Investigations into the design and fabrication of silicon photonic broadband wavelength selective switches and filters

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**INVESTIGATIONS INTO THE DESIGN AND FABRICATION OF SILICON
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FILTERS**

PATINHAREKANDY PRABHATHAN

A thesis submitted to the Nanyang Technological University in partial
fulfilment of the requirement for the award of degree of doctor of
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Abstract

Silicon photonics offers great promise for widespread deployment of Opto Electronic Integrated Circuits (OEIC) and Photonic Integrated Circuits (PIC) devices in the near future. It is highly significant that silicon photonics allows Complementary Metal-Oxide-Semiconductor (CMOS) compatible fabrication of highly compact and efficient devices, in a cost effective way. Optical fiber communication network which uses Wavelength Division Multiplexing (WDM) technology needs highly efficient and sophisticated wavelength filtering functionality to meet the total bandwidth efficiency. Micro photonic technologies based on silicon waveguides are very promising in their functionality to provide telecom grade devices which meet these requirements. They are expected to escape the limitations of currently used bulk optical technologies in terms cost effective fabrication and implementation, stability, reconfigurability, compactness, complex wavelength routing/switching functionalities and integration with other active or passive devices. In this thesis investigations into the design and fabrication of Thermo Optic Wavelength Selective Switch (TO-WSS) and band pass filters in silicon platform is done to achieve desired spectral features and wavelength selection routing functionalities.

In the first part of the thesis a broadband tunable TO-WSS has been demonstrated using silicon Micro Ring Resonator (MRR). The TO-WSS can achieve a 94 nm($\sim$ C+L Band) tuning range with a total power of 154 mW through the proposed tuning procedure, hence reducing the total power consumption for a full C+L band tuning to 32.7% of that of a single ring tuning. The thermal cross talk between the rings is considerably reduced with the separated ring configuration. The proposed TO-WSS can be arranged in matrix array configurations to achieve dynamically reconfigurable

add/drop filter suitable for DWDM communication network with narrow channel spacing.

In the second part, series and parallel coupled ring resonators are designed and fabricated and analysed as a TO-WSS. Wavelength filters with an out of band rejection ratio >30 dB, 3 dB bandwidth <1.4 nm, pass band ripple <0.3 dB and drop loss of 0.5 dB have been obtained in series configuration. Among the possible detuning combinations in the WSS, detuning a single ring adjacent to input bus-waveguide and two rings adjacent to drop line waveguide are observed to be more effective for an OFF state with high channel extinction, low switching cross talk and low loss of OFF state. A maximum channel extinction of 22 dB, lowest switching cross talk -30 dB and a zero loss of OFF state has been achieved with a single ring detuned OFF state using a switching power of 48 mW.

In the last part of the thesis, phase shifted vertical side wall gratings has been proposed as a resonant transmission filter suitable for DWDM optical communication network. The grating resonator, which is designed to operate in the C-band of optical communication, has a high free spectral range (~ 50 nm) and a narrow band resonant transmission ($\Delta\lambda < 0.8$ nm). The results show that resonant wavelength can be controlled by changing the phase shift length or effective refractive index of the grating. Coupled cavity configurations in the grating resonator have been analyzed to get high channel selectivity and a flat-top spectrum for the resonant wavelength. The -1 dB bandwidth (0.275 nm), 3 dB bandwidth (0.32 nm), and channel cross talk (-28 dB) are comparable to that of a typical DWDM wavelength filter in a 100 GHz channel spaced network. Fabrication demonstration of these grating resonators on an SOI wafer through electron beam lithography shows promising results which are comparable to the simulation and analysis.

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List of symbols

<i>Symbol</i>	<i>Meaning</i>
Λ	Grating period
Λ_p	Quarter wave phase shift length
ΔW	Grating etch depth
W	Grating waveguide width
n_{eff}	Effective refractive index
n_{clad}	Cladding refractive index
n_{Si}	Silicon refractive index
λ_B	Bragg wavelength
K	Grating constant
L	Total grating length
L_{out}	Grating length outside the phase shift
Q	Quality factor
D	Grating duty cycle
n_g	Group index
$\Delta\lambda_{3\text{dB}}$	Full Width at Half Maximum (FWHM)
S	Sensitivity
$\Delta\lambda$	Wavelength shift

List of abbreviations

<i>Abbreviation</i>	<i>Full form</i>
BPM	Beam Propagation Method
CMOS	Complementary Metal Oxide Semiconductor
CDF	Channel Dropping Filter
CIFS	Coupling Induced Frequency Shift
DWDM	Dense Wavelength Division Multiplexing
DUV	Deep Ultra Violet
DUT	Device Under Test
DPG	Double Phase Shifted Grating
EO	Electro Optic
FDTD	Finite Difference Time Domain
FSR	Free Spectral Range
FBG	Fiber Bragg Grating
ITU	International Telecommunication Union
IL	Insertion Loss
ICP	Inductively Coupled Plasma
MRR	Micro Ring Resonator
MZI	Mach-Zehnder Interferometer
OADM	Optical Add Drop Multiplexer

PECVD	Plasma Enhanced Chemical Vapor Deposition
RIE	Reactive Ion Etching
RIU	Refractive Index Unit
SSC	Spot Size Converter
SPG	Single Phase Shifted Grating
SOI	Silicon On Insulator
TO	Thermo Optic
TE	Transverse Electric
TM	Transverse Magnetic
TPG	Triple Phase Shifted Grating
TO-WSS	Thermo Optic Wavelength Selective Switch
WSS	Wavelength Selective Switch

Chapter 1: Introduction

In this chapter a general introduction to the thesis is given. The chapter begins with explaining the background and motivation of the research undertaken. The objectives and scope of the project are discussed in the subsequent sections followed by a research road map at the end of the chapter.

1.1. Background

The recent research and development of silicon based photonics offers great promise for the widespread deployment of Opto Electronic Integrated Circuits (OEIC) or Photonic Integrated Circuit (PIC) devices in the near future[1]. Such devices would find potential applications in hi-tech arenas such as microelectronics, telecommunications, smart sensing and lab-on-a chip devices[2]. A great amount of cost reduction, efficiency and stability can be achieved through this approach. The main reasons for choosing silicon as a platform for this approach are summarized below.

- i) Silicon is inexpensive when compared to other III-V and electro-optic materials (LiNbO_3) materials and there is a mature fabrication technology already available from electronic industry.
- ii) It exhibits low loss at infrared wavelength suitable for optical communication.
- iii) Silicon allows the merging of standard CMOS electronics with the high speed optoelectronics. Other components such as laser diodes, detectors etc can be monolithically integrated with silicon passive waveguide structures.
- iv) The higher refractive index contrast of silicon with respect to its cladding layer [$\text{Si} \sim 3.5$ and $\text{SiO}_2/\text{Air} \sim 1.5/1$] allows fabrication of highly compact devices with strong light confinement.

1.2. Motivation

During the recent past, there has been an explosive growth in optical telecommunications, with the increased demand from internet users. Great amount of

effort has been put in the research and development of optical communication systems with improved performance and capacity. The optical communication systems which were primarily used in point-to-point long distance communication links has been evolved up to the Fibre to the X (FTTX) and optical Network-on-Chip (NoC) like technologies. As copper cables and copper interconnects are being replaced with optical fibres and waveguides many of the electronic network components should be replaced with their equivalent photonic components such as splitters, filters, routers, and switches. An Optical communication network which uses Dense Wavelength Division Multiplexing (DWDM) technology needs highly efficient and sophisticated filtering functionality to meet the total bandwidth efficiency.

Due to the increasing demand from the end customers in terms of high band width and fast bit rate there is a growing interest in deploying Wavelength Division Multiplexed (WDM) optical network in the access network[3, 4]. This network includes Fibre-To-The-Home (FTTH) and Fibre-To-The-Premises (FTTP) like technologies to deliver the data to the customers. Unlike the metropolitan networks, this network has enormous number of installations and has a need for reconfiguration in their operation frequently to meet the customer requirements. One of the main challenges faced by service providers is in the cost effective implementation of these networks. Currently used technologies such as Micro Electro Mechanical Systems (MEMS), Thin Film Filter (TFF) and Liquid Crystal (LC) are costly apart from being bulky and difficult for planar waveguide integration. The silicon planar waveguide technologies is highly promising for achieving cost effective devices with high reconfigurability and sophisticated functionalities. Through this approach low cost, high volume manufacturability can be achieved for these devices through complementary metal oxide semiconductor (CMOS) fabrication technology. Many of

the electronic-photonic components such as photo detectors and laser sources can be monolithically integrated into a single chip, hence reducing the assembly processes and drastically reducing the component sizes.

1.2.1. Wavelength Selective switches (WSS) and wavelength filters in Wavelength Division Multiplexed(WDM) optical network

Wavelength Division Multiplexing (WDM) is a technology through which many different wavelengths are transmitted as different streams of data over an optical fibre in a telecommunication network at the same time. There is a continuous effort in putting more and more wavelengths on a single fibre, to form a Dense Wavelength Division Multiplexed (DWDM) network. A great amount of researches in this WDM technology is concentrated on developing photonic components that could work at higher data rates, wider optical bandwidth, closer channel spacing and higher spectral efficiency through a variety of innovations. The main target is to obtain high capacity, high speed and improved reliability for the next generation optical communication system. The respective channel spacing is standardized based on International Telecommunication Union (ITU) grid [5], defining 100GHz spaced frequencies $f = 193.1 \pm m \times 0.1 \text{ THz}$, where m is an integer. The centre of the grid is 193.1THz which corresponds to 1552.524 nm wavelength. There are two ways to increase the capacity of the network, either increase the operation wavelength range or decrease the channel spacing to either 50 GHz, or 25 GHz, or even 12.5GHz. To pack more channels in to narrow channel spacing, researchers will have to overcome a series of technical challenges. Amongst these challenges include the development highly efficient Optical Add Drop Multiplexers (OADM) and Optical Cross Connect(OXC) circuits. Fig. 1-1 illustrates the functionality of OADM and OXC in a WDM ring/mesh network.

An OADM in a network selects a set of channels from the input channels and add/drop these channels from a local port with a minimum loss. Several architectures exist for an OADM which can add/drop signals in single wavelength or multi-wavelengths manner[6]. As dynamic reconfigurability is becoming more and more important in a WDM optical communication network, an OADM should be able to tune its wavelengths or reconfigure its operation occasionally. This kind of a Reconfigurable Optical Add Drop Multiplexer (ROADM) is mainly dependent on the reconfigurable Wavelength Selective Switches (WSS) as one of its important component. A WSS used in such systems should be able to dynamically route, block and attenuate all the WDM/DWDM wavelengths in the network. Also they must be compact and inexpensive, have low power consumption, and have the required design flexibility.

Fig. 1-1: Schematic diagram of a ring/mesh network showing the function of an OADM and OXC[7].

Typical transmission characteristics and some of the important spectral features of a wavelength filter in an optical network are shown in the Fig. 1-2. Also, the wavelength filter should meet some of the necessary performance parameters when deployed in a DWDM network, which are explained below.

- Wide wavelength range (or wide Free Spectral Range (FSR)) - C to L band of optical communication network [1520 nm-1630 nm].
- Channel wavelength, channel spacing and bandwidth [see Table 1-1.] in accordance with ITU specifications.

Fig. 1-2: Typical transmission characteristics of a wavelength filter at (a) drop and (b) through ports, showing some of the important spectral features [7]

Parameter	200 GHz	100GHz	50 GHz	25 GHz
Channel spacing	1.6 nm	0.8 nm	0.4 nm	0.2 nm
-1 dB band width	> 0.4 nm	> 0.2 nm	> 0.1 nm	> 0.05 nm
-3 dB band width	< 0.8nm	<0.4 nm	<0.2 nm	< 0.1 nm

Table 1-1: Channel spacing and band width requirements in DWDM system.

- Adjacent channel drop/add rejection >30 dB
- Non-adjacent channel drop/add rejection >40 dB
- Low Insertion Loss (IL) and drop/add loss < 3 dB.
- A box like transmission spectrum (High channel selectivity, $S = \frac{(\Delta\lambda)_{-1dB}}{(\Delta\lambda)_{-10dB}} > 0.5$)

and a flat-top spectrum with minimum ripples (< 0.5 dB) in the pass band.

For a WSS in optical communication network, hitless wavelength switching and tuning is highly desirable, as this will avoid the disturbances on the other wavelength

channels and allow them to pass through the device. Fig. 1-3 shows the schematic of a hitless WSS used in an optical communication network.

Fig. 1-3: Schematic of a hitless wavelength selective switch (a) ON state (b) OFF state

When the switch is in the ON state a single wavelength is dropped without affecting the adjacent channels. When the switch is OFF no channel is dropped and all the channels are passed through the switch without any disturbance. Normally a hitless WSS is realized by combining multiple component devices such as 1x2 optical switches, tunable filters etc. This type of configuration will lead to response time delay because the entire individual components should operate synchronously. Micro Ring Resonator (MRR) architectures are well suitable for such hitless WSS applications with its single wavelength or multi-wavelength functionality. Among the two common approaches which are used to tune the resonant wavelengths in a MRR such as, Electro-Optic(EO) or Thermo-Optic(TO), TO method in silicon has been shown to be highly efficient in circuit switched optical networks, providing long-term stability, wide wavelength tunability and with an operating time scale of a few μs under direct heating [8-12]. When compared to EO tuning, TO tuning provides an easy fabrication procedure and there is no inherent loss present in the method. One of

the challenges and requirements in a TO-WSS routers and switches lies in the control of the temperature in the vicinity of the waveguide and the efficiency in delivering the thermal power. A low thermal cross talk between the rings is desirable for a hitless TO-WSS application. Also, TO-WSS should have the required spectral features with a broad band ($\sim$ C+L band) tunability and low power consumption.

Similar to micro ring resonators, photonic crystal based resonators are also highly promising as a wavelength selective filter with their compactness and flexibility in wavelength selection[13-15]. Although not much studied extensively, the Bragg gratings inscribed on the side wall of a Silicon-On-Insulator (SOI) waveguide can act like a 1-D photonic crystal and can provide strong reflection band with a short length of the grating[16, 17]. By introducing a phase shift into one section of the grating can give a resonant transmission filter [18]. This waveguide side wall grating resonant filter is easy to optimize in its structural features and dimensions to get the desired spectral response. Hence, the design and fabrication of such waveguide resonant filters in SOI is investigated in this thesis inorder to achieve a band pass filter suitable for DWDM optical communication network.

The main objectives of the thesis can be summarized as below.

1.3. Objectives

The main objectives of the thesis is to design and fabricate Wavelength Selective Switches(WSS) and wavelength filters in a Silicon-On-Insulator (SOI) platform to meet the spectral features and wavelength selection/routing functionalities for optical communication applications. These can be mainly grouped as

- i) Investigations into Thermo Optic-Wavelength Selective Switches (TO-WSS) and channel add drop filters in silicon Micro Ring Resonators (MRR) to achieve the

desired telecom grade spectral features and broad band (~C+L band) wavelength selection/routing functionalities with low power consumption.

ii) Investigations into the waveguide vertical side wall grating as a resonant transmission filter suitable for DWDM optical communication network.

1.4. Scope

As the research is focused on TO-MRR based WSS and silicon waveguide grating resonant filters, with emphasis given to their design and fabrication challenges, the planned research will have the following major scopes to achieve the targeted objectives.

- Design and numerical simulation of silicon MRR WSS which has single and multiple channel wavelength selectivity over a broad band of operation.
- Design and fabrication of thermo-Optic (TO) tunability in silicon MRR wavelength filters for wide tunability with low power consumption and low thermal cross talk.
- Investigation into the fabrication challenges in silicon MRR on SOI platform to obtain the telecom grade performance parameters.
- Theoretical analysis and numerical simulations of sub micrometer phase shifted vertical side wall grating resonant filters.
- Study of variation in spectral behaviour of the phase shifted grating resonant filters such as Q -factor, transmittivity, bandwidth etc with respect to its grating parameters.
- Analysis of coupled cavity configuration in grating resonant filters to tailor its spectral shape.
- Development of design rules to overcome the potential challenges in the development of high index contrast (HIC) devices such as couplers for effective fibre/laser diode waveguide coupling and polarization independent operation.

1.5. Research roadmap

The planned road map of this thesis is shown in

Fig. 1-4, which describes the major focus research areas of this thesis.

Fig. 1-4: Research road map

1.6. Organization of the thesis

Chapter 1 begins with a general introduction about silicon photonics and its advantages as a promising technology for future Opto Electronic integrated Circuits (OEIC)/Photonic Integrated Circuits (PIC). The motivations to undertake this research work is explained in the later section. This section explains the requirements and challenges in a modern optical communication network, with emphasis on wavelength filters and its role in various devices such as OADM and OXC. The objectives, scope and a research road map of the thesis are explained in the subsequent sections.

A comprehensive literature review has been carried out and reported in chapter 2. The detailed literature review covers trends and developments in silicon photonics, silicon micro ring resonators and its application in optical communication network. Literature review also includes theoretical explanations and fabrication challenges in the area of ring resonators and grating resonators. Finally, the outcome of the literature review has been discussed.

In chapter 3 design, numerical simulation and fabrication of a silicon MRR thermo-optic wavelength selective switch is presented. The fabrication section explains detailed process flow chart for the device in an SOI wafer including its thermal tunability. In the characterization section, the wavelength tunability of the device is demonstrated. The device is analyzed for its performance as low power consumption WSS with low thermal cross talk with spectral characteristics suitable for DWDM optical communication network.

In chapter 4 coupled MRR and their detuning combinations are presented. The series and parallel coupled MRR are explained and fabricated on an SOI platform. The characterization results are presented to obtain telecom grade wavelength filters and the comparison between series and parallel coupling is presented. The detuning combination in a series coupled triple MRR through the applied thermal perturbations is analyzed to obtain an optimal OFF state in the WSS.

Chapter 5 presents an investigation into the design and fabrication of silicon waveguide phase shifted vertical side wall gratings as resonant transmission filter suitable for optical communication network. Initially the design and numerical simulation of the grating is presented through Finite Difference Time Domain (FDTD) method. The grating parameters are optimized to obtain a high Q-factor resonant transmission in the grating resonator with a high transmittivity. The coupled cavity

configuration in the grating resonator is analyzed to obtain a flat-top spectrum and high channel selectivity. The chapter also presents the fabrication and characterization results of this waveguide nanogratings resonators using electron beam lithography.

Chapter 6 concludes the thesis by highlighting the main contributions made followed by future work directions. Further, couple of significant and related works are carried out which are detailed in the appendix section.

The next chapter overviews the detailed literature survey relevant to the proposed research topic to identify the potential research gap and required improvement.

Chapter 2:

Literature review

In this chapter, a literature survey based on the working principle and applications of silicon photonics waveguide structures is presented along with recent research and developments in this area. A comparison between different wavelength filters in an optical communication network is given, explaining their relative advantages and disadvantages. The chapter also discusses the theoretical aspects and research and developments in silicon photonic micro ring resonators and waveguide Bragg gratings. Fundamentals of planar waveguides and silicon photonic waveguides are presented in the later sections. An outcome of literature review is presented at the end of the chapter.

2.1. Wavelength selective switching technologies in an optical communication network

Optical fiber communication systems and devices are essential for handling the massive growth of both telecom and data communications traffic of today. However, most of the networking devices in an optical communication network are still working on electronic signals. This means that the optical signals at the fibre terminal has to be converted to electrical signal inorder to amplify, regenerate or switch and then they are converted back to the optical signals for the transmission. It is well known that optical-to-electronic-to-optical (OEO) conversion is a significant bottleneck in optical fiber communication. Thus the basic idea behind all-optical switching is that by replacing existing electronic network switches with optical ones, the need for OEO conversions can be removed. Thus, optical wavelength selective switches would play an important role in an optical fibre communication network as optical cross connection, protection switching, and switch arrays for optical add-drop multiplexers(OADM) or wavelength filters. An OADM in an optical communication network add/drop specific wavelength from a multi-wavelength input. An optical wavelength selective switch(WSS) is an essential component in such an OADM configuration. Currently optical wavelength selective switches or filters in an optical communication network are implemented through optical fibre Bragg gratings (FBG) or structures like thin film dielectric filters (TFF), Micro Electro Mechanical System (MEMS), diffraction gratings, arrayed waveguide gratings (AWG) or cascaded Mach-Zehnder interferometers(MZI).

