on-chip spectrometer integrated with a Ge-on-SOI photodetector.

Figure 5.17: SEM image of coupling gap between the waveguide and MRR.

5.3.1 Experimental Setup

Figure 5.18 shows the experimental setup for characterization of the on-chip spectrometer integrated with a PD. TLS-1 and TLS-2 are used through an optical coupler. All the optical devices are connected to single-mode optical fibres (SMF). The polarization beam splitter is used to convert the laser source to two separate parts of polarized light. Then the polarization controller will control the polarization state of the input light. Here, we ensure the input light is TE polarized. The source measure unit (SMU) is used to apply DC voltage on metal pads of the heater. The output light from drop port is detected by the integrated PD. The electric signal from the PD amplified by an OPA. The amplified signal is then read out by an oscilloscope. DUT with TEC cooler under it for thermal stabilization is mounted on the holder of the XYZ stage. TEC cooler is controlled by a controller.

Figure 5.18: Experimental setup for characterization of the on-chip spectrometer using the integrated PD.

5.3.2 Characterization of the Spectrometer

The thermal tunability of the MRR is experimentally tested. The output light from throughput port of the DUT is detected by OSA. The resonance wavelength is red-shifted with increasing voltage. The free spectral range (FSR) is ~ 19 nm. The power consumption is 3.8 mW/nm. The resonance wavelength is proportional to the heating power on MRR heater which agrees well with theoretical analysis in Chapter 3.

Firstly, the characterization of the on-chip spectrometer with an off-chip PD (Artifex OPM 150) to detect light intensity in the drop port is performed. The electric signal from the PD is read out by an oscilloscope. The normalized input spectrum viewed with OSA with TLS-1 and TLS-2 input simultaneously is shown in Fig. 5.19(a). TLS-1 and TLS-2 are set at 1558 nm and 1558.2 nm, respectively. The input power of TLS-1 is set at 6 mW and the input power of TLS-2 is set at 1, 1.5, 2, and 3 mW, respectively. The normalized retrieved spectra by the on-chip spectrometer are shown in Fig. 5.19(b). The two peaks at different power values can be differentiated. Therefore, the wavelength separation at 0.2 nm can be resolved by the device using an off-chip PD.

Figure 5.19: (a) Normalized input spectra viewed with OSA with TLS-1 and TLS-2 (set at 1558 and 1558.2 nm, respectively) input simultaneously. (b) Normalized retrieved spectra by the on-chip spectrometer with an off-chip PD. TLS-1 and TLS-2 (set at 1558 and 1558.2 nm, respectively) are input simultaneously.

The characterization of the on-chip spectrometer with the integrated Ge-on-SOI PD detecting light intensity in the drop port is performed with the experimental setup shown in Fig. 5.18. Single wavelength characterization is firstly performed using TLS-1. The detected voltage by the integrated photodetector while applying a linear voltage signal on the heater with TLS-1 (set at 1562 nm) input is shown in Fig. 5.20(a). On the condition that the applied voltage is constant U and that a single laser source with wavelength λ_{in} is input, the resonance wavelength will be fixed at λ_r . If $\lambda_{in} \neq \lambda_r$, the light in MRR is off resonance. As a result, the photodetector in the drop port will detect a very low voltage. If $\lambda_{in} = \lambda_r$, the resonance condition is met and the light in the MRR will be dramatically amplified. As a result, there will be a high

voltage detected by the photodetector of the drop port. Therefore, there is a voltage peak detected by the photodetector in the drop port while applying a linear voltage signal on the heater with a single laser source input. Figure 5.20(b) shows the retrieved spectrum. The normalized retrieved spectra with TLS-1 input are shown in Fig. 5.21 and Fig. 5.22. The input wavelength is 1558 nm and the input power values are 10, 14, and 16 mW, respectively in Fig. 5.21. The input wavelength is 1562 nm and the input power values are 14, and 18 mW, respectively in Fig. 5.22. The fabricated integrated spectrometer is capable to reconstruct the input spectrum with a single laser source input.

Figure 5.20: (a) Detected voltage by the integrated PD while applying a linear voltage signal to the microheater with TLS-1 (set at 1562 nm) input. (b) Retrieved spectrum with TLS-1 (set at 1562 nm) input.

Figure 5.21: Retrieved normalized spectra with single laser source input (1558 nm) at different power values.

Figure 5.22: Retrieved normalized spectra with single laser source input (1562 nm) at different power values.

Double wavelength characterization is then performed using TLS-1 and TLS-2. Figure 5.23 shows the normalized retrieved spectra with TLS-1 and TLS-2 (set at 1558 and 1558.1 nm, respectively) input simultaneously. The input power of TLS-1 is 10 and 16 mW, respectively. The input power of TLS-2 is 6 mW. Figure 5.24 shows the normalized retrieved spectra TLS-1 and TLS-2 input simultaneously with varying input power. The input wavelength pairs are 1558 and 1558.3 nm, 1558 and 1558.5 nm, 1565.3 and 1557 nm, and 1558.8 and 1570 nm, respectively. The double wavelength components are well differentiated with a minimum resolvable value of 0.1 nm. The retrieved power is proportional to the input power. As a result, the designed on-chip spectrometer with integrated on-chip PD is capable to reconstruct

the input spectrum with a high resolution of 0.1 nm.

The temperature response of the tunable MRR is experimentally tested using TLS-1. A square wave voltage signal is applied on the heater. The off-chip PD is used to detect the change of the output light intensity. Figure 5.25 shows the response time of the thermally tunable MRR. The rise and fall time are 72 μ s and 48 μ s, respectively. Thus, the thermal response is very fast to realize an integrated spectrometer with high speed ($\sim$ 9.33 kHz).

Figure 5.23: Normalized retrieved spectra with TLS-1 and TLS-2 (set at 1558 and 1558.1 nm, respectively) input simultaneously with varying input power.

Figure 5.24: Normalized retrieved spectra with TLS-1 and TLS-2 input simultaneously with varying input power.

Figure 5.25: (a) Rise time of the tunable MRR. (b) Fall time of the tunable MRR.

5.4 Summary

In this chapter, the fabrication processes based on nano-silicon-photonic fabrication technology are presented. Problems encountered in optical lithography and solutions are presented and analysed. The approaches to achieve smoother sidewall are investigated. The fabrication processes of nano-silicon-photonic structures are developed based on nano-silicon-photonic fabrication technology including nanowire waveguide, inverse-tapered fibre-chip coupler, rib waveguide, directional coupler. Si_3N_4 single-mode waveguide, directional coupler, inverse-tapered fibre-chip coupler and microring resonator are designed, fabricated and

experimentally tested. The fabrication processes are developed based on the NSP fabrication technology. The heater fabrication processes are developed and presented. The thermal isolation trenches are designed, and fabricated. The fabrication processes are developed. The fabrication processes of the waveguide-coupled Ge-on-SOI photodetector are developed and presented. An on-chip spectrometer with a thermally tunable microring resonator integrated with the Ge-on-SOI photodetector is designed, fabricated and experimentally demonstrated. High resolution of 0.1 nm and large working band of 19 nm is experimentally demonstrated.