These optical switching technologies can be generally classified into two, namely free space and waveguide based technologies.. With the wide range of applications for these devices, it can be said that there will not be a single winning solution. Most

solutions for all-optical switching are still under study. In fact, different technologies feature different performance in terms of scalability, switching speed, insertion loss and cross-talk. An FBG has periodic refractive index variation along the core of a fibre and when the incident wavelength satisfies the Bragg condition inside the grating it is reflected back. An FBG is considered as a cheap in-line components which can filter light guided in optical fibres so that any region of the optical transmission spectrum can be manipulated[19]. MEMS are movable micro-mirrors that can deflect optical signals from input to output fibres[20, 21]. In these switches, micro-mirrors are steered in order to deflect light beams properly. The direction of the reflected light can be changed by rotating the mirror in different angles, which allows the input light to be directed to any output port. The mirrors are typically be controlled electro-magnetically, electro-statically or by piezoelectric actuators. This type of optical switch uses various techniques for its configuration, such as micro-machining techniques for fabricating the mirror, optical design techniques for achieving low-loss optical connections, and control techniques for positioning the mirror accurately. A MEMS switch is a free space switching technology with a switching time of the order of 10-30 ms and low-loss performance[22].

In a Liquid Crystal (LC) WSS the polarization state of the transmitted light is selectively controlled by application of a control voltage[23]. For the switching process to work, the LC must be followed by a polarization dependent optical element such as a Polarization Beam Splitter (PBS) to change the path of the transmitted light based on their polarization.

Thin film interference filters(TFF) are essentially multiple layers of high and low refractive index materials on a glass substrate. The thicknesses of each alternating layer determine which wavelengths of light are either reflected or transmitted. TFF has

low IL for transmission and reflection, low channel crosstalk and low channel spacing down to 50 GHz. Good thermal stability, with a thermal drift of approximately 0.002 nm/ C can be achieved[24]. Major disadvantage is in the large number layer requirement to get a narrow band spectrum. As the spectral features in a TFF are not tunable, it is commonly employed in fixed DWDM applications.

Fig. 2-1: Schematic diagrams of various wavelength selective switching technologies (a) Fiber Bragg Gratings(FBG) (b) Micro Electro Mechanical System (MEMS) [22] (c) liquid crystal(LC) and (d) thin film filter (TFF)

Fig. 2-1.shows schematic images of the above described WSS devices. All these devices are either free space operating or difficult to integrate with other passive or active optical devices in a PIC. A MEMS structure in a wavelength selective configuration is bulky and unstable and requires careful assembly process. Recently Si-CMOS compatible technologies are employed in Micro Opto Electro Mechanical System(MOEMS) structures[25, 26], has allowed to physically change the propagation

direction of the light beam by the mechanical rotation of a reflector (mirror or diffraction grating)[20, 21]. Fig. 2-2 shows the SEM image of a MOEMS switch by Zhong *et al.* Such systems have successfully miniaturized and integrated active light switching components onto a single chip; however, they are limited by delicate fabrication process, slow response time and mechanical instability[27].

Fig. 2-2: SEM image of MOEMS WSS configuration proposed by Zhong *et al.*[26]

Other structures such as AWG and MZI which are based on planar waveguide technology works on the principle of controlling the refractive index or phase variation in order to influence the light propagation[28, 29]. The advantage of the waveguide structures lies basically on the smaller dimension scale. Many devices can be integrated on a single substrate to reduce the cost per function and increase the stability and the robustness of the device. The reliability of the waveguide-based WSS is comparatively higher because of no moving parts in the device.

Fig. 2-3: Structure of a MZI based wavelength switch[30]

A Mach–Zehnder interferometer (MZI) works with interference effect and is the

most extensively studied thermo-optic switch thus far[30, 31]. The conventional and simplest form of the switch is made up of one 3-dB splitter and one 3-dB combiner connected by two channels, with a thermo-optic phase shifter placed in one arm of the interferometer as shown in Fig. 2-3. As a WSS, a MZI structure has to be arranged in cascaded form to separate different channels. This will eventually result into a higher form factor in device dimension.

Arrayed waveguide grating (AWG) has gained increasing importance as a channel-selective routing devices for WDM applications[32-34]. The AWG is essentially an imaging device that disperses the image field of an input waveguide onto an array of output waveguides. The desired diffraction properties are obtained through linear variation in the length of the arrayed waveguides. Fig. 2-4 shows the schematic diagram of an arrayed waveguide gratings.

Fig. 2-4: Schematic diagram of an arrayed waveguide grating(AWG)[24]

The arrayed waveguide grating was first proposed a solution to the WDM problem by Smith[35] in 1988 and was further developed in the following years by many researchers and extended the concept from 1 x N de-multiplexers to N x N wavelength routers which play an important role in multi-wavelength network application. The key advantage of the AWG is that its cost is not dependent on wavelength count as in the other filter solution. Other advantage of the AWG is in the flexibility of selecting channel number and channel spacing. An AWG is conventionally fabricated on a

silica platform for achieving lower IL [33, 34]. When compared to a silica based AWG, an SOI based AWG will have higher insertion loss and higher temperature dependent center wavelength drift in the device.

<i>Filter types</i>	<i>Technology /rating</i>	<i>Advantages</i>	<i>Disadvantages</i>
F.B.G	Fibre/ mature	1. Mature technology. 2..Easy to couple to fibre outside	1. Mechanical stability problem. 2. Cannot integrate with planar waveguide
LC	LC/Mature	1. Low voltage and power consumption. 2. Good robustness due to absence of moving parts.	1. Difficult for integration. 2. Slow response time.
TFF	Planar silica/ mature	1. Mature technology. 2. Good temperature Stability. 3. Good wavelength selectivity	1. Difficult to produce narrow channel spaced filters (<100GHz). 2. Not tunable .Can only be manufactured for fixed wavelength. 3.Difficult for integration
MEMS	3-D assembly, free space /mature	1. Low insertion loss 2. Good temperature stability.	1. Bulky device and high power consumption. 2. Free space operation needs careful assembly. 3. Difficult to integrate. 4.Slow response time.
A.W.G	Planar/ mature	1. CMOS fabrication possible. 2. Flexibility in selecting channel number and channel spacing	1. Complex structure and large insertion loss. 2. Not directly tunable or reconfigurable in the wavelength channel. 3. Temperature dependent drift in the centre wavelength.
MZI	Planar / mature	1. Low insertion loss and polarization effects. 2. Can produce very narrow channel spaced device.	1. High channel count device requires cascaded structures resulting into large form factor device.

Table 2-1: Characteristics of common optical wavelength selective switches in an optical communication network.

The variation of refractive index of a silicon material is $1.8 \times 10^{-4} / ^\circ\text{C}$ which is 18 times higher than that of silica material with a value $1 \times 10^{-5} / ^\circ\text{C}$. The center wavelength in an

AWG is tunable so that their wavelength range of operation can be shifted [36-38]. Many material platforms have been investigated for a TO tuning in AWG. However the observed tuning range is limited to the order of ~ 10 nm[37]. A comparison in different wavelength filter technologies with emphasis to their relative advantages and disadvantages are explained in Table 2-1.

2.2. Micro ring resonators

Micro ring resonators (MRR) are highly suitable for WSS functionality because of their four port configuration, versatility in arrangements, compactness and Complementary Metal Oxide Semiconductor (CMOS) compatibility [39, 40]. The fundamental building blocks of micro ring resonator(MRR) is a micro ring plus one or two waveguides. In the former case the structure gives a two-port device which acts as all-pass filters and introduces a wavelength-dependent phase shift only. On the other hand, a micro ring resonator consisting of a ring plus two straight waveguides represents a 4-port structure, as illustrated in Fig. 2-5.

Fig. 2-5: Schematic structure of a 4-port ring resonator

The ring waveguide and the bus waveguides are evanescently coupled and a fraction K_1 of the incoming field is transferred to the ring. When the optical path-length of a roundtrip is a multiple of the effective wavelength, constructive interference occurs

and light is ‘built up’ inside the ring: the MRR is ON resonance. As a consequence, periodic fringes appear in the wavelength response at the output ports as shown in Fig. 2-6. At resonance the drop port shows maximum transmission since a fraction K_2 of the built up field inside the ring is coupled to this port. In the through port the ring exhibits a minimum at resonance. In the ideal case with equal coupling constants at resonance all the power is directed to the drop port. Light coupled back to the through port after a roundtrip experiences an additional π phase shift with respect to the light coming directly from the in port, and as a consequence no light exits from the through port at resonance.

Fig. 2-6: The spectra of a MR at through (black) and drop (grey) port. At the right side is the simulated field intensity in the ring.[41].

Active and passive MRR based structures are promising device for wavelength filtering[42], routing[43] switching [44] modulation[45] and multiplexing de-multiplexing. They do not require facets or gratings for optical feedback and is particularly suitable for monolithic integration[46]. The pass band shape in the spectrum can be modified by using multiple coupled resonators [47-49]. The filter characteristics are strongly dependent on the energy flow within the ring and can be modified by coupling between the waveguide and ring[50]. A smooth waveguide side wall is required to reduce the propagation loss[51]. Steeper roll-off and higher out of

band rejection can be achieved by cascaded ring structures[52].

The resonance wavelength of a ring resonator is given by[53]

$$\lambda_r = \frac{2\pi R n_{eff}}{m} \quad (2.25)$$

Where R is the ring radius, m is an integer and n_{eff} is the effective refractive index of the ring.

Similar to that of a Fabry–Perot resonator a ring resonator has performance parameters like Free Spectral Range (FSR), the extinction ratio (ER) and the finesse. Q factor is often used to specify the spectral selectivity of the MRR and is defined as the resonance wavelength divided by the 3-dB band width.

The FSR is given by,

$$FSR = \frac{\lambda^2}{2\pi R n_g}, \quad (2.26)$$

Where, n_g is the group index.

To calculate the finesse or Q –factor, one must define the 3-dB bandwidth. The 3-dB band width can be approximated as

$$\Delta\lambda_{3dB} = \frac{K^2 \lambda_r^2}{2\pi^2 R n_g}. \quad (2.27)$$

Where, K is the coupling coefficient between bus waveguide and ring waveguide

Thus the finesse of the spectrum is defined by, $F = \frac{FSR}{\Delta\lambda_{3dB}}$ and Q -factor, $Q = \frac{\lambda_r}{\Delta\lambda_{3dB}}$.

Many of the photonic interconnect network architectures rely on the micro ring resonators (MRR) as their WSS because of their versatility, compact size and energy efficiency [39, 40, 54-57]. Two common approaches are used in MRR to tune their resonant wavelengths which are carrier injection based Electro-Optic (EO)[58] or Thermo-Optic (TO) method[59-63]. Among these two methods, TO method in silicon

MRR is highly promising for a WSS application and are explained in detail in the forthcoming sections. The performance of TO-WSS, in terms of cross talk and insertion losses, are acceptable for many applications[64]. In addition, the speed of waveguide devices based on the thermo-optic effect is adequate for all routing applications. The drawbacks could be high-driving-power and high-power dissipation.

2.3. Thermo-optic (TO) active devices using Micro Ring Resonators

Silicon refractive index is highly sensitive to the temperature variations. In fact thermo-optic(TO) effect in silicon is 10 times or more stronger than in silica[65]. Thermo-optic coefficient in silicon is given by[66].

$$\frac{dn}{dT} = 1.86 \times 10^{-4} / K \quad (2.52)$$

If the waveguide materials are raised in their temperature by $\sim 6^{\circ}\text{C}$, a refractive index change of 1.1×10^{-3} can be resulted into the waveguide. The refractive index change in TO effect is positive in nature than the other common method of carrier injection. It means the refractive index of the silicon waveguide increases with an increase in temperature.

Heating the silicon photonic devices can be done in two ways. In the first approach, direct joule heating of silicon device is done[67], and in the other method metallic micro heaters are placed close to the device[59, 68, 69]. The former approach requires doping of the silicon waveguide to reduce the resistivity of the intrinsic Silicon. This leads to optical absorption and higher insertion loss. Also, with moderate doping levels of the silicon layer, heater electrical resistance is high and therefore, the required drive voltage is higher in these devices. The main issues in the metallic micro

heater TO devices are in the control of the temperature in the vicinity of the waveguide and the efficiency in delivering the thermal power. Since the core volume in a silicon waveguide is much smaller than that of a silica waveguide, the power consumption for a TO silicon waveguide device is one-tenth that of a silica waveguide device. To achieve low power consumption, it is highly important that the heating power should be concentrated near to the waveguide core region[70]. In many cases the heat gets expanded in the cladding layer to a wider space. TO effect in silicon waveguide devices has been used in many devices such as reconfigurable filters[71], reconfigurable add-drop multiplexers[72, 73], dispersion compensators[74, 75] and switches[59, 60]. Recently, there are many thermo-optic switches demonstrated on silicon. When compared to an electro-optic switch, TO switch has many advantages such as lower optical loss, simpler fabrication process and lower cost. A typical TO switch in MZI configuration needs a power of more than tens of mW for a phase shift [76-79]. In such cases heaters were fabricated on thick over cladding without any lateral thermal insulation. Without any efficient heating structure, a silicon waveguide TO- MZI switch do not show any remarkable improvement in the power consumption level. So many approaches such as removal of under cladding and side cladding are done to obtain a highly efficient heating structure. An ultralow power consumption of 0.49 mW has been reported for a TO- MZI switch[80]

Thermo-Optic effect in MRR has been widely used in many devices because it can provide a high refractive index change without any optical loss [59-63]. A large tuning range is necessary to enable the wavelength filters to be employed in the whole C to L band. Significant effort has been made to increase the tuning range of a TO-MRR in various ways. A maximum thermal tuning range of 16 nm with tuning efficiency of 7 $\mu\text{W}/\text{GHz}$ has been reported in InP/InGaAsP micro rings with polymer

wafer bonding[81]. A multi-wire structure has been used to increase the tuning range up to the full-FSR range of 20 nm and with an efficiency of 28 $\mu\text{W}/\text{GHz}$ [82]. Recently, an experimental and numerical study on TO-MRR has been reported to improve the reconfiguration speed and tuning range of thermally tunable silicon photonic device[70]. It is shown that, using a cladding material of better thermal property like higher thermal conductivity under Chemical Vapour Deposition (CVD), the tuning speed in the device can be improved. A lowest reconfiguration speed of 4 μs is demonstrated with the optimised micro heater structure.

Thermally tunable higher-order micro ring resonator filter are highly promising for reconfigurable multiplexing/de-multiplexing devices and transceiver configuration for WDM applications [61, 83-85]. However, some of the issues such as the total power consumption, free spectral range, insertion loss and stability of the filter should be overcome for practically implementation of them in a high speed optical communication network or Network-on-Chip (NoC) devices. A low tuning power of 21 mW per free spectral range for a single ring has been achieved by exploiting thermal isolation trenches close to the ring waveguides[10]. Further, an ultralow tuning power of 2.4 mW per free spectral range is achieved through free-standing silicon resonators with undercut structures [9]. Eventhough the tuning efficiency is enhanced further, the proposed undercut structures are difficult to fabricate and are undesirable for active device integration. In this context, research in this direction should focus on achieving low power consumption wavelength tunability in a ring resonator based device utilizing the full band width efficiency of the network.

2.4. Waveguide gratings

Bragg gratings can work as spectral filters that typically reflect light in a narrow band

of wavelength from a broad band of input source. The principle behind this is known as Bragg reflection. Normally a Bragg grating can be formed by creating a periodic structural corrugation or refractive index modulation along the length of the gratings. Fig. 2-7 shows the schematic diagram of a waveguide Bragg grating with structural corrugation to make a periodic refractive index modulation. The surface corrugation can give rise to a refractive index modulation because the effective index of the waveguide is strongly dependent on its structure and dimension. In a Bragg grating each unit refractive index modulation is known as a period of the gratings. Each period acts as a reflector and transmitter for the incident light. If the length of the period Λ is such that all the partial reflections from each period adds up in phase and gives rise to a nearly 100 % reflection of the light, it is said that the Bragg condition is met by the gratings. This condition occurs when the round trip of light between two reflection is an integer multiple of the wavelength of light.

Fig. 2-7: Schematic of Bragg gratings on the surface of a waveguide

The Bragg condition for waveguide gratings as shown in Fig. 2-7 can be expressed as

$$2\beta_{Bragg}\Lambda = 2m\pi \quad (2.28)$$

Where ‘m’ is an integer and β_{Bragg} is the propagation constant of the optical wave meeting the Bragg condition.

$$\beta_{Bragg} = \frac{2\pi n_{eff}}{\lambda_B} \quad (2.29)$$

Where n_{eff} is the averaged effective refractive index of the waveguide grating. λ_B is

the Bragg wavelength. From Eqn (2.28) and (2.29) it is simplified as

$$m\lambda_B = 2n_{eff}\Lambda \quad (2.30)$$

Where, m is the order of the gratings.

2.4.1. Waveguide gratings as coupled mode propagator

The most common way for theoretical modelling and analyzing a waveguide gratings is through coupled mode formulations[86, 87]. In a couple mode theory, a waveguide grating is modelled as structure having perturbations through which coupling between forward propagating and backward propagating modes happen. Since the eigenmodes of a grating waveguide is significantly different from that of a usual waveguide, many authors have adopted to periodic crystal methods like Bloch waves method to analyze the waveguide grating structure [88-90]. Also full numerical methods such as Finite Difference Time Domain (FDTD) as done in this thesis can be used to analyze a Bragg grating.

In a coupled mod theory, a grating waveguide as shown in Fig. 2.5 is treated as Z-invariant structure with a periodic perturbation along Z-axis. The refractive index profile of the waveguide gratings is taken as $n^2(x, y, z)$ and the refractive index profile of simple waveguide is taken as $n_0^2(x, y, z)$.

$$n^2(x, y, z) = n_0^2(x, y, z) + \delta n(x, y, z) \quad (2.31)$$

Where $\delta n(x, y, z)$ is a periodic function in Z representing the corrugation of the waveguide.

For a uniform grating, where there is a uniform refractive index variation along the length of the grating, the refractive index can be expressed as[66]

$$n(z) = n_{eff} + \Delta n \cos\left(\frac{2\pi z}{\Lambda}\right) \quad (2.32)$$

Considering the Maxwell's wave equations for $\mathbf{E}$ and $\mathbf{H}$ fields, the role of coupled mode theory is to replace the equations with set of coupled ordinary linear differential equations which describe the evolution of a scalar coefficient $A_{\pm}(Z)$ [91]

With
$$A_{\pm}(Z) = a_{\pm}(z)e^{\mp i\pi z / \Lambda} \quad (2.33)$$

Through this method the coupled mode equation in a waveguide grating can be expressed as below

$$-i \frac{d}{dz} \begin{bmatrix} A_+(Z) \\ A_-(Z) \end{bmatrix} = \begin{bmatrix} \delta & K \\ -K^* & -\delta \end{bmatrix} \begin{bmatrix} A_+(Z) \\ A_-(Z) \end{bmatrix} \quad (2.34)$$

Substituting Eqn (2.33) into Eqn (2.34)

The coupled mode equation simplifies to

$$-i \frac{d}{dz} \begin{bmatrix} a_+(Z) \\ a_-(Z) \end{bmatrix} = \begin{bmatrix} \delta & K \\ -K^* & -\delta \end{bmatrix} \begin{bmatrix} a_+(Z) \\ a_-(Z) \end{bmatrix} \quad (2.35)$$

Where $\delta = \beta - \pi / \Lambda$ is the detuning factor, which is a measure of the deviation from the Bragg condition and the Bragg condition is given by

$$\beta_{Bragg} = \pi / \Lambda \quad (2.36)$$

K is a term which describes the magnitude of the rate at which contradirectional coupling happens inside the structure which is mainly a function of the index modulation inside the gratings. K is also defined as reflectivity per unit length of the gratings.

For a grating length of L the reflection coefficient can be expressed as

$$r(\delta) = \frac{\frac{K^*}{\gamma} \tanh(\gamma L)}{1 + i \frac{\delta}{\gamma} \tanh(\gamma L)} \quad (2.37)$$

Where γ is a function of δ .