CHAPTER 6

CONCLUSIONS

6.1 Conclusions

Two types of on-chip spectrometers using nanophotonic components have been investigated theoretically and experimentally. The first is a pre-dispersed spectrometer using an arrayed waveguide grating and tunable microring resonator array. The second type is a Fourier-transform spectrometer with resolution enhanced by a tunable microring resonator. Both approaches have high potential to innovate a spectrometer applied in spectral analysis applications such as handheld spectrometers, image spectrometry, integrated sensing system and on-chip spectroscopy. Theoretical analysis, system design, fabrication development and experimental characterization have been presented. The major conclusions drawn are listed here.

The first approach for on-chip spectrometer employs arrayed waveguide grating and tunable microring resonator to realize a pre-dispersed spectrometer. Arrayed waveguide grating presents a wavelength dispersion characteristic. The resolution is inversely proportional to channel count. Thus, the channel count will be too large to achieve a practical resolution resulting in large footprint and low signal-to-noise ratio. The working bandwidth for a single tunable microring resonator is limited to its free spectral range. The pre-dispersed spectrometer using an arrayed waveguide grating and tunable microring resonator array is aimed to achieve high resolution and large bandwidth with small channel count. The viability of thermal tuning of the microring resonator is explored and analyzed. Thermo-optic effect can induce a large refractive index change to enable large tunable range. The resonance

peak of the microring resonator has an ultra-narrow linewidth (sub-nanometer) due to high quality factor. Hence, the microring resonator can be tuned with a high resolution. Thermal tuning of microring resonator is theoretically analyzed and experimentally tested.

(a) The on-chip spectrometer using an arrayed waveguide grating and tunable microring resonator is firstly demonstrated. The arrayed waveguide grating is cascaded with tunable microring resonator array. A Ge-on-SOI photodetector is connected to the drop port of the tunable microring resonator in each channel.

(b) Thermo-optic effect is exploited to tune the microring resonator continuously to cover the working spectral range. The heating of Si waveguide by TiN heater on top is theoretically studied. Linear relation between static temperature of Si waveguide and heating power on the heater is theoretically obtained.

(c) The influences of heater dimensions and microring resonator dimensions on heating efficiency are theoretically studied. The influences of heater dimensions on temperature response are theoretically studied.

(d) Thermal isolation trenches are designed and implemented to improve heating efficiency. The influences of thermal isolation trench implementation on heating efficiency are theoretically studied. The influences of thermal isolation trench implementation on temperature response are theoretically studied.

(e) Thermal tuning of refractive index is theoretically analyzed considering waveguide dispersion, thermo-optic nonlinearity and thermal expansion. Thermal tuning of microring resonator is theoretically analyzed and the model is built and experimentally verified.

(f) The resonance wavelength affected by fabrication variation is experimentally tested. The tunable MRR is promising for resonance wavelength control and tuning.

(g) High resolution of 0.1 nm is achieved. Large working spectral range of 27 nm with only 9 output channels is realized. The device is very compact with a small footprint of $3 \times 3 \text{ mm}^2$. The thermal consumption of the tunable microring resonator is approximately 14.28 mW/nm.

The second approach innovates a Fourier-transform spectrometer with resolution enhanced by a tunable microring resonator. A tunable photonic Mach-Zehnder interferometer, the typical configuration is adopted as the Fourier-transform spectrometer. Thermo-optic effect is employed to thermally tune the Mach-Zehnder interferometer. The tunable MZI has large transparency window (up to 100 nm) and presents no trade-off between resolution and bandwidth. Hence it can resolve the trade-off between resolution and bandwidth, which normally exists in dispersion approaches. Since the resolution is limited by short maximum optical path difference between MZI arms due to small refractive index modification and short arm length. To achieve high resolution (sub-nanometer), a tunable microring resonator is cascaded before the tunable MZI with the drop port of microring resonator as the input of the MZI. The MRR pre-filters the input spectrum to a spectrum with sparsely spaced wavelength components. The wavelength difference between adjacent wavelength components equals to the free spectral range of the microring resonator. The resolution of the tunable MZI matches the free spectral range (tens of nanometers). Hence, the tunable MZI can differentiate the sparse spectrum easily. The microring resonator can be tuned to change the filtered spectrum. All the filtered spectra are thus recovered by the tunable MZI. Therefore, all the recovered spectra can be combined to retrieve the original input spectrum. The microring resonator can be tuned with an ultra-fine value (sub-nanometer). Thus, the resolution is dramatically boosted by the microring resonator far beyond the Rayleigh criterion of

the tunable MZI. Besides, only one detector is required for one single device producing high throughput and high SNR.

(a) The microring resonator-assisted Fourier-transform spectrometer is demonstrated for the first time. Photonic tunable Mach-Zehnder interferometer is adopted to work as a Fourier-transform spectrometer. A microring resonator acts as a tunable filter with ultra-narrow band pass to dramatically enhanced the final resolution.

(b) Thermal tuning of Mach-Zehnder interferometer is theoretically analysed and the model is built. For the tunable MZI, the relation between optical path difference, resolution, and heating power on heater is theoretically analysed.

(c) Thermal tuning power consumption of the tunable microring resonator is 1.23 mW/nm. The heating efficiency is 5.5×10^5 K/W Thermal tuning power consumption of the tunable Mach-Zehnder interferometer is 11.185 mW/ π . The heating efficiency is 13.8 K/W. Thermal response of both the Mach-Zehnder interferometer and the microring resonator is experimentally tested. Temperature responses of the tunable MRR and tunable MZI are experimentally tested and high speed (~ 10 kHz) is achieved.

(d) High resolution of 0.47 nm and large bandwidth of 90 nm are experimentally demonstrated. The demonstrated spectrometer has a small footprint of 2.2 mm². The resolution can be further improved by optimizing the MRR coupler. The bandwidth can be easily extended by a paralleled spectrometer array.

(e) Thermal isolation trenches near microring resonator are implemented and experimentally tested to improve heating efficiency and reduce power consumption. Tunable microring resonator is partially suspended by etching away underlying Si substrate to reduce heat dissipation to the Si substrate. The influences of the design parameters such as gap between waveguide and trench and width of isolation trenches

are experimentally tested with Mach-Zehnder interferometer testing structures.

(f) Low-loss Si rib waveguide is theoretically studied and experimentally tested. Rib waveguide with large width and thick rib is designed to reduce optical field interaction with rough sidewalls due to etching. Low loss rate of 0.1 dB/cm is obtained. It is promising to be implemented in the Fourier-transform spectrometer to reduce insertion loss and improve signal-to-noise ratio.

The fabrication processes using nano-silicon-photonic fabrication technology are developed and presented including nano-silicon-photonic strip waveguides, rib waveguide, inverse tapers, directional couplers, Si_3N_4 waveguide structures, TiN heater, thermal isolation trenches, and waveguide-coupled Ge-on-SOI photodetector. The integration with an on-chip spectrometer using a thermally tunable MRR is presented and experimentally demonstrated.

(a) The fabrication processes of nano-silicon-photonic structures are developed based on nano-silicon-photonic fabrication technology including nanowire waveguide, inverse-tapered fibre-chip coupler, rib waveguide, and directional coupler. Problems encountered in optical lithography and solutions are analysed and presented. The approaches to achieve smoother sidewall are investigated and presented.

(b) Si_3N_4 waveguide with relatively low loss and Si_3N_4 MRR with high quality factor are fabricated and experimentally tested to develop a Si_3N_4 platform potential for applications in NIR range.

(c) Fabrication processes of TiN heater are developed and presented, which are compatible with the NSP fabrication technology. Thermal isolation trenches are designed and fabricated. The fabrication processes are developed and presented, which are compatible with the NSP fabrication technology.

(d) The fabrication processes of the waveguide-coupled Ge-on-SOI photodetector are developed and presented. An on-chip spectrometer using a thermally tunable microring resonator integrated with the Ge-on-SOI photodetector is experimentally demonstrated. High resolution of 0.1 nm and large working band of 19 nm is experimentally demonstrated.

6.2 Recommendations

Recommendations for future research are summarized as follows.

(a) For the pre-dispersed spectrometer type, the radius of each microring resonator in the pre-dispersed spectrometer needs to be optimized for the purpose that the working bands of microring resonator match the arrayed waveguide grating better. Thermal isolation trenches need to be implemented to increase heating efficiency. Electronic control circuits need to be better designed for parallel working of the 9 channels and spectral retrieval.

(b) For the RAFT spectrometer type, thermal isolation trenches need optimization to further improve heating efficiency of both microring resonator and Mach-Zehnder interferometer. Methods of interference pattern correction and temperature fluctuation need be done for better performance. Electronic control circuits need to be optimized for better thermal compensation, automated sampling and spectral retrieval.

(c) Methods of increasing heating efficiency will be investigated such as placing the TiN heater on the waveguide rib and optimization of thermal isolation trenches. The inverse taper coupler is fragile due to suspension after fabrication of thermal isolation trenches. The fabrication processes will be optimized to protect the inverse taper.

(d) Low loss Si waveguides will be adopted and implemented in the system of the

both types of spectrometer to reduce insertion loss as to reduce signal-to-noise ratio.

(e) Both types of on-chip spectrometers integrated with Ge-on-SOI photodetector array will be fabricated, tested and demonstrated. Fiber-chip bonding will be performed to construct a prototype for spectroscopic measurements and testing.

(f) Si_3N_4 has the advantage of low loss and low index contrast. Si_3N_4 microring resonator has a higher quality factor than that based on Si platform. It has a large transparency window from UV to NIR range. The spectrometers based on Si_3N_4 platform to extend the spectrum band to NIR and VIS range will be developed. The thermal tuning will be optimized due to low thermo-optic coefficient of the Si_3N_4 material. Other tuning methods will also be investigated and validated.

(g) The working band will be further extended by employing paralleled on-chip spectrometer array. Waveguides with different dimensions have different transmission spectrum. The dimensions of various components such as inverse taper coupler, nanowire waveguide, rib waveguide, directional coupler, beam splitter, etc, need to be designed so that the spectrometers can work in other spectral ranges (NIR and MIR due to large transparency window of Si). The Ge-on-SOI detector also needs to be designed to detect light in certain spectral range.

AUTHOR'S PUBLICATIONS

Journal Papers

- [1] **S. N. Zheng**, J. Zou, H. Cai, J. F. Song, L. K. Chin, P. Y. Liu, Z. P. Lin, D. L. Kwong, and A. Q. Liu, " A Microring Resonator-assisted Fourier Transform Spectrometer with Enhanced Resolution and Large Bandwidth in Single Chip Solution, " Nature Communications, 2019 (Revised)
- [2] **S. N. Zheng**, H. Cai, J. F. Song, J. Zou, P. Y. Liu, Z. P. Lin, D. L. Kwong, and A. Q. Liu, " A Single-chip Integrated Spectrometer via Tunable Microring Resonator Array, " Optics Express, 2019 (submitted)

Conference Papers

- [1] **S. N. Zheng**, Y. Y. Chen, H. Cai, Y. D. Gu, and A. Q. Liu, "High-resolution and Large-bandwidth On-chip Microring Resonator Cavity-enhanced Fourier-transform Spectrometer." Conference on Lasers and Electro-Optics (CLEO) 2018, San Jose, U.S.A. (**Oral**)
- [2] **S. N. Zheng**, Y. Y. Chen, H. Cai, Y. D. Gu, Z. C. Yang, Y. L. Hao, D. L. Kwong, and A. Q. Liu, "High-resolution and Large Tunable Range Nanophotonic Spectrometer Using a Microring Resonator." Conference on Lasers and Electro-Optics (CLEO) 2018, San Jose, U.S.A. (**Oral**)
- [3] **S. N. Zheng**, H. Cai, Y. D. Gu, L. K. Chin, and A. Q. Liu, "On-chip Fourier transform spectrometer for chemical sensing applications." Conference on Lasers and Electro-Optics (CLEO) 2016, San Jose, U.S.A. (**Oral**)
- [4] **S. N. Zheng**, H. Cai, Y. D. Gu, L. K. Chin, and A. Q. Liu, "High-resolution on-

chip spectrometer with a tunable micro-ring resonator filter". Conference on Lasers and Electro-Optics (CLEO) 2016, San Jose, U.S.A. (**Oral**)

BIBLIOGRAPHY

- [1] R. G. Hunsperger, *Integrated optics: theory and technology* (Springer, 1984).
- [2] D. Sorak, L. Herberholz, S. Iwascek, S. Altinpinar, F. Pfeifer, and H. W. Siesler, "New developments and applications of handheld Raman, mid-infrared, and near-infrared spectrometers," *Appl Spectrosc Rev* **47**, 83-115 (2012).
- [3] R. E. Myers, "Handheld Laser - induced Breakdown Spectroscopy Instruments and Their Applications," *Encyclopedia of Analytical Chemistry*.
- [4] J. Antila, M. Tuohiniemi, A. Rissanen, U. Kantojärvi, M. Lahti, K. Viherkanto, M. Kaarre, and J. Malinen, "MEMS - and MOEMS - Based Near - Infrared Spectrometers," *Encyclopedia of Analytical Chemistry* (2014).
- [5] R. F. Wolffenbuttel, "State-of-the-art in integrated optical microspectrometers," *Instrumentation and Measurement, IEEE Transactions on* **53**, 197-202 (2004).
- [6] V. Kovalyuk, O. Kahl, S. Ferrari, A. Vetter, G. Lewes-Malandrakis, C. Nebel, A. Korneev, G. Goltsman, and W. Pernice, "On-chip single-photon spectrometer for visible and infrared wavelength range," in *Journal of Physics: Conference Series*(IOP Publishing, 2018), p. 051045.
- [7] A. Ruocco, D. Van Thourhout, and W. Bogaerts, "Silicon photonic spectrometer for accurate peak detection using the Vernier effect and time-domain multiplexing," *J Lightwave Technol* **32**, 3351-3357 (2014).
- [8] Z. Wang, and Z. Yu, "Spectral analysis based on compressive sensing in nanophotonic structures," *Opt Express* **22**, 25608-25614 (2014).