The reflectivity at the centre of the stop band is obtained from Eqn(2.37) as

$$R(0) = \tanh^2(|K|L) \quad (2.38)$$

And at the boundary of the stop band

$$R(|K|) = \frac{|KL|^2}{1 + |KL|^2} \quad (2.39)$$

The transmittance of the Bragg gratings can be obtained by following relationship

$$T = 1 - R \quad (2.40)$$

Fig. 2-8: Reflection spectra of waveguide grating with increasing grating length[92]

The spectral response of a Bragg grating is characterized by “sinc” shape with band width inversely proportional to the grating length. The strength of a Bragg grating is characterized by the parameter KL . A grating with $KL < 1$ is usually referred to as a weak gratings. For $KL > 10$ it can give a strong reflection within the stop band. Fig. 2-8 shows a comparative reflection spectrum of a Bragg grating for different KL values.

2.4.2. Phase shifted Bragg grating

A phase shifted Bragg a grating is characterized by a phase jump at one section of the gratings. The light inside the grating undergoes a Fabry-Perot oscillation at the phase shift section and the resulting stop band has a narrow transmission peak in it. The wavelength and transmission level of the band pass is determined by the position and size of the phase shifted grating section. In a coupled mode theory, a phase shifted grating can be considered as a compound grating with three elementary devices. Two contra-directionally coupled grating waveguides and one spacer waveguide without any coupling. Thus, the coupled mode propagator of a phase shifted grating as shown in Fig. 2-9 can be expressed as follows[91].

Fig. 2-9: Phase shifted waveguide gratings. Phase shifted region II is characterised by a spacer length L inside the gratings.

$$\begin{bmatrix} TA^+ & TA^- \\ TA^- * & TA^+ * \end{bmatrix} = \begin{bmatrix} A^+ & A^- \\ A^- * & A^+ * \end{bmatrix} \begin{bmatrix} e^{i\beta\Lambda/2} & 0 \\ 0 & e^{-i\beta\Lambda/2} \end{bmatrix} \begin{bmatrix} A^+ & A^- \\ A^- * & A^+ * \end{bmatrix} \quad (2.41)$$

Where,

$$A^+ = \cos(\delta e_{ff} z) - i\delta \sin(\delta e_{ff} z) / \delta e_{ff} \quad (2.42)$$

$$A^- = iK \sin(\delta e_{ff} z) e^{iQz} / \delta e_{ff} \quad (2.43)$$

And
$$\delta e_{ff} = \pm \sqrt{\delta^2 - |K|^2} \quad (2.44)$$

Eqn (2.41) gives

$$TA^+ = A^{+2} e^{i\beta\Lambda/2} + |A^-|^2 e^{-i\beta\Lambda/2} \quad (2.45)$$

$$TA^- = A^+ A^- e^{i\beta\Lambda/2} + A^+ * A^- e^{-i\beta\Lambda/2} \quad (2.46)$$

With

$$\frac{\beta\Lambda}{2} = \frac{\pi}{2} + \frac{\beta\delta}{2} \quad (2.47)$$

From the above equations, it can be seen that at the centre of the stop band ($\delta = 0$), the coefficients are given by

$$A^+ = \cosh(K|L) \text{ and} \quad (2.48)$$

$$A^- = i \sinh(K|L) \quad (2.49)$$

Thus the total amplitude becomes

$$TA^+ = i \text{ and } TA^- = 0 \quad (2.50)$$

and reflectivity
$$R = \left| \frac{TA^+}{TA^-} \right|^2 \quad (2.51)$$

This implies, a phase shifted gratings has a pass band in the centre of the stop band of the individual Bragg gratings. From Eqn. (2.37) it is clear that the grating reflection spectrum is strongly dependent on the grating coupling coefficient or refractive index modulation and grating length. This means that, we can tailor the grating reflectivity, reflection band width and the Bragg wavelength to meet the application requirement by changing these physical quantities of the grating. To achieve a narrow band reflection, the grating coupling strength is made weaker, such that the reflection from each grating period is smaller. This is achieved by reducing the cross section of the structural corrugation, reducing the refractive index contrast or by reducing the overlap of optical mode with grating. For a weaker grating the band width is inversely

proportional to the grating length. Hence to obtain a narrow band reflection spectrum a longer grating has to be used. A longer grating also increases its power reflectivity. Saturation in its reflectivity and bandwidth is expected as there is a limit in the interaction between guided mode and gratings after a certain grating length.

Silicon based waveguide Bragg grating has been designed and demonstrated by various researchers. The main challenge in this area of research is in the fabrication of fine period grating on a waveguide with dimensional features of the order of sub-wavelength in nature. Since silicon waveguide has an effective refractive index of the order of ~ 3 at a wavelength of 1550 nm, most of the first order grating needs a grating period less than 250 nm. This makes the fabrication process challenging with the conventional mask based lithography. Therefore many groups have turned to electron beam lithography or focused ion beam lithography to achieve this small feature size in their gratings [93-98].

2.4.3. Waveguide grating designs

Usually refractive index modulations are done in a waveguide through corrugations in the waveguide or material refractive index modification. Following sections describes the literatures relevant to silicon based waveguide Bragg grating structures explaining their characteristic features.

i) Corrugated Bragg gratings

In a surface corrugated waveguide Bragg gratings the rectangular grooves on the waveguide impose the refractive index modulation to the forward propagating mode inside the waveguide as shown in Fig. 2-10. A sequence of lithographic steps is needed to obtain this kind of gratings on the top surface of a waveguide.

Fig. 2-10: Schematic picture of a corrugated waveguide grating

One method is to use an SiO_2 hard mask patterned through e-beam lithography and subsequent reactive ion etching (RIE) with the oxide mask to get the grating pattern and subsequent silicon etching to get a waveguide[98]. The method is mainly limited by the lithographic limitation and difficult etching process as we need a grating depth of the order of 200 nm and grating pitch of $\sim 250\text{nm}$ on the top surface. The gratings fabricated on the top surface of the waveguide the effective index is more sensitive to the etch depth which is very difficult to control precisely in the fabrication process. The advantage of this structure lies in the possibility for using a relatively larger cross section waveguide for the waveguide gratings[99]. The single mode condition can be met in the large cross section waveguide through modification in the waveguide cross section shape into a ridge type[100-102]. Another method for the fabrication is the direct e-beam lithography and subsequent reactive ion etching to get the grating structures[99, 103, 104]. Here deep reactive ion etching (DRIE) can be employed to obtain high aspect ratio [105].

The gratings can also be fabricated on the side wall of a waveguide[16, 17]. In these types of gratings, both side walls of a waveguide are periodically corrugated along the waveguide such that a periodic refractive index modulation can be achieved. Bragg gratings on the side wall of a waveguide is easy to fabricate in a single lithographic step and the effective refractive index of the grating is dependent on the

lateral waveguide widths, which can be easily controlled in the procedure of photolithography. Also for a strip waveguide, the lateral waveguide width can be made larger than etch depth, which will give higher tolerance in fabricating sidewall grating and more flexibility in manipulating the reflection spectrum [106, 107]. Apodization function is applied on this side wall gratings to improve the spectrum. The apodization is found to have good effect on the spectrum with a high reduction in the side lobes. For a strip waveguide, by keeping the lateral waveguide width much larger than the grating depth, higher fabrication tolerance and more flexibility in manipulating the reflection spectrum can be achieved [106, 107]. The vertical grating in silicon stripwaveguide has been used to fabricate the phase shifted grating structure [18]. Two identical vertical grating reflectors were fabricated with a quarter wave phase shift between them using electron beam lithography. It is easy to optimize the spectral features of these waveguide gratings through variation in the grating structures [108, 109] and effective post process suppression can be employed to eliminate Fabry-Perot oscillations in the spectra [110]. Recently, effort has been made to demonstrate these grating waveguides through various fabrication processes using deep-ultraviolet lithography [111, 112]. A major problem observed in the fabrication of waveguide Bragg gratings in high index contrast waveguides is the average effective index variations caused by sidewall roughness. A study on the side wall roughness of the gratings reveals key parameter that has to be controlled in order to reduce the fluctuation in effective index [113]. A finer control over the coupling coefficient and thus over its spectral features can be achieved through cladding modulation in refractive index. It has been shown through theoretical and experimental means that a low refractive index perturbation can be achieved in these gratings through cladding refractive index modulation [114]. It has been reported that these

gratings can be effectively employed in other planar waveguide devices such as, integrated, all-optical photonic differentiators operating at terahertz (THz) speeds[115],opto-fluidic micro cavity filter[116] and waveguide coupled side-walled grating filter[117]

ii) Material refractive index modulated grating.

While the structural corrugation is good enough to provide a refractive index modulation, it can also be attained through the change in refractive index of the material of the waveguide periodically. Methods like Femto second laser annealing can be used to get the refractive index change in an amorphous silicon film[118]. With this process a pattern of alternating α -Si and microcrystalline Si lines with 2 μm period was created. The silicon with different crystalline structure exhibits different refractive index. Hence it is easy to make a refractive index modulation with laser annealing. Silicon and polycrystalline α -Si can be used to get the refractive index variation as demonstrated by Liao *et.al* in 1994 [119]. They have used a poly crystalline rib waveguide having a cross section dimension of 3.5x 4 μm to inscribe the grating patterns. The poly silicon is first etched to get the grating pattern along the waveguide and later the trenches are filled with α -Si. The amorphous material was crystallized into poly silicon using a high-temperature annealing. Here, instead of using α -Si, poly silicon is used to make the grating because the poly-silicon has a refractive index almost similar to silicon and it has got a lower propagation loss.

2.5. Photonic waveguides

The goal of this section is to give a brief explanation about some of the important

properties of a planar waveguide using ray optical and electromagnetic theory. A waveguide is the essential building block in any photonic integrated circuits.

Fig. 2-11: Different planar waveguide geometries

According to the number of dimensions in which the light is confined, waveguide can be classified as planar waveguides, channel waveguides or photonic crystal waveguides. Fig. 2-11 shows some of the waveguide cross sections that are commonly used in the silicon waveguide structure fabrication. A planar waveguide and its functional properties with ray optics and electromagnetic wave propagation is explained in the following sections.

2.5.1. Waveguide theory-Ray optics

Simplest form of planar waveguide geometry is explained in Fig. 2-12. It has a high index(n_1) dielectric layer 'core' surrounded by a lower index(n_2) material 'cladding' on both sides.

Fig. 2-12: Schematic of planar waveguide and ray propagation[120]

With simple ray optics, the necessary waveguide propagation properties can be understood at the basic level. As shown in Fig. 2-12 an incident wave $\mathbf{E}_i$ gets reflected from the dielectric interface of the waveguide to get a reflected wave $\mathbf{E}_r$ and a transmitted wave $\mathbf{E}_t$ at their respective angle as shown in the figure.

Through the simple Snell's law we can write the relationship between incident and transmitted wave as[120]

$$n_1 \sin \theta_1 = n_2 \sin \theta_2 \quad (2.1)$$

The condition for Total Internal Reflection (TIR) imposed on Eqn (2.1) will lead to the following relation

$$n_1 \sin \theta_1 = n_2 \quad (2.2)$$

Which give the critical angle as

$$\sin \theta_c = \frac{n_2}{n_1} \quad (2.3)$$

No light wave will be transmitted outside when it is propagated with an angle above this critical angle (θ_c)

Considering the Fresnel Formulae and complex amplitudes for the waves, we can write the relation between incident and reflected waves as[120]

$$E_r = r.E_i \quad (2.4)$$

Where r is the complex reflection coefficient and it is a function of angle of incidence

and polarization of the light. The polarization of an electromagnetic wave can be described in terms of the direction of oscillation of its electric field. For a TE wave the direction of oscillation of its electric field is in perpendicular to the plane of incidence and for a TM wave it is taken as parallel to the plane of incidence. For a TE and TM polarization field, their respective reflection coefficients are written as[120].

TE polarization

$$r_{TE} = \frac{n_1 \cos \theta_1 - n_2 \cos \theta_2}{n_1 \cos \theta_1 + n_2 \cos \theta_2} \quad (2.5)$$

TM polarization

$$r_{TM} = \frac{n_2 \cos \theta_1 - n_1 \cos \theta_2}{n_2 \cos \theta_1 + n_1 \cos \theta_2} \quad (2.6)$$

Using Snell's law, the above equations can be written as

$$r_{TE} = \frac{n_1 \cos \theta_1 - \sqrt{n_2^2 - n_1^2 \sin^2 \theta_1}}{n_1 \cos \theta_1 + \sqrt{n_2^2 - n_1^2 \sin^2 \theta_1}} \quad (2.7)$$

$$r_{TM} = \frac{n_2^2 \cos \theta_1 - n_1 \sqrt{n_2^2 - n_1^2 \sin^2 \theta_1}}{n_2^2 \cos \theta_1 + n_1 \sqrt{n_2^2 - n_1^2 \sin^2 \theta_1}} \quad (2.8)$$

For an angle of incidence less than the critical angle, partial reflection happens and the reflection coefficient is real. When the angle of incidence exceeds the critical angle, TIR occurs and the light gets confined inside the waveguide, giving

$$|r| = 1 \quad (2.9)$$

Since r is a complex field, a phase shift will be imposed on it

Thus,
$$r = \exp(j\phi) \quad (2.10)$$

For TE and TM wave the phase factor can be written as

$$\phi_{TE} = 2 \tan^{-1} \frac{\sqrt{\sin^2 \theta_1 - \left(\frac{n_2}{n_1}\right)^2}}{\cos \theta_1} \quad (2.11)$$

$$\phi_{TM} = 2 \tan^{-1} \frac{\sqrt{\left(\frac{n_2}{n_1}\right)^2 \sin^2 \theta_1 - 1}}{\frac{n_2}{n_1} \cos \theta_1} \quad (2.12)$$

If the reflected or transmitted wave is to be described in terms of power or intensity, Poynting vector should be used. Poynting vector S is obtained from $E \times H^*$ is approximated by E^2 and is expressed as below

$$S = \frac{1}{Z} E^2 = \sqrt{\frac{\epsilon_m}{\mu_m}} E^2 \quad (2.13)$$

Where E is the electric field, ϵ_m is the permittivity of the medium, μ_m is the permeability and Z is the impedance. Using this terms, the power reflected becomes

$$R = \frac{S_r}{S_i} = \frac{E_r^2}{E_i^2} = r^2 \quad (2.14)$$

2.5.2. Modes in a planar waveguide and condition for single mode propagation

To understand more about the propagation inside a planar waveguide, consider the lateral cross section of the waveguide as shown in Fig. 2-13.

Fig. 2-13: Schematic of lateral cross section of the planar waveguide[120]

The incident wave vector can be decomposed into two components one along Y axis and other along Z axis. The Y component, $k_0 n_1 \cos \theta_1$, undergoes multiple reflections

inside the waveguide along the Y direction forming a standing wave. The phase shifts introduced in the wave when it undergoes one round trip along the Y- axis can be written as[120]

$$\phi_h = 2k_y h = 2k_0 n_1 h \cos \theta_1 \quad (2.15)$$

Where, k_y is the wave vector in the Y-direction, h is the height of the waveguide and k_0 is the free space wave vector.

Adding the phase shifts introduced at the reflection surfaces of upper (ϕ_u) and lower (ϕ_l) regions, Eqn (2.15) can be re written as

$$\phi_h = 2k_y h = 2k_0 n_1 h \cos \theta_1 - \phi_u - \phi_l \quad (2.16)$$

This phase shift should be an integral multiple of 2π

$$2k_y h = 2k_0 n_1 h \cos \theta_1 - \phi_u - \phi_l = 2m\pi \quad (2.17)$$

From Eqn (2.17) it can be seen that the waveguide can support more than one propagation constant which corresponds to the each discrete angle of incidence which satisfies the equation. Also light cannot propagate at all the angle of incidence but only at the allowed discrete angle. Each allowed solution to the Eqn (2.17) is called mode of the waveguide and mode number is denoted by the integer 'm'. Each mode will be identified by its polarization state and mode integer m . The first mode in TE polarization is termed as fundamental mode in TE and is denoted as TE₀. There will be an upper limit on the number of modes which is set by the critical angle inside the waveguide.

To get a single mode condition inside a symmetric planar waveguide, the critical condition, angle of incidence equal to critical angle is set for the mode $m=1$. This gives the condition as

$$\theta_c < \cos^{-1}\left(\frac{\lambda_0}{2n_1h}\right) \quad (2.18)$$

2.5.3. Electromagnetic theory of planar waveguide

For a non-conducting medium and considering the propagation along z direction, the electromagnetic Maxwell's equation can be written for a TE polarization as below[120]

$$\frac{\partial^2 E_x}{\partial y^2} + \frac{\partial^2 E_x}{\partial z^2} = \mu_m \varepsilon_m \frac{\partial^2 E_x}{\partial t^2} \quad (2.19)$$

Where, E_x is the electric field in the X-direction, μ_m and ε_m are the permeability and permittivity of the waveguide.

For the TE- polarization, the electric field vector in the X-direction is written as follows

$$E_x = E_x(y)e^{-j\beta z}e^{j\omega t} \quad (2.20)$$

The Eqn (2.20) implies that there is field along the X-direction which has a variation along Y-direction propagating along the Z-direction with propagation constant β with sinusoidal time dependence.

Using the boundary conditions, the variation in the y directions of Eqn (2.20) is obtained at upper cladding, core and lower cladding as follows.

In the upper cladding

$$E_x(y) = E_u e^{-k_y \left(y - \frac{h}{2}\right)} \quad \text{for } y \geq \left(\frac{h}{2}\right) \quad (2.21)$$

In the core

$$E_x(y) = E_c e^{-k_{yc} y} \quad \text{for } -\left(\frac{h}{2}\right) \leq y \leq \left(\frac{h}{2}\right) \quad (2.22)$$

In the lower cladding

$$E_x(y) = E_l e^{-k_{yl} \left(y + \frac{h}{2} \right)} \quad \text{for } y \leq -\left(\frac{h}{2} \right) \quad (2.23)$$

With $k_{yi}^2 = k_0^2 n_i^2 - \beta^2$ (2.24)

Where k_{yi} wave vector and n_i is the refractive index in any of the three media(upper cladding, core or lower cladding)

Using these field solutions the modes in a planar waveguide can be plotted for an electric field amplitude $E_x(y)$ or intensity distribution $|E_x(y)|^2$. For example the electric field intensity profile of $m=0$ and $m=2$ modes in a planar waveguide with parameters $n_1=3.5$, $n_2=1.5$ with $h=1\mu\text{m}$ at a wavelength of propagation $\lambda=1.3\mu\text{m}$ are shown in Fig. 2-14(a) and Fig.2.4(b), respectively.

Fig. 2-14: Normalized electric field intensity distribution of (a) $m=0$ mode and (b) $m=2$ modes in a planar waveguide. [121].

2.5.4. Silicon photonic waveguides

As described in section 2.5 three most common channel waveguide structures in planar geometry are rib, strip or buried waveguides. For a waveguide of these kinds in SOI, the cross sectional dimensions more than a few hundreds of nanometre will support multimodes. This will introduce stringent dimensional requirements for these waveguide to achieve single mode propagation. The structural features and the single

mode condition requirements of rib waveguide and strip waveguides in SOI are explained in the below sections.

2.5.4.1. Rib waveguide

A waveguide can be of large cross section still having a single mode propagation through a cross sectional feature as shown in Fig. 2-15 [122]. This kind of waveguide is called rib waveguides and the single mode conditions and low loss propagations in this waveguides have been studied extensively [123-126]. Large cross section waveguides are desirable because they will reduce the fibre-waveguide coupling loss. The single mode condition in this waveguide is achieved through the geometrical adjustments as explained by Eqn (2.25)[122].

Fig. 2-15: Rib waveguide in SOI [adapted from[121]]

$$\frac{W}{H} \leq 0.3 + \frac{r}{\sqrt{1-r^2}} \quad (\text{For } 0.5 \leq r \leq 1) \quad (2.25)$$

Where, r is the ratio of slab height with respect to the waveguide height. W/H is the ratio between waveguide width and waveguide height as shown in Fig. 2-15. The waveguides which satisfies the condition as given by Eqn (2.25) are also known as shallow etched ribs. The waveguide dimensions are larger than the wavelength of propagation. The single mode analysis in this kind of waveguide is based on the assumption that, the higher order modes are coupled to the outer slab region during wave propagation and introduces higher propagation loss for the higher order modes.

In effect the waveguide behaves as single mode waveguide because all other modes are lost during their propagation. The challenges in the silicon photonic waveguide design are to achieve smaller dimension and polarization independency together for a highly compact and efficient device fabrication. The main concern is to maintain similar loss for TE and TM modes in a waveguide. Also it is highly important that same phase performance is maintained for both these polarization.