-
- [9] T. Claes, J. G. Molera, K. De Vos, E. Schacht, R. Baets, and P. Bienstman, "Label-free biosensing with a slot-waveguide-based ring resonator in silicon on insulator," *Photonics Journal, IEEE* **1**, 197-204 (2009).
 - [10] M. La Notte, B. Troia, T. Muciaccia, C. E. Campanella, F. De Leonardis, and V. Passaro, "Recent advances in gas and chemical detection by Vernier effect-based photonic sensors," *Sensors* **14**, 4831-4855 (2014).
 - [11] L. Tombez, E. Zhang, J. Orcutt, S. Kamalapurkar, and W. Green, "Methane absorption spectroscopy on a silicon photonic chip," *Optica* **4**, 1322-1325 (2017).
 - [12] N. A. Yebo, W. Bogaerts, Z. Hens, and R. Baets, "On-chip arrayed waveguide grating interrogated silicon-on-insulator microring resonator-based gas sensor," *Photonics Technology Letters, IEEE* **23**, 1505-1507 (2011).
 - [13] B. B. Kyotoku, L. Chen, and M. Lipson, "Sub-nm resolution cavity enhanced micro-spectrometer," *Opt Express* **18**, 102-107 (2010).
 - [14] E. Ryckeboer, R. Bockstaele, M. Vanslambrouck, and R. Baets, "Glucose sensing by waveguide-based absorption spectroscopy on a silicon chip," *Biomedical optics express* **5**, 1636-1648 (2014).
 - [15] E. Ryckeboer, X. Nie, A. Dhakal, D. Martens, P. Bienstman, G. Roelkens, and R. Baets, "Spectroscopic sensing and applications in Silicon Photonics," in *Group IV Photonics (GFP), 2017 IEEE 14th International Conference on*(IEEE, 2017), pp. 81-82.
 - [16] H. Podmore, A. Scott, P. Cheben, C. Sioris, P. Cameron, J. H. Schmid, A. Lohmann, Z. Corriveau, and R. Lee, "Athermal planar-waveguide Fourier-transform spectrometer for methane detection," *Opt Express* **25**, 33018-

-
- 33028 (2017).
- [17] R. Baets, W. Bogaerts, B. Kuyken, A. Rahim, G. Roelkens, T. Spuesens, J. Van Campenhout, and D. Van Thourhout, "Silicon Photonic Integrated Circuits," in *Fibre Optic Communication: Key Devices*, H. Venghaus, and N. Grote, eds. (Springer International Publishing, Cham, 2017), pp. 673-737.
 - [18] E. Ryckeboer, A. Gassenq, M. Muneeb, N. Hattasan, S. Pathak, L. Cerutti, J. Rodriguez, E. Tournie, W. Bogaerts, and R. Baets, "Silicon-on-insulator spectrometers with integrated GaInAsSb photodiodes for wide-band spectroscopy from 1510 to 2300 nm," *Opt Express* **21**, 6101-6108 (2013).
 - [19] P. Cheben, J. H. Schmid, A. Delge, A. Densmore, S. Janz, B. Lamontagne, J. Lapointe, E. Post, P. Waldron, and D. X. Xu, "A high-resolution silicon-on-insulator arrayed waveguide grating microspectrometer with sub-micrometer aperture waveguides," *Opt Express* **15**, 2299-2306 (2007).
 - [20] M. Muneeb, A. Vasiliev, A. Ruocco, A. Malik, H. Chen, M. Nedeljkovic, J. S. Penades, L. Cerutti, J. B. Rodriguez, G. Z. Mashanovich, M. K. Smit, E. Tourni, and G. Roelkens, "III-V-on-silicon integrated micro - spectrometer for the 3-10.5 μm wavelength range," *Opt Express* **24**, 9465-9472 (2016).
 - [21] M. Muneeb, X. Chen, P. Verheyen, G. Lepage, S. Pathak, E. Ryckeboer, A. Malik, B. Kuyken, M. Nedeljkovic, and J. Van Campenhout, "Demonstration of Silicon-on-insulator mid-infrared spectrometers operating at 3.8 μm ," *Opt Express* **21**, 11659-11669 (2013).
 - [22] A. Malik, M. Muneeb, Y. Shimura, J. Van Campenhout, R. Loo, and G. Roelkens, "Germanium-on-silicon planar concave grating wavelength (de)multiplexers in the mid-infrared," *Appl Phys Lett* **103**, 161119 (2013).

-
- [23] B. Momeni, E. S. Hosseini, M. Askari, M. Soltani, and A. Adibi, "Integrated photonic crystal spectrometers for sensing applications," *Opt Commun* **282**, 3168-3171 (2009).
- [24] B. Momeni, E. S. Hosseini, and A. Adibi, "Planar photonic crystal microspectrometers in silicon-nitride for the visible range," *Opt Express* **17**, 17060-17069 (2009).
- [25] F. Meng, R.-J. Shiue, N. Wan, L. Li, J. Nie, N. C. Harris, E. H. Chen, T. Schröder, N. Pervez, and I. Kymissis, "Waveguide-integrated photonic crystal spectrometer with camera readout," *Appl Phys Lett* **105**, 051103 (2014).
- [26] B. Redding, S. F. Liew, R. Sarma, and CaoHui, "Compact spectrometer based on a disordered photonic chip," *Nat Photon* **7**, 746-751 (2013).
- [27] Z. Xia, A. A. Eftekhar, M. Soltani, B. Momeni, Q. Li, M. Chamanzar, S. Yegnanarayanan, and A. Adibi, "High resolution on-chip spectroscopy based on miniaturized microdonut resonators," *Opt Express* **19**, 12356-12364 (2011).
- [28] B. Redding, S. F. Liew, Y. Bromberg, R. Sarma, and H. Cao, "On-chip spiral spectrometer," *arXiv preprint arXiv:1603.01612* (2016).
- [29] G. Calafiore, A. Koshelev, S. Dhuey, A. Goltsov, P. Sasorov, S. Babin, V. Yankov, S. Cabrini, and C. Peroz, "Holographic planar lightwave circuit for on-chip spectroscopy," *Light: Science & Applications* **3**, e203 (2014).
- [30] C. Peroz, A. Goltsov, S. Dhuey, P. Sasorov, B. Harteneck, I. Ivonin, S. Kopyatev, S. Cabrini, S. Babin, and V. Yankov, "High-resolution spectrometer-on-chip based on digital planar holography," *IEEE Photonics Journal* **3**, 888-896 (2011).