Along with other methods Finite Element Method (FEM) and Beam Propagation Method (BPM) has been used for analyzing deeply etched rib waveguide for its single mode propagation and polarization independent operation[127]. The single mode cut-off condition is determined by the critical condition for the first higher order mode propagation inside the waveguide. The boundary condition plays an important role in a waveguide with deep etch depth and hence the single mode condition is significantly different for quasi-TE and quasi-TM modes. Both single mode condition and zero birefringence conditions can be plotted on the same curve to determine the waveguide parameters that will make the waveguide to satisfy both these conditions simultaneously[128]. It is observed that for a single mode condition in a waveguide, quasi-TM mode condition plays the limiting condition. Once the single mode condition for quasi-TM mode is satisfied in the waveguide, quasi-TE condition is satisfied automatically.

2.5.4.2. Strip waveguide

Since SOI is a platform for high light confinement waveguide structures, it can offer waveguide cores with sub micrometer cross sectional dimension. In the wavelength region 1.3-1.5 μm the typical single mode waveguide cross section can be few hundreds of nanometres. The high light confinement also allows smallest bending

radius of the order of micrometers in such waveguides. The characteristics of photonic devices has been improved considerably with this small waveguide with smallest bending radii[129]. Also such small waveguide in SOI can attain ultra-high power density, which can enhance the nonlinear effect in the waveguide[130]. Unlike the rib waveguide in SOI, the strip waveguide should be having a cross sectional dimension less than $1\mu\text{m}$ to suppress the higher order modes. Similar to the case of a rib waveguide TM mode plays the critical condition for single mode propagation.

Fig. 2-16: strip waveguide in SOI.[adapted from[121]]

A general expression of $W \times H < 0.13\mu\text{m}^2$ has been proposed for the single mode condition of a strip waveguide as shown Fig. 2-16 [131]. Where, W and H are the width and height of the waveguide, respectively. An analytical expression of, $W \leq -0.1405H + 0.746$, can be given to the line representing the single mode and multimode regime[66]. A waveguide with 300 nm in height should not be wider than 350 nm to prevent higher order mode propagation. A polarization independent operation can be achieved in a strip waveguide through an equal waveguide width and height. The TE field profile in a strip waveguide is characterized by higher field intensity at the waveguide side walls. For a TM mode the light is confined in the vertical direction with high field intensity at the top of the waveguide [Fig. 2-17].

Thus the propagation loss in a strip waveguide is typically higher for its TE mode than its TM mode. The roughness of side wall can contribute much to the propagation loss of TE mode. The side wall roughness is mainly attributed to the lithography

imperfections and plasma etching process[132]. Vlasov *et al* has reported a propagation loss of $3.6 \pm 0.1 \text{ dB/cm}$ and $3.5 \pm 0.1 \text{ dB/cm}$ for TE and TM modes, respectively through a standard CMOS fabrication process for submicron fully etched SOI strip waveguide[133]. The lowest loss in monocrystalline etched silicon wires waveguide demonstrated have losses of the order of 2 dB/cm [133-135]. Using e-beam lithography propagation loss has been reduced up to 1 dB/cm [136]. Since etched strip wire waveguide are the most versatile to design integrated components such as ring resonators and Bragg gratings, any additional post processing to reduce sidewall roughness (e.g., oxidation) will affect the dimension and structural features of final device. However, to reduce the propagation loss further one can adopt the methods such as switching from strip waveguide to shallow etched waveguide or partially oxidized rib waveguide. Low loss shallow-ridge silicon waveguides with an average propagation loss of $0.274 \pm 0.008 \text{ dB/cm}$ in the C-band has been demonstrated recently through the optimised photolithography and dry etching procedure[137].

Fig. 2-17: E_x and E_y field intensity in a single mode silicon strip waveguide for (a) TM mode (b) TE mode, respectively[138].

2.6. Outcome of the literature review

In the Micro Ring Resonators (MRR) based TO-WSS configuration, the potential research challenges is in the design and fabrication of various filter configurations to achieve required spectral features, broad band wavelength selection\routing

functionalities with a low power consumption. So the design fabrication and demonstration of these functionalities in a SOI platform were considered as some of the research aims of this thesis. The broad band tunability in a MRR based WSS in SOI platform is not much reported. The wavelength tunability in a single MRR is limited by the available Free Spectral Range (FSR). The reported full FSR tuning with TO effect need a thermal power requirement of $28 \mu\text{W}/\text{GHz}$ with tuning range of $\sim 20 \text{ nm}$ [8]. For a full C+L band ($\sim 95 \text{ nm}$) tuning, a micro heater with such tunability would require a high power. Eventhough the tuning efficiency can be enhanced further through undercut structures [9], such devices are difficult to fabricate and are undesirable for active device integration. So the research in this direction should concentrate on the methods to design and fabricate TO-WSS with broader wavelength (C-L band $\sim 95 \text{ nm}$) tunability with low power consumption. For this purpose, various design configurations for increasing FSR and alternate tuning procedures should be considered. Also, investigations into novel configuration in MRR based WSS for single wavelength or multiple wavelength selection for OADM applications is a potential research focus.

The principle of phase shifted grating has been extensively demonstrated using fiber Bragg gratings (FBG). But their counter part, the one which is based on planar waveguide structures is not much explored and is well suitable for channel filtering applications in optical communication network. For a waveguide gratings which is fabricated on the top surface of the waveguide, the effective index is more sensitive to the grating etch depth. In practice, it is very difficult to control the etch depth of the gratings on the surface of a waveguide. This leads to fabrication imperfection in the gratings and hence spectral distortions. A Bragg gratings fabricated on the top surface of a waveguide should have a highly uniform low refractive index modulation and

large number of grating periods to get a narrow band reflection with a high reflectivity [98]. Moreover, multiple lithographic steps are needed to achieve the grating pattern on the top surface of the waveguide. Since the gratings are fabricated on a large cross section waveguide the waveguide cross section should be modified to get a single mode operation. The Bragg gratings on the side wall of a waveguide is easy to fabricate in a single lithographic step and the structure is easy to optimize in their dimensions to obtain a desired spectral feature. Since the grating depth in such structure is controlled by photolithography process rather than the etching process, they are less prone to the variations in uniformity along the waveguide. An investigations into the phase shifted vertical side wall gratings as a resonant transmission filter suitable for optical communication network can be one of the research focus. The main challenges under this area will be (i) proper design of the gratings to achieve the spectral features suitable for a DWDM communication, and (ii) effective fabrication followed by experimental validation to achieve the desired spectral features.

2.7. Summary

A detailed literature review and theoretical aspects of silicon photonic waveguide structures has been presented in this chapter. With reference to the objectives of this thesis work, more importance is given to silicon photonic waveguides, Bragg grating and Micro Ring Resonators as passive and active devices. The up-to-date literatures presented in this chapter throw light on the challenges and developments in these areas as faced by various researchers. Finally an outcome is drawn from the literature review, highlighting major focus areas of this thesis work,

Chapter 3:

Micro Ring Resonator based Thermo Optic-Wavelength Selective Switch (TO-WSS) for low power consumption broad band tunability

In this chapter Silicon-On-Insulator (SOI) micro ring resonator (MRR) based thermo-optic Wavelength Selective Switch (TO-WSS) is demonstrated with two stages filtering configuration so as to subdue the thermal cross talk between the rings and to get broad band wavelength tunability. The applied small difference in the ring radius will allow selection and routing of a single wavelength channel at the drop port with a wide FSR (~ 95 nm). The WSS is characterized for its spectral behaviour and its wavelength selectivity is demonstrated through discrete and fine wavelength tuning with low power consumption.

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3.1. Introduction

Optical Wavelength Selective Switches (WSS) are essential devices for high-capacity optical network systems based on reconfigurable optical add-drop multiplexing (ROADM) and optical cross connect (OXC). Micro ring resonators (MRR) are highly suitable for such WSS functionality because of their versatility, compactness and Complementary Metal Oxide Semiconductor (CMOS) compatibility [39, 40]. Two common approaches are used in MRR to tune its resonant wavelength such as Electro-Optic (EO) and Thermo-Optic (TO) methods. TO method in silicon can provide long-term stability and wide wavelength tunability with an operating time scale of a few μs , suitable for circuit switched optical networks [8, 11]. However, the wavelength tunability in a single MRR is limited by the available Free Spectral Range (FSR). A full FSR tuning of the order of 20 nm can be achieved with an optimized micro heater having a tunability 28 $\mu\text{W}/\text{GHz}$ [8]. For a full C+L band (~ 95 nm) tuning, a micro heater with such tunability would require a high power. Eventhough the tuning efficiency can be enhanced further [9], the proposed undercut structures are difficult to fabricate and are undesirable for active device integration. The high power requirement for a full band tuning should be avoided as far as energy efficiency is considered. Also, a micro heater cannot withstand a high power due to its operating temperature limit. Thus, two major challenges should be overcome in a full C+L band tunable Thermo-Optic Wavelength Selective Switch (TO-WSS). Firstly, WSS should have the required high FSR (~ 95 nm). Secondly, WSS should circumvent the high power requirement for its full band tuning.

Usually, the FSR in a MRR based WSS is increased through two methods. In the first method, the FSR of the ring is increased by reducing the ring radius [139]. The

radiation loss and bending loss present at the extremely small radius and the fabrication challenges to achieve this small dimension are the main drawbacks of this method. The second method involves creating Vernier configurations through directly coupled ring resonators [140]. Vernier effect has been demonstrated in polymer [141] and dielectric [142] ring resonators for WSS applications. Only a few works have reported on a Silicon-on-Insulator(SOI) platform [143, 144], with specific applications such as sensing and tunable lasers.

For a TO-WSS application, as mentioned before, the device should allow wavelength selection over a high FSR with low power consumption and low thermal cross talk between rings. To meet these requirements, a MRR based TO-WSS is proposed. A Vernier MRR in a two stage filtering configuration on an SOI platform is used to achieve high FSR (~C+L band) and low thermal cross talk between the rings. An alternate tuning procedure with optimized micro heaters is proposed and demonstrated to achieve low power consumption wavelength selection over a broadband.

3.2. Device design

The design of the proposed device is shown in Fig. 3-1(a). It has two rings coupled serially through an intermediate waveguide with a separation of 20 μm between them. The ring with higher radius is the first ring (R1) and ring with smaller radius is the second ring (R2). The Free Spectral Range (FSR) is the span of wavelength between two adjacent resonances of a single ring. Here the FSR of the R1 is termed as FSR_1 and FSR of R2 is termed as FSR_2 . Only the wavelengths which are in resonance with both rings will be dropped from the device with a separation between them given by an extended FSR ($FSR_{extended}$) at the drop port.

The resonance inside a single ring happens when the perimeter of the ring L is an integral number of the guided wavelength. *i.e.* $L = N\lambda_0 / n_{eff}$. Where N is an integer.

The expression for FSR involves the group index term

$$n_g = n_{eff} - \lambda(\partial n_{eff} / \partial \lambda) \quad (3.1)$$

and is written as,

$$FSR = \frac{\lambda_0^2}{n_g L} \quad (3.2)$$

Where λ_0 is the resonant wavelength and n_{eff} is the effective refractive index of the waveguide.

Fig. 3-1: (a) Schematic diagram of the double ring WSS (b) Cross sectional view of the device, showing waveguides and micro heaters.

The Vernier principle is expressed by the expression

$$FSR_{extended} = m_1 FSR_1 = m_2 FSR_2 \quad (3.3)$$

Where m_1 and m_2 are co-prime integers and is known as FSR expansion factor. To get the maximum FSR expansion and maximum suppression of main interstitial modes

(modes adjacent to main resonance peak and twin resonance peaks in the middle), the relationship between m_2 and m_1 is set as follows [145]

$$m_2 = m_1 - 1 \quad (3.4)$$

With the above condition and taking $m_1 = M$ Eqn.(3.3) can be rewritten as

$$FSR_{extended} = M.FSR_1 = (M - 1)FSR_2 \quad (3.5)$$

Substituting Eqn(3.2) into Eqn(3.5) , the following relationship can be obtained for ring radii.

$$R_2 = \frac{M - 1}{M} R_1 \quad (3.6)$$

Considering the bending loss and other lithographic limitations the ring radius R_1 is taken as $10\mu\text{m}$, which gives a Free Spectral Range, $FSR_1 \sim 9.5\text{nm}$ from Eqn (3.2). Once the FSR_1 is known the FSR expansion factor can be calculated from the following relation

$$M = \left\lceil \frac{FSR_{desired}}{FSR_1} \right\rceil_{\text{int}} \quad (3.7)$$

$FSR_{desired}$ is set as total C+L band width of optical communication network, which is 95 nm. Thus, the FSR expansion factor is obtained from Eqn. (3.7) as $M = 10$. With this value in M the second ring radius is calculated from Eqn. (3.6) as $R_2 = 9\mu\text{m}$.

3.3. Numerical simulation

Numerical simulations are performed for the designed structures using 2-D FDTD method. The Rsoft Photonic Component Design Suite (Full WaveTM module) is used to design and simulate the structure through Full wave FDTD[146]. A mesh grid size of $\Delta x = 10\text{ nm}$, $\Delta z = 10\text{ nm}$ and time step size of $\Delta t = 1.2 \times 10^{-17}\text{ s}$ were used in the

simulation. The time step is based on Courant condition, $\Delta t \leq 1/(c\sqrt{1/(\Delta x)^2 + 1/(\Delta z)^2})$.

The input source was a Gaussian modulated continuous wave in TE polarization at a wavelength of 1.55 μm having a spectral bandwidth of 281 nm. Detailed explanation of 2-D FDTD method and algorithm is given in the appendix D.

The device has two through ports, one at the first ring R1 and other at the second ring R2. Fig. 3-2 (a) shows the combined spectrum obtained for the device at the through and drop ports. It can be seen that the out of band rejection at the drop port channel has been increased considerably due to the two ring resonance for the dropped channels. Fig. 3-2(b) is the through port spectrum of ring R2 and Fig. 3-2(d) is the drop port spectrum of the device.

Fig. 3-2: A 2-D FDTD simulated spectrum for two ring WSS (a) combined through and drop port spectrum.(b) Through port spectrum at R2(ThruR2)(c)Through port spectrum of R1(ThruR1)(d) Drop port spectrum

Through port spectrum at R1 [Fig. 3-2(c)] shows single channel extinction at the dropped channel wavelength with all other channels undisturbed. The observed spectral behaviour shows that ring resonator configuration is suitable for a hitless WSS with a high FSR at the drop port. The full band spectrum at the drop port with the extended FSR ~ 100 nm and suppressed interstitial peaks is shown in Fig. 3-3. An adjacent channel suppression of ~ 15 dB is observed in the spectrum. No twin resonance peaks is seen between the main resonance peaks. The slight deviation in the extended FSR from the designed value (which is 95nm) is attributed to the refractive index variation in the effective index method used in the 2-D FDTD simulation.

Fig. 3-3: Full band spectrum at the drop port of the WSS showing the extended FSR and interstitial peaks

3.4. Fabrication

With these ring radius values, the device fabrication is done on an 8 inch SOI wafer with a 220 nm top silicon layer thickness and 2 μ m buried oxide layer. Detailed

fabrication process flow chart is shown in Fig. 3-4 and the process steps are explained below.

1. The waveguide structure is patterned with mask based Deep Ultra-Violet (DUV) lithography. Nikon scanner with 248 nm DUV exposure facility is used to pattern the structures. A resist layer of 4100Å with Bottom Anti-Reflection Coating (BARC) is used for pattern development.
2. Silicon etching is done with Inductively Coupled Plasma (ICP) Reactive Ion Etching (RIE). RIE is done using Chlorine (Cl_2) plasma at 60 mTorr chamber pressure.
3. Plasma photo resist strip is done on the wafer.
4. 2µm Silicon dioxide (SiO_2) cladding layer is deposited over the silicon waveguide layer through Plasma Enhanced Chemical Vapour Deposition (PECVD) process using SiH_4 and N_2O plasma at a process temperature of 400°C with the chamber pressure of 3Torr, applied power 270 W and an average deposition rate of 29Å/sec.
5. 100 nm Titanium (TiN) metal deposition is done over the wafer through Physical Vapour Deposition (PVD) for heater element fabrication.
6. Pattern definition of TiN- micro heaters is done through DUV lithography using mask layer 2. The heater elements are of 100 nm thick and 800 nm wide in their dimension.
7. Metal etching is done using Cl_2 plasma in RIE chamber.
8. Plasma photo resist strip is done on the wafer.

9. Silicon dioxide (SiO_2) cladding layer of $1\mu\text{m}$ thickness is deposited over the Ti micro heater layer through Plasma Enhanced Chemical Vapour Deposition (PECVD) as a separation layer for Aluminium (Al)-electrode fabrication.

Fig. 3-4: Process flow chart for the fabrication of micro ring resonator based thermo-optic wavelength selective switch.

10. Pattern definition using mask layer 3 for via etching.

11. Via etching is done through RIE.
12. Plasma photo resist strip is done on the wafer.
13. 1 μm Aluminium metal deposition is done on the wafer through PVD for electrode fabrication.
14. Pattern definition using mask layer 4 for the Al electrode fabrication.
15. Aluminium metal etching is done through RIE using Cl_2 plasma.
16. Final plasma photo resist strip is done on the wafer and the wafer is diced and the waveguide ends are diamond polished to get the device.

Fig. 3-5: SEM images of (a) double ring WSS (b) Ti micro heater (c) single ring of radius $10\ \mu\text{m}$ (d) SSC tip. Optical micro scope image of the (e) device and (f) magnified image of Ti-micro heater and rings.

Fig. 3-1(b) shows the cross sectional image of the SOI based device showing various dimensions. The cross sectional dimensions of bus waveguide and ring

waveguides were $470 \text{ nm} \times 220 \text{ nm}$ and $525 \text{ nm} \times 220 \text{ nm}$, respectively. To increase the coupling efficiency between input-fibre and the device, the waveguide ends were terminated with Spot Size Converters (SSC) having a length $200 \mu\text{m}$ and tip width 180 nm . The coupling gap was kept the same for all the four couplers and was varied between 200 nm and 350 nm to get different channel bandwidths. Different SEM and optical micro scope images of the device are shown in Fig. 3-5.

3.5. Experimental results and discussion.

The device characterisation is done using an Amplified Spontaneous Emission (ASE) light source (EXFO FLS 2300B) with spectral range 1530 nm to 1600 nm and Optical Spectrum Analyser (OSA) (AQ6317B). Two lensed polarisation maintaining fibres, input fibre (IF) and output fibre (OF), are used to couple the light in and out of the silicon waveguide, respectively. A polarisation controller (PC) and associated optical elements are used to select a TE mode (electric field parallel to the substrate plane) from the ASE source. Only TE polarization is considered in the entire filter characterization procedure. Since a silicon waveguide device is highly dependent on the state of polarization of the input light, method such as polarization diversity scheme[147] should be used to eliminate the polarization dependency.

Precise in- and out- coupling is achieved with 3-axis nano positioning stages S1 and S2 that are controlled by motor controller. One I-V sweep and a voltage-current source meters are used to supply DC current to both micro heaters through a micro probe (P). A Charge Coupled Device (CCD) camera with an objective (O) is used for visual inspection of Device Under Test (DUT) during the initial alignment. Fig. 3-6 shows the schematic diagram of the experimental set up used to characterise the

thermo optic WSS. Fig. 3-7 shows the characterization set up, DUT, input and output fibres and micro probe supplying external DC current to the micro heaters.

Fig. 3-6: Illustration of the experimental set up used to characterise the thermo optic WSS.

Fig. 3-7: Photograph of the experimental set up showing DUT, micro- probes and input/output fibres.

3.5.1. Discrete wavelength tuning

Initially, with no electric power given to the rings, no drop wavelength is observed due to the resonance mismatch between the rings. The electrical power on R1 (P1) is increased slowly while keeping the power on R2 (P2) to 0 mW. The first peak is observed at 1554.28 nm with P1=4.93 mW. When P1 is increased further to 5.73 mW, the device has gone to the OFF state. With a linear increase in P1, the device has shown discrete wavelength switching from one drop wavelength to the other with equal wavelength spacing. The wavelength spacing is observed to be exactly the FSR of the R2 (FSR_2), ~10.7 nm. Fig. 3-8 shows one of the ON spectrums at a power, P1=11.36 mW, at a wavelength of 1564.9 nm.

Fig. 3-8: Drop port spectrum of the Vernier configured rings showing a wide FSR and a single resonant transmission

The resonance shows a 3 dB bandwidth of ~10 GHz and extinction >15 dB. An insertion loss (IL) of -6 dB is observed for the device. All the side band channels were suppressed below the noise level through the Vernier effect, so that they were not visible in the spectrum. It has been reported that maximum suppression of interstitial peaks occurs when the critical conditions for waveguide-ring coupling and difference

in ring radii ($m_2 = m_1 - 1$) are satisfied in the device[145]. Also the effect of waveguide loss plays an important role on the interstitial peak suppression. Fig. 3-9 shows the superimposed wavelength switching spectrum with increase in P1. Five resonant wavelengths have been dropped when the power is increased up to a maximum of 33.59 mW on R1. The observed spectral range (1554.33 nm-1597.7 nm) is limited by the band width of our input ASE source, which is 70 nm. An average switching power of 7.3 mW is observed for the WSS to switch from one drop wavelength to the other. The spectrum exhibited almost equal band width, out of band rejection and transmission power. The slight increase in the wavelength shift for higher powers is due to the group index variation with respect to the increase in wavelength. This is observed as slight increase in the FSR of the ring resonator with increase in wavelength.

Fig. 3-9: Discrete wavelength tuning in WSS through electrical power variation (ΔP_1) applied on R1 (at $P_2=0$ mW)

3.5.2. Fine wavelength tuning

Fine tuning of drop wavelength can be done through electrical power variation given to both heaters. The voltage on R2 heater is varied in steps of 2 V to set different electrical powers on R2, (P2) from 0 mW to 20.4 mW. The power on R1, (P1) is increased at each stage to attain the shifted resonance, so that the dropped spectrum is tuned in small wavelength ranges. Fig. 3-10 shows the tuned drop spectrum from 1564.9 nm to 1568.2 nm with different electric powers (P2, P1) applied on the rings. With P2=0 mW and P1=11.36 mW the peak (1) shows the initial dropped channel with no tuning. For P2=2.32 mW, P1 is increased to 13.38 mW to attain the shifted resonance at peak (3), tuning the spectrum by 0.35 nm. For P2=2.32 mW, P1 is increased to 13.38 mW to attain the shifted resonance at peak (3), tuning the spectrum by 0.35 nm.

Fig. 3-10: Fine wavelength tuning in WSS through electrical power variations (ΔP_2 , ΔP_1) applied on R2 and R1

The spectral shift has shown a linear variation with respect to the input electrical powers. Fig. 3-11 shows the variation in electrical powers, ΔP_1 and ΔP_2 required on

R1 and R2, to shift the drop spectrum through the desired wavelengths. The spectral shift has shown a linear variation ~ 5 mW/nm for this fine wavelength tuning. Even though the electrical resistance of the micro heaters are of different values (here $R1=4.1$ K Ω and $R2=1.84$ K Ω) the required power to shift the spectrum should be the same for both heaters. However, slightly lower slope of $\Delta P1$ is attributed to the longer length and coiled nature of R1 heater, causing higher heat transfer efficiency for R1.

Fig. 3-11: Variation in power differences on both rings R1 and R2 to fine tune the drop port channel.

3.5.3. Broadband wavelength selection through discrete and fine wavelength tuning

Low power consumption broadband wavelength selection is demonstrated utilising the fine tunability and discrete tunability of the WSS. Within the available FSR the initial drop channel from 1554 nm has been tuned up to 1600 nm ($\Delta\lambda \sim 46$ nm) with micro heater driving powers of $P1=41.59$ mW and $P2=8$ mW. The device can drop channel wavelengths with a spectral spacing of 100 GHz and 50 GHz with a channel cross talk less than -15 dB.

Fig. 3-12: Wavelength selection in 100 GHz (0.8 nm) channel spaced system through the combined fine and discrete tunability.

Fig. 3-13: Wavelength selection in 50 GHz (0.4 nm) channel spaced system through combined fine and discrete tunability

Fig. 3-12, and Fig. 3-13 shows the dropped channel spectra through the combined fine and discrete tunability for 100 GHz and 50 GHz spaced channels, respectively. The average power difference (ΔP_2) applied on R2 to fine tune the drop spectrum to 100 GHz and 50 GHz channel spacing is observed to be 5 mW and 2.5 mW, respectively. The discrete tuning power (ΔP_1) is observed to be ~ 7.3 mW, which is in accordance with the observations made in section 3.5.1.

Fig. 3-14: Channel selection procedure and the power variations required for 117 channel selection with 100 GHz spacing.

Using the observed fine tunability (5mW/nm) and discrete tunability (7.3 mW/FSR), the power variation required for 117 channels selection with 100 GHz spacing has been calculated. A schematic of channel selection procedure and the power requirement on the rings are shown in Fig. 3-14. Tuning process includes full FSR tuning through fine tunability and selection of all other channels through discrete tunability. The FSR_2 amounts to approximately 13 channels with 100 GHz spacing. With this approach, the total power requirement for the selection of 117th channel ($\Delta\lambda \sim 94$ nm) is observed to be $P1=106$ mW and $P2=48$ mW. For a single ring (with our fabricated micro heater tunability 5 mW/nm), the power requirement to achieve this tuning range would be 470 mW. The device with Vernier configured rings effectively increased the FSR of the WSS and reduced the power requirement for a full band tuning to 32.7% of that of single ring tuning through the proposed tuning procedure. Also, the maximum power subjected on one ring would be 22.5% of that of single ring tuning, circumventing the micro heater breakdown problem at higher powers.

The WSS can be employed in a matrix array as depicted in the Fig. 3-15 to demultiplex, select and route different DWDM wavelength channels in an optical communication network. For example, consider a set of input channels $\lambda_1, \lambda_2 \dots \lambda_9$ is being given to the device. Where the first column in the matrix will drop the channels with separation given by FSR2 (Let it be $\lambda_1, \lambda_4, \lambda_7$), at $P2=X1$ and the selection of these channels can be done with discrete tuning to these channels through electric power variations ($P1=Y1, Y4, Y7$) applied on R1 rings. Fine tuning to other set of FSR2 ($\lambda_2, \lambda_5, \lambda_8$) can be done with electrical power variation $\Delta P2$ applied on R2 in the second column, setting its power at $P2=X2$ and selection of these channels is possible through the power variation ($P1=Y2, Y5, Y8$) applied on R1 rings. Through this way the entire wavelength channels in a DWDM system can be selected, demultiplexed or routed using the designed WSS matrix array. The device can be reconfigured to any of the desired channels through electrical power variation over the rings.

Fig. 3-15: Schematic diagram showing the matrix array of the proposed WSS to dynamically select and route DWDM channels with different electrical powers ($P1, P2$) on the switches.

3.6. Thermal cross talk between the rings

Thermal cross talk between the rings will introduce undesirable effects on the switching characteristics of the device, in the form of thermal interference and switching cross talk. This will be observed as the shift in the drop port spectrum while the device switches between ON and OFF states. Fig. 3-16 shows one of the ON/OFF spectrums at wavelength 1565 nm showing the parameters such as ON/OFF ratio, ON/OFF power, thermal interference and switching cross talk in the device. The OFF state, peak (2), shows two small peaks, which corresponds to the resonance mismatched ring spectrums. The left peak corresponds to the resonance in R2 while the right peak that of R1.

Fig. 3-16: ON/OFF spectrum showing ON/OFF ratio, ON/OFF power, thermal interference and switching cross talk

For a zero thermal cross talk between rings, the R2 spectrum should remain stable while the R1 spectrum undergoes a right shift when the power is applied on R1. Here the thermal interference during switching is observed to be 0.009 nm with an applied ON/OFF power of 1.43 mW on R1. The switching cross talk, which is defined as the amount of R2 spectral power present in the drop port at the OFF state, is observed to

be ~ -14 dB.

Fig. 3-17: (a) Through port spectrum of R1 with increase in electrical power P1

(b) variation in R1 through port wavelength with P1.

To quantify the thermal cross talk between the rings, spectral shift observations are made with varying electrical powers on the rings. Here, the thermal cross talk between R1 and R2 is defined as the amount of spectral shift in one ring with electrical power variation is given in the other ring. Fig. 3-17(a) shows the through port spectra of R1 with increasing electrical power P1 on it. This shows a thermal tunability of 0.161 nm/mW for the ring [Fig. 3-17 (b)]. The spectral shift in R2 through port spectrum is recorded with respect to the electric power variations ($\Delta P1$) on R1. Fig. 3-18(a) shows the spectral shift in R2 when P1 is increased up to a maximum value of

75.7 mW. From these observations, thermal cross talk of 0.0068 nm/mW (0.85 GHz/mW) is calculated for the device with a ring separation of 20 μm [Fig. 3-18(b)].

Fig. 3-18: (a) Through port spectrum of R2 with increase in electrical power P1
(b) Variation in R2 through port wavelength with P1, showing thermal cross talk=0.0068nm/mW.

Thermal cross talk is also calculated to be 4.2% with respect to the thermal tunability of the single ring. This observed thermal cross talk is considerably smaller when compared to a directly coupled configuration and it can be further reduced in the proposed configuration through an increased separation between R1 and R2.

3.7. Comparison with previously reported work on thermally tunable micro ring resonators

Thermal tunability in micro ring resonators has been reported by many researchers through various methods on different materials platforms.

Micro ring device/ material	Year	Tuning method	Observed tunability	Maximum tuning range/FSR
Directly coupled Vernier rings/polymer[141]	2005	Al- heater	0.087 nm/mA	2.17 nm
Single ring/silicon[148]	2006	Ni- micro heater/ Part of the ring	0.0053 nm/mW	0.3 nm
Directly coupled Vernier (Ta ₂ O ₅ - SiO ₂)[142]	2006	Cr- heater	0.0568 nm/mA	13.3 nm
Single ring/silicon[8]	2007	Ti-micro heater/Coiled	0.28 nm/mW	16 nm
Three rings ring/silica[40]	2008	Unknown	0.0044 nm/mW	6.4 nm
Single ring/silicon[59]	2008	Ni- Cr heater/ Coiled	0.062 nm/mW	18 nm
Single ring/Silicon[9]	2010	Ti-micro heater/ Free standing undercut structure	2.7 nm/mW	11.5 nm
<i>Proposed two stage Vernier rings/silicon</i>	<i>2012</i>	<i>Ti-micro heater/Coiled</i>	<i>0.2 nm/mW</i>	<i>46 nm (demonstrated). Available FSR~ 95 nm. Power consumption 32.7 % of single ring tuning</i>

Table 3-1: Comparison in performance parameters of various thermo-optic tunable micro ring resonators.

The ring resonator devices in such configurations are fabricated with intention to

achieve a low power consumption broad band tunability through an easy fabrication procedure. A bench mark comparison chart detailing the advantages of the proposed two stage configuration with other reported silicon MRR tunable filter is shown in Table 3-1.

3.8. Summary

A broadband tunable TO-WSS has been demonstrated on an SOI platform with low power consumption and low thermal cross talk between rings. Instead of single ring tuning, a Vernier configured two stage filter configuration has been used in the WSS to achieve single wavelength selection over a high FSR. Using the fine tunability (5 mW/nm) and discrete tunability (7.3 mW/FSR) of the WSS, the initial drop channel has been tuned from 1554 nm to 1600 nm ($\Delta\lambda \sim 46$ nm) with micro heater driving power of $P_1=41.59$ mW and $P_2=8$ mW. The WSS can achieve a 94 nm tuning range with electric powers of $P_1=106$ mW and $P_2=48$ mW through the proposed alternate tuning procedure, hence reducing the total power consumption for a full C+L band tuning to 32.7% of that of a single ring tuning. The thermal cross talk is observed to be considerably smaller (0.85 GHz/mW, 4.2%) for a ring separation of 20 μm . The device which can work as ON/OFF switch shows an ON/OFF ratio ~ 15 dB, ON/OFF power 1.43 mW and thermal interference of 0.009 nm. The proposed MRR based TO-WSS can be arranged in a matrix array configuration to achieve dynamically reconfigurable add/drop WSS suitable for OADM applications in DWDM communication network with narrow channel spacing.

Chapter 4:

Series and parallel coupled micro ring resonator thermo optic- Wavelength Selective Switches (TO-WSS)

This chapter discusses the series and parallel configuration of micro ring resonators as a wavelength filter. The theoretical aspects of both these filters are explained, along with the fabrication and characterisation results. The series configuration in micro ring resonators is analyzed as a TO-WSS through various detuning combinations in micro ring resonators to obtain an OFF state in the WSS with highest channel extinction, low switching cross talk and low loss of OFF state. The chapter also presents parallel configuration in ring resonators and comparison between series and parallel configuration is given at the end.

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4.1. Introduction

Dynamically reconfigurable optical add/drop multiplexers (OADM) are one of the key device requirements for practical implementation of next generation wavelength agile optical networking systems in a metro/access network. An OADM configuration enables add/drop of single or multiple channels from an optical communication network without affecting other channels in the network. Thus, one of the important components in any OADM configuration is a hitless wavelength selective switch (WSS) to add/drop the desired channels[6]. Micro Ring Resonators (MRR) are highly suitable for such add/drop functionalities due to their design flexibility, energy efficiency, ability to filter response synthesis, compactness using high-index-contrast waveguides and Complementary Metal Oxide Semiconductor (CMOS) compatibility [54, 55, 149, 150]. Higher order series coupled MRR can offer a box-like filter response with higher channel isolation [149, 151]. In a series coupled MRR based WSS, the ON/OFF selection of a wavelength channel is done through cavity detuning among the resonators through an applied external perturbation to affect its refractive index [141, 142, 152]. When the resonance wavelength matches inside the rings, the device drops that wavelength to make the switch into ON state. When the resonance-mismatch happens through an applied cavity detuning, the device goes into OFF state and allow the channels to pass through the device unaffected. Single channel or multichannel WSS using such an element can be achieved through arranging them in a matrix array or cascaded configurations [40, 55]. For instance, in the previous chapter we have reported a single channel thermo optic WSS (TO-WSS) using series coupled Vernier MRR in a two stage filter configuration for a C+L band tunability. The configuration is characterised by low power requirement for full band tuning with a

lower thermal cross talk between rings. However, the spectral shape in the WSS should be improved to achieve better signal stability and lower channel cross talk. Easy way to improve the spectral shape is to use series coupled resonators at each stage of the Vernier configured rings. In such a configuration an optimal OFF state should be achieved at each stage with minimum power requirement for higher channel extinction and low loss of OFF state.

In this context, series coupled triple ring resonators are designed and fabricated on an SOI platform and experimentally analysed as a thermo-optic Wavelength Selective Switch (TO-WSS) to obtain an optimal detuning combination of MRR for an effective OFF state. The ring resonators are subjected to external TO perturbation to obtain an OFF state in the WSS with highest channel extinction, lowest switching cross talk and low loss of OFF state. Similar to a series configuration, a parallel configuration in the ring resonators is also subjected to study in this chapter. A general conclusion is drawn related to the performance differences between these two configurations and presented at the end of the chapter.

4.2. Series coupled triple ring resonator TO-WSS- design and fabrication

The schematic diagram of the series coupled triple ring resonator TO-WSS on an SOI platform is shown in Fig. 4-1. The device comprised of three MRR of equal radius coupled in series with micro heaters on the top of them for resonant wavelength control. The configuration is suitable for non-blocking wavelength selective switch, through individual control of resonant wavelength through applied electric power over micro-heaters. Considering the series configuration of ring resonators as shown in Fig. 4-2, the spectral response can be optimised through proper coupling efficiencies

between bus waveguide and ring resonators.

Fig. 4-1: Schematic of series coupled triple ring resonator TO-WSS

Fig. 4-2: Light flow in a series coupled triple ring resonator.

Different electric field components and coupling coefficients are shown in Fig. 4-2. In the configuration, the term I represents the input field amplitude, T is the transmission amplitude at through port, D is the drop wave amplitude and A represents the added wave amplitude. The term α is the propagation loss per unit length in the ring waveguide, β is the propagation constant in the ring resonator and L is the half perimeter of the ring resonator. The term C_N represents the transmission efficiency matrix of the directional couplers and is defined as[153]

$$C_N = j \begin{bmatrix} -\frac{\sqrt{1-K_N}}{\sqrt{K_N}} & \frac{1}{\sqrt{K_N}} \\ -\frac{1}{\sqrt{K_N}} & \frac{\sqrt{1-K_N}}{\sqrt{K_N}} \end{bmatrix} \quad (4.1)$$

Where the term K_N represents the coupling efficiency between waveguides. The relationship between optical field amplitudes at four ports can be expressed by transfer matrix model as follows.

$$\begin{bmatrix} A \\ D \end{bmatrix} = C_4 \begin{bmatrix} \exp[(\alpha_3 + j\beta)L_3] & 0 \\ 0 & \exp[-(\alpha_3 + j\beta)L_3] \end{bmatrix} * C_3 \begin{bmatrix} \exp[-(\alpha_2 + j\beta)L_2] & 0 \\ 0 & \exp[(\alpha_2 + j\beta)L_2] \end{bmatrix} \\ C_2 \begin{bmatrix} \exp[(\alpha_1 + j\beta)L_1] & 0 \\ 0 & \exp[-(\alpha_1 + j\beta)L_1] \end{bmatrix} * C_1 \begin{bmatrix} I \\ T \end{bmatrix} \quad (4.2)$$

Eqn (4.2) can be reduced to a simpler form as below

$$\begin{bmatrix} A \\ D \end{bmatrix} = \begin{bmatrix} m_{00} & m_{01} \\ m_{10} & m_{11} \end{bmatrix} * \begin{bmatrix} I \\ T \end{bmatrix} \quad (4.3)$$

Substituting $I=1$ and $A=0$, in Eqn (4.3), the drop port and through port wave amplitudes is obtained as,

$$T = -\frac{m_{00}}{m_{01}}, \quad (4.4)$$

$$D = \frac{m_{01}m_{10} - m_{00}m_{11}}{m_{01}} \quad (4.5)$$

If we set the coupling coefficients $K_1=K_4=K$ and $K_2=K_3=K_m$, and assuming the round trip propagation power loss in the ring to be a minimum (lossless case), the optimum coupling efficiencies in the series coupled ring resonators to achieve a flat top spectrum and box like filter response has been shown to be[154]

$$K_m^2 = \frac{K^4}{8} \quad (4.6)$$

If the ring resonator is lossy, the optimum coupling condition is shown to be [155]

$$K_m = \frac{K^2}{2(2 - K)^2} \quad (4.7)$$

The relationship between the coupling coefficients suggested by the above equations shows general design requirements for a series coupled triple ring resonator, to get a maximally flat (Butterworth) spectral response. The coupled resonators should be designed in such a way that the coupling gap between the bus line and ring waveguide should be kept smaller than the gap between the rings. The micro ring radius was kept 10 μm for all the three resonators. The coupling gaps 'g' and 'g_m' were varied between 200 nm to 260 nm and 300 nm to 440 nm, respectively, to get different channel bandwidths.

4.3. Series coupled triple ring resonator-Experimental results

The device fabrication is done on an 8-inch SOI wafer with a 220 nm top silicon layer thickness and 2 μm buried oxide layer. The detailed fabrication process flow is given in chapter 3, section 3.4 and it is briefly explained below. The waveguide structure is patterned with mask based Deep Ultra-Violet (DUV) lithography and silicon etching is done with Inductively Coupled Plasma (ICP) Reactive Ion Etching (RIE). To increase the coupling efficiency between input fibre and the device, the waveguide ends were terminated with Spot Size Converters (SSC) having a length of 200 μm and tip width of 180 nm. Silicon dioxide (SiO₂) cladding layer of 2 μm is deposited over the silicon waveguide layer through Plasma Enhanced Chemical Vapour Deposition (PECVD)

process. After that the titanium (Ti) micro heaters are fabricated over the structure through DUV lithography and dry etching. The heater elements are of 100 nm thick 800 nm wide in their dimension. After this, another 1 μm SiO₂ cladding layer is deposited and contact holes were etched. Afterwards, Aluminium (Al) wire and connection pads were fabricated on top of the structure for external electrical connection.