-
- [31] B. Momeni, E. S. Hosseini, and A. Adibi, "Cascaded silicon-nitride integrated spectrometers for wideband high-resolution spectral interrogation," in *OPTO*(International Society for Optics and Photonics, 2010), pp. 76090L-76090L-76097.
- [32] P. R. Griffiths, and J. A. De Haseth, *Fourier transform infrared spectrometry* (John Wiley & Sons, 2007).
- [33] O. Manzardo, H. P. Herzig, C. Marxer, and N. F. de Rooij, "Miniaturized time-scanning Fourier transform spectrometer based on silicon technology," in *Symposium on Micromachining and Microfabrication*(International Society for Optics and Photonics, 1999), pp. 39-47.
- [34] O. Manzardo, H. P. Herzig, B. Guldemann, C. Marxer, and N. F. de Rooij, "New design for an integrated fourier transform spectrometer," in *Micromachining and Microfabrication*(International Society for Optics and Photonics, 2000), pp. 310-319.
- [35] K. Yu, D. Lee, U. Krishnamoorthy, N. Park, and O. Solgaard, "Micromachined Fourier transform spectrometer on silicon optical bench platform," *Sensors and Actuators A: Physical* **130**, 523-530 (2006).
- [36] B. Saadany, H. Omran, M. Medhat, F. Marty, D. Khalil, and T. Bourouina, "MEMS tunable Michelson interferometer with robust beam splitting architecture," in *Optical MEMS and Nanophotonics, 2009 IEEE/LEOS International Conference on*(IEEE, 2009), pp. 49-50.
- [37] E. Le Coarer, S. Blaize, P. Benech, I. Stefanon, A. Morand, G. Léronnel, G. Leblond, P. Kern, J. M. Fedeli, and P. Royer, "Wavelength-scale stationary-wave integrated Fourier-transform spectrometry," *Nature Photonics* **1**, 473 (2007).

-
- [38] G. D. Osowiecki, M. Madi, I. Shorubalko, I. Philipoussis, E. Alberti, T. Scharf, and H. P. Herzig, "Standing wave integrated Fourier transform spectrometer for imaging spectrometry in the near infrared," in *SPIE Optical Engineering+ Applications*(International Society for Optics and Photonics, 2015), pp. 96110P-96110P-96117.
 - [39] M. Florjańczyk, P. Cheben, S. Janz, A. Scott, B. Solheim, and D.-X. Xu, "Multiaperture planar waveguide spectrometer formed by arrayed Mach-Zehnder interferometers," *Opt Express* **15**, 18176-18189 (2007).
 - [40] P. J. Bock, P. Cheben, A. V. Velasco, J. H. Schmid, A. Delâge, M. Florjańczyk, J. Lapointe, D. X. Xu, M. Vachon, and S. Janz, "Subwavelength grating Fourier - transform interferometer array in silicon - on - insulator," *Laser & Photonics Reviews* **7**, L67-L70 (2013).
 - [41] A. V. Velasco, P. Cheben, P. J. Bock, A. Delâge, J. H. Schmid, J. Lapointe, S. Janz, M. L. Calvo, D.-X. Xu, and M. Florjańczyk, "High-resolution Fourier-transform spectrometer chip with microphotonic silicon spiral waveguides," *Opt Lett* **38**, 706-708 (2013).
 - [42] A. Herrero-Bermello, A. V. Velasco, H. Podmore, P. Cheben, J. H. Schmid, S. Janz, M. L. Calvo, D.-X. Xu, A. Scott, and P. Corredera, "Temperature dependence mitigation in stationary Fourier-transform on-chip spectrometers," *Opt Lett* **42**, 2239-2242 (2017).
 - [43] H. Podmore, A. Scott, P. Cheben, A. V. Velasco, J. H. Schmid, M. Vachon, and R. Lee, "Demonstration of a compressive-sensing Fourier-transform on-chip spectrometer," *Opt Lett* **42**, 1440-1443 (2017).
 - [44] H. Podmore, A. Scott, and R. Lee, "A compressive-sensing Fourier-transform on-chip Raman spectrometer," in *Photonic Instrumentation*

-
- Engineering V*(International Society for Optics and Photonics, 2018), p. 105390L.
- [45] S. Zheng, H. Cai, Y. D. Gu, L. K. Chin, and A. Q. Liu, "On-chip Fourier Transform Spectrometer for Chemical Sensing Applications," in *Conference on Lasers and Electro-Optics*(Optical Society of America, San Jose, California, 2016), p. AM1J.6.
 - [46] M. C. Souza, A. Grieco, N. C. Frateschi, and Y. Fainman, "Fourier transform spectrometer on silicon with thermo-optic non-linearity and dispersion correction," *Nature communications* **9**, 665 (2018).
 - [47] X. Nie, E. Ryckeboer, G. Roelkens, and R. Baets, "CMOS-compatible broadband co-propagative stationary Fourier transform spectrometer integrated on a silicon nitride photonics platform," *Opt Express* **25**, A409-A418 (2017).
 - [48] D. M. Kita, H. Lin, A. Agarwal, K. Richardson, I. Luzinov, T. Gu, and J. Hu, "On-chip infrared spectroscopic sensing: redefining the benefits of scaling," *Ieee J Sel Top Quant* **23**, 1-10 (2017).
 - [49] D. M. Kita, B. Miranda, D. Favela, D. Bono, J. Michon, H. Lin, T. Gu, and J. Hu, "Digital Fourier transform spectroscopy: a high-performance, scalable technology for on-chip spectrum analysis," *arXiv preprint arXiv:1802.05270* (2018).
 - [50] A. Dhakal, A. Z. Subramanian, P. Wuytens, F. Peyskens, N. Le Thomas, and R. Baets, "Evanescent excitation and collection of spontaneous Raman spectra using silicon nitride nanophotonic waveguides," *Opt Lett* **39**, 4025-4028 (2014).
 - [51] L. Zhou, X. Zhang, L. Lu, and J. Chen, "Tunable vernier microring optical

-
- filters with-type microheaters," *IEEE Photonics Journal* **5**, 6601211-6601211 (2013).
- [52] L.-W. Luo, N. Ophir, C. Chen, L. H. Gabrielli, C. B. Poitras, K. Bergman, and M. Lipson, "Simultaneous mode and wavelength division multiplexing on-chip," *arXiv preprint arXiv:1306.2378* (2013).
- [53] L.-W. Luo, N. Ophir, C. P. Chen, L. H. Gabrielli, C. B. Poitras, K. Bergmen, and M. Lipson, "WDM-compatible mode-division multiplexing on a silicon chip," *Nature communications* **5** (2014).
- [54] H. Toda, T. Yamashita, T. Kuri, and K.-i. Kitayama, "Demultiplexing Using an Arrayed-Waveguide Grating for Frequency-Interleaved DWDM Millimeter-Wave Radio-on-Fiber Systems," *J Lightwave Technol* **21**, 1735 (2003).
- [55] E. Timurdogan, C. M. Sorace-Agaskar, J. Sun, E. S. Hosseini, A. Biberman, and M. R. Watts, "An ultralow power athermal silicon modulator," *Nature communications* **5** (2014).
- [56] S. Gan, C. Cheng, Y. Zhan, B. Huang, X. Gan, S. Li, S. Lin, X. Li, J. Zhao, and H. Chen, "A highly efficient thermo-optic microring modulator assisted by graphene," *Nanoscale* **7**, 20249-20255 (2015).
- [57] C. Zhang, P. A. Morton, J. B. Khurgin, J. D. Peters, and J. E. Bowers, "Ultralinear heterogeneously integrated ring-assisted Mach–Zehnder interferometer modulator on silicon," *Optica* **3**, 1483-1488 (2016).
- [58] B. Stern, X. Zhu, C. P. Chen, L. D. Tzuang, J. Cardenas, K. Bergman, and M. Lipson, "On-chip mode-division multiplexing switch," *Optica* **2**, 530-535 (2015).
- [59] N. C. Harris, Y. Ma, J. Mower, T. Baehr-Jones, D. Englund, M. Hochberg,