Fig. 4-3: Microscope image of series coupled triple ring resonator

Fig. 4-3 shows the microscope image of one of the series coupled triple ring resonators fabricated on a SOI wafer. The cross sectional dimensions of bus waveguide and ring waveguide were 470 nm x220 nm and 525 nm x220 nm, respectively. The obtained drop and through port spectra of various series-coupled triple ring resonators for a TM polarised input, without any micro heater voltage applied on the rings are shown in Fig. 4-4. Most of the spectrum is observed to be distorted with Coupling Induced Frequency Shift (CIFS) present in the high index contrast waveguides, in addition to the fabrication related resonance frequency offset between ring resonators. CIFS in a series coupled ring resonators arises out of the self coupling perturbations that give rise to new uncoupled resonance frequencies, resulting into severe spectral distortions. A complete description of CIFS can be found in[156].CIFS is a coupling effect in linear system and refers to the perturbation in the resonance property of an

electromagnetic cavity. CIFS can be explained through a simple example as shown in Fig. 4-5. An ideal two cavity system as shown in Fig. 4-5(a) will have an analytic TM_{10} -mode solution. Coupling between the cavity results into frequency splitting $\Delta\omega$ of the supermodes as shown in Fig. 4-5(b). This also results into a shift $\delta\omega$ in the mean supermode frequency and is known as CIFS.

Fig. 4-4: Through and drop port spectra of series coupled triple ring resonators without any post fabrication spectral trimming (micro heater voltages set to zero)

The CIFS in series coupled resonators can be positive or negative depending upon which is the dominant contributing factors such as, index perturbation, mode non-orthogonality and mode field distortion[156]. Through port notch response are seen to be distorted too much, with asymmetric notch peaks. The spectrum shown in Fig. 4-4 (d) is found to be symmetric in their response and exhibiting a flat-top spectrum for the drop port. In that particular spectrum, the through port extinction is found to be higher and drop loss is observed to be very low, showing a reduced CIFS effect in the structure. The frequency distortion due to CIFS can be compensated in a series coupled resonator through an effective refractive index change in the cavities or through slight variation in the cavity geometry. Not all the cavities may need to be compensated in their resonant frequency to achieve an ideal filter response. The condition for a flat-top spectral response in a series coupled ring resonator as given by Eqn (4.6), $K_m^2 = \frac{K^4}{8}$ suggests that the cavities directly coupled to the bus waveguides are more affected by the CIFS, because CIFS is higher for strongly coupled waveguides.

Fig. 4-5: (a) Coupled dielectric resonator system (b) frequency splitting and CIFS vs. resonator spacing[adapted from[156]

The cavities are subjected to refractive index changes through the applied TO perturbation to compensate for any of the CIFS effect present in the structure. Initially each individual rings are subjected to thermal perturbation and the spectral response is observed. No spectral recovery has been observed through this approach. After this, two ring combinations are subjected to thermal perturbation. Fig. 4-6 shows one of the CIFS recovered ideal filter responses in a series coupled triple ring resonator together with their original spectrum, with an applied detuning power of 4 mW on rings ($g=260$ nm, $g_m=440$ nm). Here, the rings R1 and R3 are subjected to a positive refractive index change through an applied electrical power of 4 mW over their respective micro heater.

Fig. 4-6: Resonant spectra of series coupled triple ring resonator filter before and after CIFS compensation.

From the Fig. 4-7 it can be seen that after the CIFS compensation, the through port notch response has regained their spectral shape and the extinction at through port is increased from 7.5 dB to 16 dB.

Fig. 4-7: Resonant spectrum of the series coupled triple ring resonator showing the extinction ratios at through and drop port ($g=260$ nm, $g_m=440$ nm).

The drop port spectrum has become maximally flat-top and drop loss is reduced to a low value (~ 0.5 dB) in the filter. The drop port spectrum has an out of band rejection ratio of 30 dB, 3 dB bandwidth of 1.4 nm and channel selectivity $S=B_{-1}/B_{-10}=0.6$.

4.4. Optimal detuning combinations in a series coupled triple ring resonator as a TO-WSS

The proposed series configuration in MRR with optimised micro heaters on top of each resonator is suitable for a TO-WSS application through individual control of resonant wavelength inside it. For such a WSS, an OFF state in the WSS should provide a highest channel extinction, lowest switching cross talk and low loss of OFF state through the applied micro heater driving voltage.

Fig. 4-8(a) and Fig. 4-8(b) shows the typical ON / OFF spectral response of a series coupled triple MRR TO-WSS at their drop and through port, respectively. The ON state should have a narrow band flat top spectrum with highest channel isolation. The OFF state of the WSS should have high channel extinction at both through and

drop port, while achieving a low switching cross talk in the drop port. Also, for an optimal OFF state in the WSS the loss of OFF state at the through port should be a minimum. Thermal interference corresponds to the shift in wavelength of drop port spectrum with the applied detuning voltage.

Fig. 4-8: Typical ON/OFF response of a series coupled triple MRR TO-WSS at their (a) drop and (b) through port, defining important parameters such as extinction ratio, switching cross talk, thermal interference and loss of OFF state.

Here, the OFF state in the WSS is achieved by shifting the resonant wavelength of one or more ring resonators through the applied TO perturbation. The same experimental setup which is explained in Fig. 3-6 is used to characterize the WSS. The microscope image of the series coupled TO-WSS and photograph of the device under test is shown in Fig. 4-9. The amount of spectral shift in the WSS should be greater than the bandwidth of drop channel to get a higher channel extinction for the OFF state. Considering the bandwidth of the dropped spectrum (~ 1.4 nm) and thermal tunability in the structure (~ 0.2 nm/mW), an electrical power higher than 10 mW would be sufficient for an OFF state in the WSS. Two sets of detuned OFF state in the WSS is analyzed through the applied electric powers $P_1 = 27$ mW ($V = 9$ V, $I = 3$ mA) and $P_2 = 48$ mW (12 V, $I = 4$ mA).

<i>Number of detuned MRR</i>	<i>Combination of micro rings</i>	<i>Label of detuning combination</i>
1	R1	1-1
	R2	1-2
	R3	1-3
2	R1,R2	2-12
	R1,R3	2-13
	R2,R3	2-23

Table 4-1: Detuning combinations of series coupled triple ring resonator WSS

Using the different combinations of the ring resonators which are possible in the WSS an OFF state in the WSS should be achieved through any one of the combination which are explained in Table 4-1. The label of detuning combination shows the number of detuned rings and their labels. For example, 2-13 shows the OFF state achieved in the WSS through electric power applied on two ring resonators R1 and R3.

Fig. 4-9: Microscope image and photograph of the experimental set up of a series coupled triple ring resonator TO-WSS

Fig. 4-10(a)-(f) and Fig. 4-10(g)-(l) shows the respective detuned spectra of the TO-WSS for the aforementioned detuning combinations for the applied two micro heater driving powers $P_1=27$ mW and $P_2=48$ mW. The observed spectral features such as drop port channel extinction, switching cross talk and loss of OFF state at through port are shown in Table 4-2. It is observed that, a TO-WSS using a series coupled triple ring resonators can go into an effective OFF state through only a selected detuning combinations. Most of the detuned OFF state has considerable amount of switching cross talk and loss of OFF state present in the spectrum. The detuned OFF states 1-2 and 2-13 are observed to be symmetric to each other and the OFF state spectra is characterized by spectral splitting effect, making these combinations not suitable for an effective OFF state.

Fig. 4-10: Detuned through/drop spectra of TO-WSS together with their original drop(green)/through(blue)spectrum for different detuning combinations (a)1-1 (b)1-2 (c)1-3(d)2-12 (e)2-13 (f)2-23 for detuning power $P_1=27$ mW and (g)1-1 (h)1-2 (i)1-3(j)2-12 (k)2-13 (l)2-23 for detuning power $P_2=48$ mW.

It is observed that detuning a single ring adjacent to input line waveguide is more effective in achieving an OFF state with higher channel extinction, lower switching cross talk and lower loss of OFF state. A channel extinction of 22 dB, a switching cross talk of -30 dB and zero loss of OFF state is achieved through the single ring resonance detuning with a switching power 48 mW. An equivalent OFF state is achieved through detuning two rings adjacent to the drop waveguide, detuning combination 2-23, requiring lesser switching power. A drop port channel extinction of 30 dB, switching cross talk of -10 dB and zero loss of OFF state is observed for this double ring resonance detuning requiring a switching power of 27 mW. The double ring resonance detuning is characterized by higher channel extinction at lower switching power. However, when compared to single resonance detuning, the double ring detuning has higher switching cross talk in the spectrum. A channel switching cross talk of -10 dB is observed for double ring detuned OFF state [Fig. 4-10(l)], which is 20 dB higher than that of single ring detuned OFF state.

<i>Label of detuning combination</i>	<i>Channel extinction at drop port(dB)</i>		<i>Switching cross talk (dB)</i>		<i>Loss of OFF state at through port (dB)</i>	
	P1	P2	P1	P2	P1	P2
1-1	11.8	22	-23	-30	4	0
1-2	7.8	6.4	-3	-0.5	7	6
1-3	12.8	18	-25	-28	6	4
2-12	26	30	-10	-10	4	4
2-13	0	30	-4	-2	12	7
2-23	26	30	-10	-10	0	0

Table 4-2: Spectral parameters of the TO-WSS OFF State for different detuning combinations with applied detuning power P1=27 mW and P2=48 mW.

The variations in the spectral features for different detuning combinations is plotted in

Fig. 4-11, highlighting two optimal detuning combinations 1-1 and 2-23 in dotted circles.

Fig. 4-11: Variations in drop port channel extinction, switching cross talk and loss of OFF state with respect to different ring resonator detuning combinations at micro heater driving power 48mW.

4.5. Parallel coupled triple micro ring resonator

Coupled micro ring resonators can be also be achieved through a parallel combinations to obtain a maximally flat transfer function. In the case of a series coupled ring all the rings should be in the same resonance condition to achieve a desired drop spectrum. Since the signal has to travel through all the rings in series, a small deviation in the structure feature or effective refractive index will distort the dropped spectrum completely. In a parallel combination, ring resonators are arranged in a periodic grating format with each ring acting as a reflection element. Fig. 4-12 shows the schematic of the parallel coupled micro ring resonator and their respective coupled matrix representation. The response of the drop spectrum is strongly dependent on the phase relationship between the signals which are reflected from each ring resonator.

Since the structure acts in a distributed format the signals are less susceptible to fabrication imperfections.

Fig. 4-12: Schematic of a parallel coupled triple ring resonator and their coupled matrix representation

The transfer function of the parallel coupled triple ring resonator can be obtained through transfer matrix method. As shown in Fig. 4-12(b), whole system can be represented with their respective input and output fields given to the transfer matrix representation of the individual rings [157].

$$\begin{bmatrix} A_1 \\ B_1 \end{bmatrix} = T1 * T_\phi * T2 * T_\phi * T3 \begin{bmatrix} C_3 \\ D_3 \end{bmatrix} \quad (4.8)$$

Where $T1$, $T2$, $T3$ are the transfer matrix of ring resonators $R1$, $R2$ and $R3$, respectively. The matrix element T_ϕ represents the transfer matrix of the bus waveguide between the rings.

The transfer function of a single ring can be represented as follows

$$T1 = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \quad (4.9)$$

The matrix terms are explained as below

$$T_{11} = \frac{1 - \tau_1 \tau_2 a_r^2 e^{-j\Delta\omega t_r}}{\tau_1 - \tau_2 a_r^2 e^{-j\Delta\omega t_r}} \quad (4.10)$$

$$T_{12} = -T_{21} = \frac{K_1 K_2 a_r^2 e^{-j\Delta\omega t_r / 2}}{\tau_1 - \tau_2 a_r^2 e^{-j\Delta\omega t_r}} \quad (4.11)$$

$$T_{22} = \frac{\tau_1 \tau_2 - a_r^2 e^{-j\Delta\omega t_r}}{\tau_1 - \tau_2 a_r^2 e^{-j\Delta\omega t_r}} \quad (4.12)$$

K_1 and K_2 are the coupling coefficients of a single ring resonator at the input and output couplers, respectively. The respective transmission coefficients are $\tau_1 = 1 - K_1^2$ and $\tau_2 = 1 - K_2^2$. The term $a_r^2 = \exp(-\alpha\pi R)$ is the loss inside the ring for one round trip.

$\Delta\omega = \omega - \omega_r$ and ω_r is the resonant frequency. The term t_r represents the round trip time inside the ring, $t_r = 2\pi n_r R / c$ with n_r , the effective refractive index inside the ring.

The transfer matrix of the bus waveguide is represented as below.

$$T_\phi = \begin{bmatrix} e^{j\beta_b \Lambda} & 0 \\ 0 & e^{-j\beta_b \Lambda} \end{bmatrix} \quad (4.13)$$

Where β_b is the propagation constant inside the bus waveguide.

A synthesis techniques for parallel coupled micro ring resonators is given through the modification of a classic method used for the synthesis of microwave stop-band filters, to achieve a maximally flat top spectral behaviour[158]. For a constructive interference to occur between the reflected waves from each resonator, the separation between the rings Λ should be an odd multiple of quarter wavelength[159] i.e.

$$\Lambda = (2M + 1) \frac{\lambda_r}{4n_b} \quad (4.14)$$

Where n_b is the effective index of the bus waveguide. λ_r is the resonance wavelength and $M=0,1,2,\dots$

Inorder to get a flat and deepened rejection level, a condition, $2\pi R = 2\Lambda$, should be assumed[159].

4.5.1. Parallel coupled triple ring resonator-Experimental result

Parallel coupled silicon micro ring resonators are fabricated on an SOI wafer through the same process flow as explained in section 3.4. The design consideration was to assign a proper ring separation to reduce the Fabry-Perot interference effect in the spectrum and to vary the ring-bus coupling gaps to obtain different channel bandwidths. Considering the ring radius as 10 μm , the separation between rings is set as $\Lambda = \pi R = 31.4 \mu m$. Parallel coupled resonators were fabricated through same fabrication procedure as explained in section 3.4. One of the micro scope images of the fabricated parallel coupled ring resonator is shown in Fig. 4-13. The obtained spectral response without any cavity detuning applied on the ring resonators are shown in Fig. 4-14 and various spectral parameters of the spectrum is tabulated in Table 4-3.

The spectral response is characterized by high channel selectivity (~ 0.7) and a very low drop loss (0.07 dB) when compared to a series coupled resonator. However, the spectral response of the parallel coupled triple ring resonator has side lobes present in their stop band [Fig. 4-14]. This effect is due to the periodicity in the wavelength characteristics of the parallel coupled resonators, leading to the interference effect with the delay loop present in the structure, similar to that of a Mach–Zehnder interferometer.

Fig. 4-13: Microscope image of the fabricated parallel coupled micro ring resonator with micro heaters on the top

Fig. 4-14: Through /Drop port spectrum of parallel coupled ring resonator with ring-bus coupling gaps (a) 400 nm and (b) 350 nm

The spectral detuning is done on the ring resonators through different applied voltages, and no improvement in the spectral shape is observed. The spectral interference effect and distortions in the drop channels is undesirable for a channel dropping or WSS application. The side peaks present with dropped channels limit the operating bandwidth of the filter due to channel cross talk. As such parallel configurations are mainly applied for increasing the through port extinctions in a multistage ring configurations as reported in[149]. However, a parallel coupled ring configuration would find following advantages when compared with a series coupled configuration

1. High power transference is possible even if all the rings are not in resonance.
2. The spectral shape is dependent on the phase relationship between the ring

resonators as opposed to the coupling strength between the rings. This is evident from the experimental result as undisturbed spectral shape under various micro heater driving voltages.

3. Higher through port channel extinction can be achieved without post fabrication channel trimming.

A comparison of spectral parameters between series and parallel coupled triple ring resonator is given in Table 4-3

Configuration	Drop port channel isolation	Through port channel extinction	Drop loss	Channel selectivity, $S = (\Delta\lambda)_{-1dB} / (\Delta\lambda)_{-10dB}$
<i>Series</i>	30 dB	7.5 dB	2.3 dB	0.62
<i>Parallel</i>	20 dB	15 dB	0.07 dB	0.7

Table 4-3: various spectral parameters of series and parallel coupled micro ring resonator

4.6. Summary

Series coupled triple micro ring resonators have been demonstrated as TO-WSS on an SOI platform. The thermal perturbations applied on the MRRs to compensate for the Coupling Induced Frequency Shift (CIFS) allowed a filter response with telecom grade spectral features with a maximally flat-top spectrum. The WSS with an out of band rejection ratio >30 dB, 3 dB bandwidth <1.4 nm, pass band ripple < 0.3 dB and drop loss of 0.5 dB has been obtained through the optimized design and fabrication. The individual resonators have been subjected to resonance detuning through the applied micro heater driving powers to analyze the switching characteristics in the WSS. Among the possible detuning ring combinations analyzed, detuning a single ring adjacent to input bus-waveguide and two rings adjacent to drop line waveguide are

observed to be more effective for an OFF state with high channel extinction, low switching cross talk and low loss of OFF state. A maximum channel extinction of 22 dB, lowest switching cross talk -30 dB and a zero loss of OFF state has been achieved with a single ring detuned OFF state using a switching power of 48 mW. An equivalent amount of channel extinction with a higher switching cross talk (~ -10 dB) and zero loss of OFF state is achieved through two ring resonance detuning, requiring a lesser switching power of 27 mW.

The parallel combination of ring resonators has been demonstrated as wavelength filters to achieve narrow band drop spectrum with a deep rejection level. Eventhough the filter spectra has shown spectral side peaks due to interference effects, a very low drop loss and high through port extinction is achieved in the spectrum. The spectral response has been observed to be invariant under various applied detuning micro heater driving voltages. A drop port channel isolation of -20 dB, through port channel extinction of 15 dB, drop loss 0.07 dB and a channel selectivity of 0.7 has been achieved in the device without applying any micro heater detuning voltages

Chapter 5:

Phase shifted vertical side wall grating resonant transmission filter

In this chapter Silicon-on-insulator (SOI) based phase shifted vertical side wall grating is presented as a resonant transmission filter suitable for dense wavelength division multiplexing (DWDM) communication channels with 100GHz channel spacing. The fabrication and characterisation results of these grating structures are also presented at the end of the chapter.

Part of this chapter has been published as

1. "P. Prabhathan, V. M. Murukeshan, Zhang Jing, and Pamidighantam V. Ramana, "Broadband tunable band pass filters using phase shifted vertical side wall grating in a sub micrometer silicon-on-insulator waveguide," **Appl. Opt.** 48, 5598-5603 (2009).
2. P. Prabhathan, V. M. Murukeshan and Zhang Jing, "Compact resonant Bragg-grating filters using submicron silicon-on-insulator(SOI) waveguide for optical communication network", **Proc. SPIE** 7847, 78470H (2010)

5.1. Introduction.

Among the many planar waveguide devices used for wavelength filtering functionality a Bragg grating based filter is characterized by its unique advantage of available wide free spectral range and flexibility in wavelength selection. Mainly two kinds of waveguide corrugations can lead to a Bragg grating structure in a waveguide. In one case the corrugations are made on the surface of the waveguide as shown in Fig. 5-1.

Fig. 5-1: Waveguide surface corrugated Bragg gratings[98]

A uniform Bragg gratings fabricated on the top surface of a waveguide as shown in Fig. 5-1 should have a high uniformity low refractive index modulation and large number of grating periods to get a narrow band reflection with a high reflectivity [98]. Here the effective refractive index of the grating is highly dependent on the grating depth and which will put more efforts on the fabrication procedure to get a uniform gratings. Moreover, multiple lithographic steps are needed to achieve the grating pattern on the top surface of the waveguide. Since this kind of gratings are usually fabricated on a wide waveguide the waveguide cross section should be designed in such a way that a single mode condition is met in the waveguide[122]. Another waveguide corrugation which can lead to a Bragg gratings effect in a waveguide is a vertical side wall grating as shown in Fig. 5-2.

Fig. 5-2: Waveguide vertical side wall Bragg gratings

The Bragg gratings on the side wall of a waveguide is easy to fabricate in a single lithographic step and the effective refractive index of the grating which is dependent on the lateral waveguide widths can be easily controlled in the lithographic step[160, 161]. Since the gratings can be applied on a strip waveguide, it is easy to satisfy the single mode propagation in these waveguide gratings. This gratings have been used to demonstrate Optical Add Drop Multiplexer (OADM) and tunable filter [162, 163]. This waveguide vertical sidewall gratings can be converted into a resonant filter through a phase shift applied in one section of the gratings[18, 164]. However, the spectral response in the gratings has to be further improved to make it more suitable for an optical communication network with a DWDM technology.

In this context, this chapter presents the design, theoretical analysis, numerical simulation, fabrication and characterization of a phase shifted vertical side wall grating in a submicron SOI waveguide as a resonant transmission filter suitable for DWDM systems with 100 GHz channel spacing to achieve good spectral features, such as high free spectral range, narrow band width, high transmittivity, high selectivity and a flat-top spectrum.