- hr/>
- and C. Galland, "Efficient, compact and low loss thermo-optic phase shifter in silicon," *Opt Express* **22**, 10487-10493 (2014).
- [60] H. Rong, S. Xu, Y.-H. Kuo, V. Sih, O. Cohen, O. Raday, and M. Paniccia, "Low-threshold continuous-wave Raman silicon laser," *Nature Photonics* **1**, 232-237 (2007).
- [61] Z. Zhou, B. Yin, and J. Michel, "On-chip light sources for silicon photonics," *Light: Science & Applications* **4**, e358 (2015).
- [62] S. Bisschop, A. Guille, D. Van Thourhout, Z. Hens, and E. Brainis, "Broadband enhancement of single photon emission and polarization dependent coupling in silicon nitride waveguides," *Opt Express* **23**, 13713-13724 (2015).
- [63] J. Leuthold, C. Koos, and W. Freude, "Nonlinear silicon photonics," *Nature Photonics* **4** (2010).
- [64] K. Okamoto, *Fundamentals of optical waveguides* (Academic press, 2010).
- [65] D. Lockwood, and L. Pavesi, "Silicon photonics II: components and integration series: topics in applied physics," (Springer, Berlin, 2011).
- [66] M. J. Heck, J. F. Bauters, M. L. Davenport, D. T. Spencer, and J. E. Bowers, "Ultra - low loss waveguide platform and its integration with silicon photonics," *Laser & Photonics Reviews* **8**, 667-686 (2014).
- [67] T. Barwicz, and H. A. Haus, "Three-dimensional analysis of scattering losses due to sidewall roughness in microphotonic waveguides," *Lightwave Technology, Journal of* **23**, 2719-2732 (2005).
- [68] R. J. Deri, and E. Kapon, "Low-loss III-V semiconductor optical waveguides," *Quantum Electronics, IEEE Journal of* **27**, 626-640 (1991).
- [69] Q. Xia, P. F. Murphy, H. Gao, and S. Y. Chou, "Ultrafast and selective

- reduction of sidewall roughness in silicon waveguides using self-perfection by liquefaction," *Nanotechnology* **20**, 345302 (2009).
- [70] P. Rai-Choudhury, *Handbook of microlithography, micromachining, and microfabrication: microlithography* (Iet, 1997).
- [71] B. Rahman, D. Leung, S. Obayya, and K. Grattan, "Numerical analysis of bent waveguides: bending loss, transmission loss, mode coupling, and polarization coupling," *Appl Optics* **47**, 2961-2970 (2008).
- [72] J. Cardenas, C. B. Poitras, J. T. Robinson, K. Preston, L. Chen, and M. Lipson, "Low loss etchless silicon photonic waveguides," *Opt Express* **17**, 4752-4757 (2009).
- [73] P. Dong, W. Qian, S. Liao, H. Liang, C.-C. Kung, N.-N. Feng, R. Shafiiha, J. Fong, D. Feng, and A. V. Krishnamoorthy, "Low loss shallow-ridge silicon waveguides," *Opt Express* **18**, 14474-14479 (2010).
- [74] G. Li, J. Yao, H. Thacker, A. Mekis, X. Zheng, I. Shubin, Y. Luo, J.-H. Lee, K. Raj, and J. E. Cunningham, "Ultralow-loss, high-density SOI optical waveguide routing for macrochip interconnects," *Opt Express* **20**, 12035-12039 (2012).
- [75] J. F. Bauters, M. J. Heck, D. D. John, J. S. Barton, C. M. Bruinink, A. Leinse, R. G. Heideman, D. J. Blumenthal, and J. E. Bowers, "Planar waveguides with less than 0.1 dB/m propagation loss fabricated with wafer bonding," *Opt Express* **19**, 24090-24101 (2011).
- [76] H. Lee, T. Chen, J. Li, O. Painter, and K. J. Vahala, "Ultra-low-loss optical delay line on a silicon chip," *Nature communications* **3**, 867 (2012).
- [77] A. Subramanian, P. Neutens, A. Dhakal, R. Jansen, T. Claes, X. Rottenberg, F. Peyskens, S. Selvaraja, P. Helin, and B. Du Bois, "Low-loss singlemode

-
- PECVD silicon nitride photonic wire waveguides for 532–900 nm wavelength window fabricated within a CMOS pilot line," *IEEE Photonics Journal* **5**, 2202809-2202809 (2013).
- [78] X. Zhang, Y. Zhang, C. Xiong, and B. J. Eggleton, "Correlated photon pair generation in low-loss double-stripe silicon nitride waveguides," *arXiv preprint arXiv:1602.07915* (2016).
- [79] R. Heideman, A. Melloni, M. Hoekman, A. Borreman, A. Leinse, and F. Morichetti, "Low loss, high contrast optical waveguides based on CMOS compatible LPCVD processing: technology and experimental results," (2005).
- [80] J. P. Epping, M. Hoekman, R. Mateman, A. Leinse, R. G. Heideman, A. van Rees, P. J. van der Slot, C. J. Lee, and K.-J. Boller, "High confinement, high yield Si₃N₄ waveguides for nonlinear optical applications," *Opt Express* **23**, 642-648 (2015).
- [81] R. Dangel, U. Bapst, C. Berger, R. Beyeler, L. Dellmann, F. Horst, B. Offrein, and G.-L. Bona, "Development of a low-cost low-loss polymer waveguide technology for parallel optical interconnect applications," in *Biophotonics/Optical Interconnects and VLSI Photonics/WBM Microcavities, 2004 Digest of the LEOS Summer Topical Meetings*(IEEE, 2004), p. 2 pp.
- [82] L. Zhuang, D. Marpaung, M. Burla, W. Beeker, A. Leinse, and C. Roeloffzen, "Low-loss, high-index-contrast Si₃N₄/SiO₂ optical waveguides for optical delay lines in microwave photonics signal processing," *Opt Express* **19**, 23162-23170 (2011).
- [83] J. Ye, and T. W. Lynn, "Applications of optical cavities in modern atomic,