5.2. Vertical side wall gratings in a single mode submicron SOI strip waveguide

Unlike the rib waveguide in SOI, the strip waveguide should have a cross sectional dimension less than 1 μm to suppress the higher order modes. A general expression of $W \times H < 0.13 \mu\text{m}^2$ has been proposed for the single mode condition of a strip waveguide[121]. Where, W and H are the width and height of the waveguide, respectively [Fig. 5.2(a)]. It has been shown that a strip waveguide with an air cladding and height of 300 nm will be necessarily single mode when its width is set

between 400 nm to 600 nm for TE wave propagation[131]. Here, the single mode condition in a submicron SOI waveguide has been analyzed using a 3-D Beam Propagation Method (BPM) mode solver[165] for various waveguide cross sections. Fig. 5-3 shows the critical cross sectional dimension requirements in a silicon strip waveguide (with oxide cladding layer) for single mode propagation. It has been observed that TM polarization exhibits stringent dimensional requirements for its single mode condition.

Fig. 5-3: Critical cross sectional dimension requirement for SOI strip waveguide for a single mode propagation

The cross sectional view of one of the SOI single mode strip waveguides and its TE mode field distributions are shown in Fig. 5-4 (a) and Fig. 5-4 (b), respectively. A periodic refractive index modulation can be applied on to this waveguide by periodic corrugation along the side wall of the waveguide. The amount of effective refractive index modulation along the waveguide is determined by the amount of corrugation

depth and refractive index contrast between the core and cladding. Fig. 5-5 shows the schematic of a vertical side wall gratings (top side view) with all its grating parameters explained. Where, Z is the direction of propagation of input light.

Fig. 5-4: (a) Cross section (X-Y Plane) view of single mode silicon strip waveguide in SOI wafer (b) Field distribution of fundamental TE mode.

W is the width of the grating, ΔW is the grating depth and Λ is the pitch of the gratings. The structure can give a good Bragg reflection if each section of the grating acts like a weak reflector for the incident light. The length of each grating pitch Λ should be such that all the reflected waves from each period interfere constructively for a particular wavelength, so that all the input light at this wavelength will be efficiently reflected back. This condition is known as the Bragg condition and the reflected wavelength is known as the Bragg wavelength, λ_B .

Fig. 5-5: The schematic diagram of a vertical side wall grating.

Here, the grating lengths l_g and l_w are related by the Bragg condition as

$$l_g n_1 + l_w n_2 = \frac{m \lambda_B}{2} \quad (5.1)$$

Where, n_1 and n_2 are the effective indices of the waveguide at λ_B in the grating region and waveguide region, respectively. The term, m is the order of the grating.

The characteristics of a Bragg grating is essentially defined by its grating constant (K). The constant K of a grating is defined as the reflectivity of the gratings per unit length of the gratings. The parameters which defines K of a Bragg gratings are its grating depth (ΔW), waveguide (W) width, and refractive index contrast. For a uniform gratings K is made constant throughout the gratings. An apodization can be done on the gratings through the variations in K at the waveguide gratings ends inorder to achieve improved filter response from the gratings [160, 161]. Inverse of the K , defined as Bragg length L_B is an interesting parameter for the gratings which gives the length of the gratings for 100% reflectivity.

The grating constant (K) for a TE wave propagation through this grating is given by [166].

$$K = \Gamma \left[\frac{\pi}{\lambda} \frac{\Delta W}{W_{eff}} \frac{n_s^2 - n^2}{nq} \right] \left[\frac{n^2}{n_s^2} - \frac{n^2}{n_{Clad}^2} + 1 \right] \quad (5.2)$$

Where, Γ is the fraction of power confined within the waveguide. For a TE polarized wave it is ~85% [167, 168]

$$q \equiv \left(\frac{n}{n_s} \right)^2 + \left(\frac{n}{n_{Clad}} \right)^2 - 1, W_{eff} \equiv W + \frac{2}{q\gamma} \quad \gamma \equiv \sqrt{(\beta^2 - k^2 n_{clad}^2)}, \text{ and } n \equiv \frac{\beta}{k}.$$

Fig. 5-6 shows the variation in Grating constant (K) and Bragg length ($L_B = 1 / K$) with respect to the grating depth (ΔW) for various waveguide widths (W).

Fig. 5-6: The variation of grating constant (K) and Bragg length (L_B) with respect to the grating depth dW for different waveguide widths. (a) $W=300$ nm (b) $W=400$ nm (c) $W=500$ nm (d) $W=600$ nm.

The graph shows a linear variation in K with respect to grating depth. From Eqn (5.2) it is clear that for a high index contrast waveguide gratings with side wall corrugations, the waveguide width should be shorter to get a stronger gratings [Fig. 5-7].

Fig. 5-7: Grating constant (K) variation with respect to the waveguide width (W)

The waveguide gratings are simulated using 2-D Finite Difference Time Domain (FDTD) method [165] for Transverse Electrical (TE) wave propagation. Unless otherwise mentioned the entire device simulations in the following sections are done for TE polarization. Fields polarized in the plane of the device are termed as TE polarized, and the field polarized perpendicular to the device surface is termed as TM polarized. Usually a high index contrast waveguide support modes with hybrid polarization. This means the modes supported by a waveguide are not necessarily pure TE or TM modes. They are quasi-TE or quasi-TM modes. These kinds of modes are referred as TE or TM modes in this chapter. Since a silicon waveguide is highly polarization dependent, methods such as polarization diversity circuit[147] should be used to eliminate the polarization dependency. Since the waveguide thickness is very small and there is no structural variation in the Y-direction uniformly over X-Z plane, the structure can be analyzed as a 2-D device without losing much generality. In order to get an exact Bragg wavelength in the simulation the effective index in 2-D simulation is set to a value that obtained from the 3-D Beam Propagation Method (BPM) mode solver. Since a 3-D simulation needs a long running time, one simulation in 3-D is done initially and compared with the 2-D simulation to get a generalized input parameters for the simulation consistency. 3-D simulation required two and half days (~60 hrs) for its completion using a PC with Intel core 2 duo CPU @2.2GHz having a memory capacity 8GB. Except a slightly lower band rejection (~5 dB difference) observed for 3-D simulation, all other spectral features were similar for both 3-D and 2-D simulation. Assuming a silicon substrate, the refractive indices of the core and cladding were set $n_{Si} = 3.467$ and $n_{Clad} = 1$ (air). The effective indices n_1 and n_2 were calculated as 2.2526 and 2.5398 through BPM mode propagation.

From Eqn (5.1) the grating lengths l_g and l_w is obtained as $l_g = 161.5nm$ and $l_w = 161.5nm$ for a Bragg wavelength $1.55 \mu m$ and a duty cycle ($D=l_w/\Lambda = 50\%$). With these values, the grating period is calculated as $\Lambda = l_g + l_w = 323nm$. The waveguide width (W) was same along the Z -direction and the gratings are introduced by corrugating the waveguide with a dimension ΔW towards the axis of the waveguide. Typical simulation window dimension used were $20 \mu m$ (propagation direction) by $5 \mu m$ (transverse direction). A mesh grid size of $\Delta x = 5nm$, $\Delta z = 5nm$ and time step size of $\Delta t = 1.2 \times 10^{-17} s$ were used in the simulation. The time step is based on Courant condition, $\Delta t \leq 1/(c\sqrt{1/(\Delta x)^2 + 1/(\Delta z)^2})$.

Fig. 5-8: Simulated field intensity distribution in the X-Z plane and reflectivity spectrum of waveguide vertical side wall grating of lengths (a) $L=10\Lambda$ and (b) $L=36\Lambda$. (c) $L=65\Lambda$.

The input source was a Gaussian modulated continuous wave in TE polarization at a wavelength of 1.55 μm having a spectral bandwidth of 281 nm. Two observation points, one behind the input plane and other at the end of the waveguide, are used to get the spectral properties of reflected and transmitted waves, respectively. Some of the simulated field intensity distribution and reflectivity spectra obtained are shown in Fig. 5-8. The spectral response suggests that the grating has a high reflectivity with a short grating length. The wide reflection band corresponds to the wavelength range of 1500 nm to 1600 nm, which is the common wavelength window used for optical communication. Variation in grating reflectivity and reflection band width is analyzed for different grating lengths and is plotted in Fig. 5-9. Saturation in the reflectivity of the grating is observed after certain grating length. The maximum reflectivity observed is $\sim 95\%$. This is due to the power loss inside the gratings and this might be due to the scattering loss or mode coupling loss inside the gratings.

Fig. 5-9: Grating reflectivity and band width variation with respect to grating length

5.3. Phase shifted vertical side wall grating as a resonant cavity filter

A phase shifted grating has a phase jump at one section of the grating. Here the phase shift is introduced by altering the dimension of one of the grating pitches so that the reflected wave from that section suffers an out of phase with respect to the other reflected waves. Fig. 5-10 illustrates the structure of a phase shifted vertical side wall grating with a quarter wave phase shift at the centre of the grating.

Fig. 5-10: Schematic diagram of the waveguide gratings showing various grating parameters.

The defect layer dimension for a quarter wave phase shift is calculated as, $\Lambda_p = \lambda / (4n_2) = 0.1526 \mu\text{m}$, where $\lambda = 1550 \text{ nm}$, and $n_2 = 2.5398$. The length of the defect region will be termed as phase shift length in the forthcoming sections.

Fig. 5-11(a) and Fig. 5-11(b) shows the transmission / reflection spectrum and the field intensity distribution (X-Z plane) obtained for a gratings with $W=400 \text{ nm}$, $\Delta W=80 \text{ nm}$, $L= 27\Lambda$ and $D= 60 \%$, respectively. The spectrum has shown a sharp

resonant transmission peak and a reflection dip exactly at the centre of the stop band verifying the magnitude of the quarter wave phase shift used in the simulation. The resonant wavelength (λ_r) is observed to be at 1547.6 nm from the spectrum. Fig. 5-11(c) shows the transmission spectrum in dB showing Full Width at Half Maximum (FWHM) or 3dB bandwidth ($\Delta\lambda_{3dB}$) of the transmission peak, which is observed as 0.26 nm for the simulated gratings. The observed results suggest that the phase shifted vertical side wall gratings in a silicon strip waveguide has a resonant behaviour and the gratings can be applied as a band pass filter having high free spectral range.

Fig. 5-11: (a) Reflection/transmission spectrum (normalized with the input) of the waveguide grating. (Inset shows the magnified transmission peak at the centre of stop band). (b) Field intensity distribution (X-Z plane view) (c) Transmittivity in dB showing the 3 dB bandwidth.

5.4. Grating parameters to get a narrow band resonant transmission (High Q -factor) with high transmittivity

The high Q - factor ($Q = \lambda_r / \Delta\lambda_{3dB}$) is dependent on a number of factors such as grating depth, grating duty cycle and grating length (L_{out}) on each side of the phase shift. The transmittivity on the other hand is dependent on the loss inside the cavity, which in turn can be minimised by optimising the grating parameters. The following section describes how the transmission bandwidth (or cavity Q) and the transmittivity of the resonant transmission peak varies with respect to various grating parameters.

Fig. 5-12: Variation in the 3dB bandwidth ($\Delta\lambda_{3dB}$) and loss (L) inside grating with respect to (a) Duty cycle, D and (b) grating depth, ΔW for a fixed L_{out}

The effect of variation in grating duty cycle(D) and grating depth(ΔW) on the resonant spectrum is shown in Fig. 5-12(a) and Fig. 5-12(b), respectively. The band width is observed to be narrower when the D is kept between 50% and 70 %. With an increase in ΔW the 3dB band width($\Delta\lambda_{3dB}$) is observed to be decreasing. On the other hand, the transmittivity of the peak is dependent on the loss inside the cavity and the length of the gratings. A low loss is observed inside the cavity for a higher value in D and a smaller ΔW , for a fixed length of the grating. The loss inside the structure is the part of the power which is not being detected outside and is calculated as $L=1-(T+R)$. Where, R and T are the reflectivity and transmittivity at the resonant wavelength [please see Fig. 5-11(a) inset]. The reduced loss can be attributed to reduction in scattering loss or mode mismatch loss inside the gratings. This can be explained using the filling factor (ff) of the grating. The ff is defined as the percentage of air gap in a period of the grating and is given by $ff = 2\Delta W(\Lambda - l_w) / (W.\Lambda)$ [169]. An increase in D or decrease in ΔW will reduce the ff resulting into a lesser air gap per grating pitch. This in turn increases the effective index per grating pitch and hence reducing the mode mismatch loss.

The variation with respect to grating length $L_{out} = N\Lambda$ shows that a longer grating can give a narrow band width but at the expense of transmittivity. With a fixed grating $D= 60\%$ and $\Delta W=80\text{ nm}$ L_{out} is varied to study the spectral behaviour. The superimposed transmission spectrum as shown in Fig. 5-13(a) shows that band width decreases with an increase in L_{out} but with a reduced transmittivity. The variation in $\Delta\lambda_{3dB}$ and transmittivity (T) is plotted in Fig. 5-13(b). It can be seen that beyond certain grating length (here $L_{out}=30\Lambda$) the band width is constant but transmission suddenly reducing to lower values. These observations in the spectral behaviour suggests that, to obtain a narrow band width in the resonant transmission with a

reasonably high transmittivity there should be a compromise in the design of the gratings between the parameters L_{out} and ΔW . To get a compact design, the grating length is made shorter and band width is made narrow by through a high ΔW . After this, the transmittivity can be further optimised by adjusting the grating length.

Fig. 5-13: (a) Resonant transmission spectrum for various L_{out} (d) Variation in 3 dB bandwidth ($\Delta\lambda_{3dB}$) and transmittivity (T) with L_{out}

For a strip waveguide having a width of 400 nm, a maximum value $\Delta W = 150$ nm can give a compact structure, without having a problem in the fabrication and etching procedure. The transmission spectrum behaviour of the grating with etch depth $\Delta W = 150$ nm, for a grating length between 9Λ and 14Λ is shown in Fig. 5-14. An

exponential variation in band width and transmittivity is observed between these two grating lengths. The grating length $L_{out} = 14\Lambda$ shows a band width of 0.11 nm ($Q=13,265$) with a transmittivity of 42.7%. For a higher transmission in the resonant spectrum, a grating length $L_{out} = 12\Lambda$ can be used with a band width and transmittivity of 0.17 nm ($Q= 8584$) and 85 %, respectively.

Fig. 5-14: The transmission spectrum of a phase shifted grating with $\Delta W = 150$ nm, for different L_{out}

5.5. Channel tunability using the vertical side wall grating filter

Shift in the resonance wavelength is observed with respect to the variation in phase shift length. With respect to the designed quarter wavelength phase shift length of the gratings $\Lambda_p = 153$ nm, the phase shifted dimension is varied in steps of 5 nm above and below this value. Fig. 5-15(a) shows the superimposed transmission spectra for these phase shifted gratings with phase shift length from 138 nm to 173 nm. A grating with grating parameters such as, $W=400$ nm, $\Delta W=80$ nm, $L= 27\Lambda$ and $D= 60$ % has been used in the simulation. A linear variation in resonant wavelength is observed with respect to the change in phase shift length [Fig. 5-15(b)]. For an increase in phase

shift length, the resonance has been shifted to a higher wavelength region and for a decrease in phase shift length the resonance has been shifted to the lower wavelength region. It is also observed that the resonant spectrum is highly sensitive to the dimensional variation in phase shifted region. The resonant spectrum can be shifted through 0.465 nm through a unit variation in phase shift length. This in effect will impose stringent fabrication requirements on the waveguide grating resonators to obtain a desired spectral response. The band width of the resonant wavelength is observed to be invariant with respect to the variation in phase shift length as far as the variation is around the quarter wavelength value [Fig. 5-15(c)].

Fig. 5-15: (a) superimposed transmission spectra for different phase shift lengths (Inset showing the magnified centre region). Variation in (b) λ_r and (c) $\Delta\lambda_{3dB}$ with respect to Δp .

The variation in resonant band width for higher value phase shift length is due to the band edge effect on the resonant peak. It is also observed that a phase shift length

value between 100 nm and 208 nm keeps resonant peak bandwidth less than 0.4 nm for the particular grating design under consideration.

Apart from the length variation in phase shifted region, resonant transmission is also sensitive to effective refractive index variation inside the phase shifted region. The resonant transmission has shown a linear variation with respect to the effective refractive index variation inside the phase shifted region [See Fig. 5-16]. The observed shift in wavelength ($\partial\lambda/\partial n_{eff}$) = 533 nm suggests the possibility for wavelength tunability in the grating resonant filter through a thermo-optic effect or a carrier injection based plasma dispersion effect.

Fig. 5-16: Variation in resonant transmission with respect to the effective index variation inside the phase shifted region

5.6. Spectral shape and channel selectivity improvement in the grating resonant filter

Additional phase shifts has been applied inside the grating resonators to observe the multiple cavity resonance effect. This has been lead to an improved spectral response by grating resonators in terms of channel selectivity and spectral shape. With two grating cavities having equal phase shift length and grating strength, the Lorentzian

shape of a Single Phase shifted Grating (SPG) has been converted into a Gaussian shape. Fig. 5-17(a) shows the schematic diagram of Double Phase shifted Grating (DPG) filter and the superimposed transmission spectrum of an SPG and DPG filters for different grating length conditions. A unity transmission is observed for DPG filter for a critical condition of $k=1$. Where k is defined by the relation $k=2L_{out}/L_{in}$

Fig. 5-17: a) Schematic diagram of a DPG filter .b) Transmission spectrum of an SPG filter and DPG filter for different grating lengths conditions, where $k=2L_{out}/L_{in}$. ($W=500$ nm, $\Lambda=312.4$ nm, $\Delta W=110$ nm, $D=50\%$)

The resonance inside this multiple phase shifted grating resonators is observed to be highly sensitive to the dimensional variation inside the structure. With the addition or deletion of a single grating pitch inside the grating resonator the resonant transmission is decreased considerably. The spectral responses at these conditions, ($k<1$) and ($k>1$), are shown in Fig. 5-17(b). This effect is due to the resonant wavelength mismatch between the two grating resonant cavities when there is a tunnelling from one cavity to the other. It is observed that this effect is stronger for a resonator with higher grating strength. As we have seen in the earlier sections, the transmission of a stronger grating is always narrower than that of a weaker grating.

This has lead to stringent requirements on the grating resonators to make the two resonances from two cavities match each other. For a weaker grating the spectrum has shown resonance splitting, exhibiting two peaks for ($k<1$) and ($k>1$) conditions.

Three cavity resonance oscillations is obtained by properly placing three phase shifts in the gratings to make it a Three Phase Shifted Grating (TPG). A better roll-off and out of band rejection are obtained by doing this [Fig. 5-18.].

Fig. 5-18: a) Schematic diagram of the TPG filter. b) Resonant transmission for different grating length conditions, where $k=2L_{out}/L_{in}$. ($W=500$ nm, $\Lambda=312.4$ nm, $\Delta W=110$ nm, $D=50\%$)

No resonant transmission is obtained when a stronger gratings is used in the simulation. As mentioned in the previous section, it is difficult to make three cavities in resonance for a narrow band resonant wavelength. Even though the spectral shape has improved in this TPG resonant filter, the top of the spectrum has shown large ripples as seen in the Fig. 5-18(b) ($k=1$). This distortion is attributed to the Coupling Induced Frequency Shift (CIFS) when the tunnelling happens from one cavity to the other. The effective refractive index variations are applied in each cavity to compensate for the frequency shift. A nearly flat-top spectrum is obtained, when the

central cavity refractive index has been increased by 2×10^{-3} . The CIFS recovered transmission spectrum which is shown in Fig. 5-18(b) ($k=1$, optimized) has a nearly flat- top spectrum having much reduced ripples. The critical condition which has been observed in a DPG filter is observed here also as $k=1$ to get a unity transmission spectrum. For the other conditions $k>1$ and $k<1$, the transmission is decreased with an increase or decrease in their bandwidth, respectively.

Table 5-1 shows a comparison of -1 dB and -10 dB band width of a SPG and DPG filter, showing the channel selectivity improvement for the multiple phase shifted gratings.

No of phase shifts	$B_{-1}(nm)$	$B_{-3}(nm)$	$B_{-10}(nm)$	$S=B_{-1}/B_{-10}$
1	0.275	0.33	1.55	0.177
2	0.275	0.32	0.6	0.45

Table 5-1: Bandwidth at -1 dB (B_{-1}), -3 dB (B_{-3}), -10 dB (B_{-10}) and selectivity (S) variation with respect to number of phase shifts.