- molecular, and optical physics," *Adv At Mol Opt Phys* **49**, 2-84 (2003).
- [84] D. G. Rabus, "Ring resonators: Theory and modeling," *Integrated Ring Resonators: The Compendium*, 3-40 (2007).
- [85] C. Wang, "A Nonlinear Microresonator Refractive Index Sensor," *J Lightwave Technol* **33**, 4360-4366 (2015).
- [86] J. T. Robinson, L. Chen, and M. Lipson, "On-chip gas detection in silicon optical microcavities," *Opt Express* **16**, 4296-4301 (2008).
- [87] N. A. Yebo, P. Lommens, Z. Hens, and R. Baets, "An integrated optic ethanol vapor sensor based on a silicon-on-insulator microring resonator coated with a porous ZnO film," *Opt Express* **18**, 11859-11866 (2010).
- [88] N. A. Yebo, D. Taillaert, J. Roels, D. Lahem, M. Debliqy, D. Van Thourhout, and R. Baets, "Silicon-on-insulator (SOI) ring resonator-based integrated optical hydrogen sensor," *Photonics Technology Letters, IEEE* **21**, 960-962 (2009).
- [89] Y. Sun, and X. Fan, "Optical ring resonators for biochemical and chemical sensing," *Analytical and bioanalytical chemistry* **399**, 205-211 (2011).
- [90] A. Ksendzov, and Y. Lin, "Integrated optics ring-resonator sensors for protein detection," *Opt Lett* **30**, 3344-3346 (2005).
- [91] H. Li, Y. Chen, J. Noh, S. Tadesse, and M. Li, "Multichannel cavity optomechanics for all-optical amplification of radio frequency signals," *Nature communications* **3**, 1091 (2012).
- [92] A. Schliesser, and T. J. Kippenberg, "Cavity optomechanics with whispering-gallery mode optical micro-resonators," *Advances In Atomic, Molecular, and Optical Physics* **58**, 207-323 (2010).
- [93] S. Tallur, and S. A. Bhave, "Simultaneous radiation pressure induced

-
- heating and cooling of an opto-mechanical resonator," *Appl Phys Lett* **100**, 111115 (2012).
- [94] B. Dong, H. Cai, G. Ng, P. Kropelnicki, J. Tsai, A. Randles, M. Tang, Y. Gu, Z. Suo, and A. Liu, "A nanoelectromechanical systems actuator driven and controlled by Q-factor attenuation of ring resonator," *Appl Phys Lett* **103**, 181105 (2013).
- [95] D. Van Thourhout, and J. Roels, "Optomechanical device actuation through the optical gradient force," *Nature Photonics* **4**, 211-217 (2010).
- [96] B. Liu, A. Shakouri, and J. E. Bowers, "Wide tunable double ring resonator coupled lasers," *Photonics Technology Letters, IEEE* **14**, 600-602 (2002).
- [97] D. Rabus, M. Hamacher, U. Troppenz, and H. Heidrich, "High-Q channel-dropping filters using ring resonators with integrated SOAs," *Photonics Technology Letters, IEEE* **14**, 1442-1444 (2002).
- [98] A. Melloni, "Synthesis of a parallel-coupled ring-resonator filter," *Opt Lett* **26**, 917-919 (2001).
- [99] A. Lelievre, R. Brenot, G.-H. Duan, and A. Maho, "Fast tunable silicon ring resonator filter for access networks," in *Optical Fiber Communication Conference*(Optical Society of America, 2015), p. Tu3E. 5.
- [100] A. A. Savchenkov, A. B. Matsko, V. S. Ilchenko, I. Solomatine, D. Seidel, and L. Maleki, "Tunable optical frequency comb with a crystalline whispering gallery mode resonator," *Phys Rev Lett* **101**, 093902 (2008).
- [101] F. Ferdous, H. Miao, D. E. Leaird, K. Srinivasan, J. Wang, L. Chen, L. T. Varghese, and A. M. Weiner, "Spectral line-by-line pulse shaping of on-chip microresonator frequency combs," *Nature Photonics* **5**, 770-776 (2011).
- [102] F. Horst, W. M. J. Green, S. Assefa, S. M. Shank, Y. A. Vlasov, and B. J.

-
- Offrein, "Cascaded Mach-Zehnder wavelength filters in silicon photonics for low loss and flat pass-band WDM (de-)multiplexing," *Opt Express* **21**, 11652-11658 (2013).
- [103] J. S. Fandiño, P. Muñoz, D. Doménech, and J. Capmany, "A monolithic integrated photonic microwave filter," *Nature Photonics* **11**, 124 (2017).
- [104] S. Kumar, S. K. Raghuwanshi, and A. Kumar, "1× 8 signal router using cascading the Mach-Zehnder interferometers," in *Advanced Infocomm Technology (ICAIT), 2013 6th International Conference on*(IEEE, 2013), pp. 161-162.
- [105] G. T. Reed, and A. P. Knights, *Silicon photonics: an introduction* (John Wiley & Sons, 2004).
- [106] B. J. Frey, D. B. Leviton, and T. J. Madison, "Temperature-dependent refractive index of silicon and germanium," in *Optomechanical Technologies for Astronomy*(International Society for Optics and Photonics, 2006), p. 62732J.
- [107] G.-D. Kim, H.-S. Lee, C.-H. Park, S.-S. Lee, B. T. Lim, H. K. Bae, and W.-G. Lee, "Silicon photonic temperature sensor employing a ring resonator manufactured using a standard CMOS process," *Opt Express* **18**, 22215-22221 (2010).
- [108] E. Li, X. Wang, and C. Zhang, "Fiber-optic temperature sensor based on interference of selective higher-order modes," (2006).
- [109] J. C. Matthews, A. Politi, A. Stefanov, and J. L. O'Brien, "Manipulation of multiphoton entanglement in waveguide quantum circuits," *Nature Photonics* **3**, 346-350 (2009).
- [110] J. W. Silverstone, D. Bonneau, K. Ohira, N. Suzuki, H. Yoshida, N. Iizuka,

- M. Ezaki, C. M. Natarajan, M. G. Tanner, and R. H. Hadfield, "On-chip quantum interference between silicon photon-pair sources," *Nature Photonics* **8**, 104-108 (2014).
- [111] A. Politi, J. C. Matthews, M. G. Thompson, and J. L. O'Brien, "Integrated quantum photonics," *Selected Topics in Quantum Electronics, IEEE Journal of* **15**, 1673-1684 (2009).
- [112] A. Nitkowski, A. Baeumner, and M. Lipson, "On-chip spectrophotometry for bioanalysis using microring resonators," *Biomedical optics express* **2**, 271-277 (2011).
- [113] A. Nitkowski, and M. Lipson, "Cavity-enhanced on-chip absorption spectroscopy," (Google Patents, 2015).
- [114] C. K. Ho, A. Robinson, D. R. Miller, and M. J. Davis, "Overview of sensors and needs for environmental monitoring," *Sensors* **5**, 4-37 (2005).
- [115] W. Baird, and N. S. Nogar, "Compact, self-contained optical spectrometer," *Appl Spectrosc* **49**, 1699-1704 (1995).
- [116] B. C. Smith, *Fundamentals of Fourier transform infrared spectroscopy* (CRC press, 2011).
- [117] P. Cheben, A. L. Bogdanov, A. Delage, S. Janz, B. Lamontagne, M.-J. Picard, E. Post, and D.-X. Xu, "A 100-channel near-infrared SOI waveguide microspectrometer: Design and fabrication challenges," in *Photonics Asia 2004*(International Society for Optics and Photonics, 2005), pp. 103-110.
- [118] N. Cvetojevic, N. Jovanovic, J. Lawrence, M. Withford, and J. Bland-Hawthorn, "Developing arrayed waveguide grating spectrographs for multi-object astronomical spectroscopy," *Opt Express* **20**, 2062-2072 (2012).
- [119] B. I. Akca, B. Považay, A. Alex, K. Wörhoff, R. M. de Ridder, W. Drexler,

- hr/>
- and M. Pollnau, "Miniature spectrometer and beam splitter for an optical coherence tomography on a silicon chip," *Opt Express* **21**, 16648-16656 (2013).
- [120] J. Zou, T. Lang, Z. Le, and J.-J. He, "Ultracompact silicon-on-insulator-based reflective arrayed waveguide gratings for spectroscopic applications," *Appl Optics* **55**, 3531-3536 (2016).
- [121] P. Gatkin, S. Veilleux, Y. Hu, J. Bland-Hawthorn, and M. Dagenais, "Arrayed waveguide grating spectrometers for astronomical applications: new results," *Opt Express* **25**, 17918-17935 (2017).
- [122] J. Brouckaert, G. Roelkens, S. Selvaraja, W. Bogaerts, P. Dumon, S. Verstuyft, Z.-Q. Yu, D. Van Thourhout, and R. Baets, "Miniature integrated spectrometer fabricated on a silicon-on-insulator substrate," in *IEEE Lasers and Electro-Optics Society, 2008. LEOS 2008. 21st Annual Meeting of the* (IEEE, 2008), pp. 55-56.
- [123] X. Gan, N. Pervez, I. Kymissis, F. Hatami, and D. Englund, "A high-resolution spectrometer based on a compact planar two dimensional photonic crystal cavity array," *Appl Phys Lett* **100**, 231104 (2012).
- [124] A. C. Liapis, Z. Shi, and R. W. Boyd, "Optimizing photonic crystal waveguides for on-chip spectroscopic applications," *Opt Express* **21**, 10160-10165 (2013).
- [125] A. C. Liapis, B. Gao, M. R. Siddiqui, Z. Shi, and R. W. Boyd, "On-chip spectroscopy with thermally tuned high-Q photonic crystal cavities," *Appl Phys Lett* **108**, 021105 (2016).
- [126] P. Varytis, D.-N. Huynh, W. Hartmann, W. Pernice, and K. Busch, "Design study of random spectrometers for applications at optical frequencies," *Opt*

-
- Lett **43**, 3180-3183 (2018).
- [127] C.-M. Tsai, H. Taga, C.-H. Yang, Y.-L. Lo, and T.-C. Liang, "Demonstration of a ROADM using cyclic AWGs," *J Lightwave Technol* **29**, 2780-2784 (2011).
- [128] S. Dhoore, A. Rahim, G. Roelkens, and G. Morthier, "12.5 Gbit/s discretely tunable InP-on-silicon filtered feedback laser with sub-nanosecond wavelength switching times," *Opt Express* **26**, 8059-8068 (2018).
- [129] D. Seyringer, "Arrayed waveguide gratings," (Society of Photo-Optical Instrumentation Engineers (SPIE), 2016).
- [130] B. Momeni, and A. Adibi, "Preconditioned superprism-based photonic crystal demultiplexers: analysis and design," *Appl Optics* **45**, 8466-8476 (2006).
- [131] H. Podmore, A. Scott, P. Cheben, A. V. Velasco, J. H. Schmid, M. Vachon, and R. Lee, "A compressive-sensing Fourier-transform spectrometer chip using subwavelength grating waveguides," *Opt Lett* (2017).
- [132] D. M. Kita, B. Miranda, D. Favela, D. Bono, J. Michon, H. Lin, T. Gu, and J. Hu, "High-performance and scalable on-chip digital Fourier transform spectroscopy," *Nature Communications* **9**, 4405 (2018).
- [133] R. Wolffenbuttel, "MEMS-based optical mini-and microspectrometers for the visible and infrared spectral range," *J Micromech Microeng* **15**, S145 (2005).
- [134] M. Florjańczyk, P. Cheben, S. Janz, B. Lamontagne, J. Lapointe, A. Scott, B. Solheim, and D.-X. Xu, "Development of a slab waveguide spatial heterodyne spectrometer for remote sensing," in *SPIE MOEMS-MEMS*(SPIE, 2010), p. 9.

-
- [135] M. Nedeljkovic, A. V. Velasco, A. Z. Khokhar, A. Delâge, P. Cheben, and G. Z. Mashanovich, "Mid-infrared silicon-on-insulator Fourier-transform spectrometer chip," *Ieee Photonic Technol L* **28**, 528-531 (2016).
 - [136] K.-W. Ang, G.-Q. Lo, and D.-L. Kwong, "Germanium Photodetector Technologies for Optical Communication Applications," in *Semiconductor Technologies*(InTech, 2010).
 - [137] J. Song, X. Luo, J. S. Kee, K. Han, C. Li, M. K. Park, X. Tu, H. Zhang, Q. Fang, and L. Jia, "Silicon-based optoelectronic integrated circuit for label-free bio/chemical sensor," *Opt Express* **21**, 17931-17940 (2013).
 - [138] N. A. Yebo, W. Bogaerts, Z. Hens, and R. Baets, "On-chip interrogation of a silicon-on-insulator microring resonator based ethanol vapor sensor with an arrayed waveguide grating (AWG) spectrometer," in *Integrated Optics: Devices, Materials, and Technologies XVI*(2012).
 - [139] H. Venghaus, and N. Grote, *Fibre optic communication: key devices* (Springer, 2017).
 - [140] B. Nabet, *Photodetectors: Materials, Devices and Applications* (Woodhead Publishing, 2015).
 - [141] A. Y. Liu, C. Zhang, J. Norman, A. Snyder, D. Lubyshev, J. M. Fastenau, A. W. Liu, A. C. Gossard, and J. E. Bowers, "High performance continuous wave 1.3 μ m quantum dot lasers on silicon," *Appl Phys Lett* **104**, 041104 (2014).
 - [142] K. D. Cole, J. V. Beck, A. Haji-Sheikh, and B. Litkouhi, *Heat conduction using Green's functions* (Taylor & Francis, 2010).
 - [143] D. B. Leviton, and B. J. Frey, "Temperature-dependent absolute refractive index measurements of synthetic fused silica," in *Optomechanical*

-
- Technologies for Astronomy*(International Society for Optics and Photonics, 2006), p. 62732K.
- [144] Y. Okada, and Y. Tokumaru, "Precise determination of lattice parameter and thermal expansion coefficient of silicon between 300 and 1500 K," J Appl Phys **56**, 314-320 (1984).
- [145] F. G. Della Corte, M. Esposito Montefusco, L. Moretti, I. Rendina, and G. Cocorullo, "Temperature dependence analysis of the thermo-optic effect in silicon by single and double oscillator models," J Appl Phys **88**, 7115-7119 (2000).
- [146] Q. Fang, J. Song, X. Luo, L. Jia, M. Yu, G. Lo, and Y. Liu, "High efficiency ring-resonator filter with NiSi heater," Ieee Photonic Technol L **24**, 350-352 (2012).
- [147] R. G. Baets, A. Z. Subramanian, S. Clemmen, B. Kuyken, P. Bienstman, N. Le Thomas, G. Roelkens, D. Van Thourhout, P. Helin, and S. Severi, "Silicon Photonics: Silicon Nitride Versus Silicon-on-insulator," in *Optical Fiber Communication Conference*(Optical Society of America, 2016), p. Th3J. 1.