5.7. Channel cross talk and Free Spectral Range

To get an amount of adjacent channel cross talk, the gratings are simulated for different ITU grid channel wavelengths.

Fig. 5-19: Channels 14 to 20 in a DWDM ITU grid C band with 100GHz spacing, simulated with two-phase-shifted vertical side wall grating.

The channels 14 to 20 in a DWDM ITU grid C band with 100 GHz spacing is simulated by varying the phase shift length and the obtained superimposed spectrum is shown in Fig. 5-19. The phase shift length is increased in the order of $0.0113\Lambda_p$ (Where Λ_p is the quarter wavelength phase shift length of the grating) to get a 0.8 nm wavelength shift in the resonant transmission. The adjacent channel cross talk at the peak wavelength of the channel under consideration is observed to be ~ -28 dB from the spectrum. Table 5-2 shows the comparison of the ITU grid wavelength with the simulated wavelengths and their respective grating phase shift lengths.

<i>ITU grid Channel No</i>	<i>ITU grid wavelength (nm)</i>	<i>Grating Phase Shift length</i>	<i>Grating Transmission Peak wavelength(nm)</i>
14	1566.31	$1.257 \Lambda_p$	1566.42
15	1565.50	$1.246 \Lambda_p$	1565.63
16	1564.68	$1.235 \Lambda_p$	1564.76
17	1563.86	$1.223 \Lambda_p$	1563.9
18	1563.05	$1.2113\Lambda_p$	1563.1
19	1562.23	$1.2 \Lambda_p$	1562.24
20	1561.42	$1.189 \Lambda_p$	1561.45

Table 5-2: DWDM Channel Wavelength from 14 to 20 (ITU grid C Band 100 GHz Spacing) and Simulated Grating Resonant Wavelength with Their Respective Phase Shift Lengths

The number of channels that can be demultiplexed in a DWDM system using this filter is limited by the band width of the stop band and the band width of the channel under consideration. The number of channels that can be demultiplexed using such a wavelength filter is estimated as follows. With the observed data from Fig. 5-15(c) a phase shift length between 100 nm and 208 nm can give a 3 dB band width less than 0.4 nm for the transmission. For a 100GHz DWDM communication channel, 3 dB

band width < 0.4 nm is required for a better channel isolation[5]. Thus the free spectral range of the filter, which determines the channel capacity of the filter, is strongly dependent on these phase shift length dimensions. The effective free spectral range (FSR) can be taken as the range of wavelength between these two phase shift lengths, which is calculated as (1572.7 nm- 1521 nm = 51.7 nm). This range corresponds to the channels 7 to 71 in a DWDM ITU Grid C-Band with 100 GHz spacing. The results shows that the filter can work as a demultiplexer or tunable filter in a DWDM system with a good performance parameters over a wide range of wavelength. The -1 dB band width, -3 dB band width and channel cross talk between the channels are comparable to that of a typical DWDM filter in a 100 GHz channel spaced network. Table 5-3 shows a comparison of parameters of the phase shifted vertical side wall grating filter with ITU specified values and with one of the commercially available gaussian demultiplexer.

<i>Parameters</i>	<i>ITU specifications</i>	<i>Commercial AWG-Gaussian DEMUX *</i>	<i>Phase shifted Vertical side wall grating</i>
Wavelength range	C or L band	C - Lband 1530 - 1625 nm	1521 -1572 nm
Band width@ 1dB	>30 GHz (0.24 nm)	(27.5GHz) 0.22 nm	(34.4GHz) 0.275 nm
Bandwidth@ 3dB	≤ 50 GHz (0.4 nm)	50GHz (0.4 nm)	40GHz (0.32 nm)
Adjacent channel cross talk	> 30 dB	33 dB (T)	28 dB
Non-adjacent channel cross talk	>40 dB	35 dB (T)	35 dB

*Photonic Planar Integration Technology INC. Kwangju, Korea (T-Typical)

Table 5-3: Comparison of parameters of vertical grating de-multiplexer with ITU specified values and a commercial AWG.

5.8. The observation of saturation in Q-factor of a phase shifted grating resonant cavity

Quality factor or Q -factor of a resonator is a dimensionless parameter that explains how under-damped a resonator is. In an equivalent way, the Q -factor also describes resonator's bandwidth relative to its resonant wavelength. Higher Q -factor in a resonator indicates a lower rate of energy loss relative to the stored energy in the oscillator.

Fig. 5-20: Variation in quality factor (Q), Transmission (T) and Loss (L) of the waveguide grating resonator with varying number of grating periods (N) ($W=500$ nm, $\Lambda=312.4$ nm, $\Delta W=110$ nm, $D=50\%$).

In terms of resonance band width and resonant wavelength the Q -factor can be explained with the following relation.

$$Q = \frac{\lambda_r}{\Delta\lambda_{3dB}} \quad (5.3)$$

The variation in the value of quality factor (Q), Transmission (T) and Loss (L) with number of grating periods (N) on both sides of the cavity is shown in Fig. 5-20. The variation in Q can be divided into two stages. In the first stage the variation shows an

exponential increase in the Q with respect to the increase in N . In the second stage it shows a slow variation and seems getting saturated beyond $N=35$. This type of quality factor variation is evident with a Fabry-Perot model of resonant filter, where two types of loss mechanisms are dominant in the structure. One of them is the longitudinal loss from both the grating mirrors and the other is the vertical radiation loss inside the cavity. In a Bragg grating based F-P resonant filter, longitudinal loss is a function of the grating coupling coefficient and length of the gratings on each side of the cavity. On the other hand the vertical loss is dependent on the out of plane scattering loss inside the cavity and is a result of mode coupling between resonant mode and radiation mode in the cavity. Considering these two types of loss mechanism in a 2-D model of a Bragg grating micro cavity the Q -factor can be expressed as below.

$$\frac{1}{Q} = \frac{1}{Q_l} + \frac{1}{Q_v} \quad (5.4)$$

Where, Q_l is the longitudinal quality factor of the grating resonant cavity which is a function of the grating strength, and grating length and Q_v is the vertical quality factor which is dependent on the vertical radiation loss per unit length of the grating (α). The factor Q_l is an exponential function grating mirror strength, which in turn is dependent on the grating coupling coefficient (K) and length of the grating ($L=N\Lambda$). The two quality factors are explained with the following equations[170].

$$Q_l \cong \left(\frac{\pi}{4K\Lambda} \right) \exp(2KL), \quad (5.5)$$

$$Q_v = \left(\frac{\pi}{2\alpha\Lambda} \right) \quad (5.6)$$

The reciprocal relationship of the Q - factor explains much about the variation in Q -factor with respect to two loss mechanism in the cavity. The total quality factor Q is

limited by either Q_l or Q_v depending upon which is the dominant loss mechanism inside the cavity, namely longitudinal loss or vertical loss, respectively. From Eqn (5.5) it can be seen that, one of the factors on which the Q_l depends upon is the grating coupling strength K . The grating coupling strength can be increased through an increase in ΔW or by a decrease in W . For a small N the grating mirror reflectivity will be less leading to higher longitudinal loss in the F-P resonant cavity. Therefore, for small N , longitudinal quality factor term will be much lower than the vertical quality factor. i.e., $Q_l \ll Q_v$ and from Eqn(5.4) it follows that $Q \approx Q_l$. This is implied by the exponential variation in the quality factor for small number of grating periods as shown in Fig. 5-20. With an increase in N the vertical loss inside the structure increases due to the increased out of plane scattering. However, the longitudinal loss in the structure decreases due to the increase in grating mirror reflectivity and becomes saturated after certain number of grating periods. Thus for a higher value of N , longitudinal quality factor term will be much higher than the vertical quality factor. i.e., $Q_l \gg Q_v$ and $Q \approx Q_v$. This effect is visible in Fig. 5-20 as a slow variation and saturation in the Q value after $N=35$, marked as region II. This type of variation in the Q -factor of this grating based F-P resonant filter suggests that there is a maximum value in the quality factor that can be achieved and is limited by the vertical loss inside the structure. Thus the maximum quality factor can be approximated as $Q \approx Q_v$. From Fig. 5-20 this maximum value is found to be 8×10^3 , for the particular grating dimensions considered here ($W=500$ nm, $\Lambda=312.4$ nm, $\Delta W=110$ nm, $D=50\%$) by optimizing the number of grating period (N). The Q -factor cannot be larger than Q_v , irrespective of how many grating periods are added on each side of the cavity. Thus

the design consideration should be to find an optimum grating number (N) that gives saturation in the Q -factor and then to find a method to reduce the vertical loss inside the structure. The out of plane loss inside the structure can be reduced by reducing the filling factor of the grating. The filling factor which is defined as the percentage of air gap in a period of the grating can be expressed as [16] $ff = 2d(\Lambda - l_w)/(W.\Lambda)$. This can be achieved by reducing the grating depth (d) and increasing the grating duty cycle (D). The variation in total loss (L) inside the structure is also shown in Fig. 5-20. The total loss inside the structure (L) is defined as the part of the power which is not being detected at transmission spectrum and reflection spectrum and is calculated as $L=1-(T+R)$, shows a gradual initial increment reaching to a maximum value and then decreasing to a saturated lower value with respect to increase in N . In addition to the major vertical radiation loss another factor which adds to the total loss inside the structure is the mode mismatch loss at the grating-waveguide interface. The initial gradual increment in L value with increase in N is due to the increase in scattering loss at the grating edges. For a smaller N most of the input light is transmitted through input grating mirror and passes through the second grating mirror due to the lower reflectivity of the gratings, and contribute to the increase in loss. For a higher value in N , a broad spectrum of input light is decoupled from the cavity due to the high reflectivity of the input mirror, eventually leading to a narrow band resonant wavelength oscillation inside the cavity. This leads to a reduced loss at higher value in N . The transmission shows a decrease in value with increase in N . The initial decrease in transmission is attributed to the increase in loss with N and for the higher N the resonant wavelength is tightly bound inside the cavity so that only a small fraction of light energy can escape from the cavity.

Fig. 5-21: Variation in quality factor (Q), Transmission (T), and loss (L) with respect to ΔW for different grating lengths (a) $N=5$, (b) $N=10$ and (c) $N=15$.

A similar type of variation in Q , T and L is observed with respect to variation in ΔW [see Fig. 5-21]. The grating strength increases with increase in the ΔW . This is evident as an exponential variation in Q -factor for higher values in ΔW . For a smaller value in grating number (e.g. $N=5$) the initial variation is found to be linear. Although the variation is exponential with increase in ΔW , no saturation in Q is observed. The smaller grating depth will lead to a smaller out of plane scattering loss giving a higher transmission with a lower Q -factor. From the figure it is seen that the grating with length $N=15$ and grating depth of $\Delta W=170$ nm can give a Q -factor of $\sim 1 \times 10^4$. Same order of magnitude in Q - factor ($\sim 8 \times 10^3$) with a grating depth of $\Delta W=110$ will require a longer grating length ($N=40$).

Although, the spectral characteristics variations look almost similar in both the graphs, it is intuitive to conclude that a longer grating length is less suitable for a wavelength filter design, as it will lead to reduced transmission level with the additional loss present in the structure. Thus, to achieve a compact structure which gives a high Q - factor and high transmission (T) spectrum, the better choice would be

a grating with shorter length and higher grating depth.

5.9. Fabrication and characterization of grating resonators

The fabrication of the structure is done on silicon wafer using electron beam lithography followed by Reactive Ion Etching (RIE) process. Two process flows have been tested to obtain nearly sharp grating edges and vertical side wall for the waveguide gratings. In the first process flow, the waveguide gratings are directly etched down to the silicon layer using the e-beam resist as the etch mask. In the second process flow, a hard mask (SiO_2 or SiN) has been coated over the silicon layer before the e-beam exposure. In this process, as a first step the e-beam pattern is transferred to the hard mask layer through the patterned e-beam resist. After that, the resist pattern is removed and further silicon etching is done using the hard mask layer. JOEL e-beam lithography system has been used to get the e-beam pattern of this waveguide nanograting. The e-beam litho specifications such as exposure dose, spot size, beam deflection step etc, are optimized to obtain a better resolution and defect free resist pattern on the test wafer. Positive tone resist ZEP 520A is used in the litho process. Since the resist used is positive in nature, the e-beam exposure is done outside the waveguide region (Region I, Fig. 5-22), to get the pattern.

Fig. 5-22: Cropped Section of the Layout design of one of the waveguide gratings showing the GDS data for region I

The optimized e-beam lithography specifications are given below.

1. Resist coating RPM and thickness: 4000 RPM in 30 sec, thickness=2600 Å.

2. Exposure Dose: $180 \mu\text{C}/\text{cm}^2$
3. Voltage: 50 KV
4. The main beam deflection field size: $80 \mu\text{m} \times 80 \mu\text{m}$
5. Beam deflection step: 2 nm.

The flow chart for the two process flows and the obtained grating patterns on a test wafer are shown below.

5.9.1. E- Beam resist as etch mask.

The fabrication process flow chart for the grating fabrication using e beam resist as etch mask is shown in Fig. 5-23.

Fig. 5-23: Process flow chart with e -beam resist as etch mask.

Fig. 5-24: Fabricated gratings using resist as etch mask a) the grating pattern after RIE without resist removal. b), c), d) different grating pattern after resist removal.

The process gave good results in the structure features except some problem with the curved side wall for the waveguide. This is due to the poor etch resistance of the e beam resist (ZEP 520A) for the RIE process. The waveguide is over etched yielding a sidewall dimension of 330 nm. The SEM images of different waveguide gratings obtained through this process are shown in Fig. 5-24.

5.9.2. SiO₂ or Si₃N₄ (SiN) hard mask based etching

The fabrication process flow chart for the hard mask based silicon etching is shown in Fig. 5-25. In the first step, hard mask layer of thickness 600 Å is coated over the silicon layer through PECVD process. After that e-beam patterning is done on the wafer. The e-beam resist pattern is transferred to the hard mask layer through RIE of hard mask layer. The RIE is done by time to reach at the hard mask-silicon layer end point. After this, the resist pattern over the wafer is removed through Plasma Resist strip (PR strip) to avoid degradation to the hard mask in the further etching process. Afterwards, silicon layer is etched with hard mask pattern to obtain the grating pattern. After the silicon etching is done up to the required waveguide depth, the hard mask is removed using HF (1:25) solution and the wafer is cleaned. The obtained waveguide structures for SiO₂ and SiN hard mask are shown in Fig. 5.26. The pattern shows a nearly vertical sidewall, even though the process faced some of the following issues. The initial hard mask etching didn't give proper end point for the etching due to extremely small dimensions of the pattern. This resulted into over etching of the structure as shown in Fig. 5-26(a) and this problem is evident in the final structure as shown in Fig. 5-26(c). The SiN hard mask based etching resulted into higher side wall roughness.

With these test wafer fabrication results, it is concluded that SiO₂ hard mask gives

better result with sharp grating edge and smooth vertical waveguide side wall the waveguide grating. Also, if an oxide hard mask is used in the process, the additional process of removal of hard mask can be avoided in the fabrication since the cladding layer in the structure is SiO_2 . Fig. 5-27 shows the SEM images of fabricated grating structures on an SOI wafer, with SiO_2 hard mask based etching.

Fig. 5-25: Process flowchart with SiO_2 / SiN hard mask based etching.

Fig. 5-26: Fabricated gratings with hard mask(SiO_2 / SiN) (a) Grating pattern after SiN hard mask etch, with resist layer on the top.(b) Grating pattern after silicon etching, with SiN hard mask (top layer showing the SiN hard mask). (c) Etched grating pattern with SiO_2 hard mask (top layer showing SiO_2 hard mask) d) grating structure after hard mask removal and surface roughness reduction

Fig. 5-27: SEM images of the fabricated waveguide grating resonators on an SOI wafer. (a),(b) waveguide gratings(c)SSC(d),(e),(f),(g),(h)waveguide gratings with different dimensions(i)two phase shifted gratings(j)gratings showing the dimensions(k)gratings showing the phase shifted region.

5.9.3. Spectral characterization

The spectral response of some of the grating resonators ($\Lambda=330$ nm, $\Delta W=150$ nm and $L_{\text{out}}=35 \Lambda$.) are shown in Fig. 5-28 for a TE polarization input.

Fig. 5-28: Spectral response of the fabricated waveguide grating resonators with single phase shift for (a) $\Delta p=140$ nm (b) $\Delta p=150$ nm (c) $\Delta p=160$ nm (d) $\Delta p=170$ nm.

Fig. 5-29: Resonant wavelength variation with respect to phase shift length

A shift in the resonant spectrum is clearly observed with respect to the variation in phase shift length. The variation is linear with a wavelength of shift of $\Delta\lambda/\Delta\Lambda_p = 0.52$ with the variation in phase shift length [Fig. 5-29].

Fig. 5-30: Resonant spectrum showing the channel isolation

This value is in close resemblance to the shift, $\Delta\lambda/\Delta\Lambda_p=0.47$, observed in simulation. Narrow band resonant transmission (3 dB band width ~ 0.6 nm) which is observed within a stop band of (FSR ~ 50 nm) has an out of band extinction of ~ 14 dB [Fig. 5-30]. However, the spectral features appeared to be highly noisy and with high insertion loss. The observed limitations in the spectral characteristics and their causes are discussed below.

1. High insertion loss for both polarization of input light. The waveguide region of the grating structure which is more than 2 mm in length has contributed much to the insertion loss inside the structure. Even though smallest spot size has been used in the e beam fabrication the e-beam pattern had stitching error at the waveguide regions. This has contributed to the insertion loss as scattering loss from the waveguide

imperfections. Also, the waveguide vertical side wall roughness should be minimized further to reduce the waveguide propagation loss.

2. Fabricated multiple phase shifted grating resonators didn't give resonant transmission spectrum. This might be due to the resonance mismatch inside the two phase shifted region. As observed in the simulation sections, the resonance inside the structure is highly sensitive to the dimensional variations inside the gratings. An external perturbation such as thermo optic or electro-optic methods can be applied to tune the resonant spectrum of individual cavities to make them in resonance to get an output spectrum.

3. The whole stop band of the gratings has been shifted to the lower wavelength region than it is observed in the simulations. This is due to the effective index reduction in the whole grating structure because of the curved grating regions.

5.10. Summary

The phase shifted vertical side wall gratings has been proposed as a resonant transmission filter suitable for DWDM optical communication network. Theoretical analysis and numerical simulation reveals the possibility of achieving a narrow band wavelength filters with the phase shifted vertical side wall gratings. The grating is designed for minimum loss in the resonant cavity by adjusting the grating parameters, so that a high transmittivity can be obtained in the resonant transmission. The grating resonator, which is designed to operate in the DWDM ITU grid C-band of optical communication, has a high free spectral range (~50 nm) and a narrow band resonant transmission ($\Delta\lambda < 0.8$ nm). The results show that resonant wavelength can be controlled by changing the phase shift length or effective refractive index of the grating. Coupled cavity configurations in the grating resonator have been analyzed

to get high channel selectivity and a flat-top spectrum for the resonant wavelength. The -1 dB bandwidth (0.275 nm), 3 dB bandwidth (0.32 nm), and channel cross talk (-28 dB) are comparable to that of a typical DWDM wavelength filter in a 100 GHz channel spaced network. Fabrication and characterization the grating resonators are done on an SOI wafer using electron beam lithography and RIE. A vertical side wall and nearly sharp grating edges for the waveguide grating resonators is achieved in the fabrication. The characterisation result of this grating resonator shows a narrow band resonant transmission ($\Delta\lambda_{3dB} < 0.8$ nm) with a wide FSR (~ 50 nm). A shift in resonant transmission is clearly observed with respect to the variation in grating phase shift length with close resemblance to the simulated data.

Chapter 6:

Conclusion and future work

This chapter concludes the thesis highlighting the significant and original contributions made. Further, the future research directions are explained by highlighting the potential research challenges ahead.

6.1. Conclusions

Investigations into the design and fabrication of SOI based broad band tunable wavelength selective switches (WSS) and filters were done through this thesis with emphasis on achieving telecom grade spectral features and wavelength selection/routing functionalities. Two waveguide structures such as Micro Ring Resonators (MRR) and grating resonators were subjected to study, considering their potential capability as a highly compact Wavelength Selective Switch (WSS) and band pass filters.

A broadband tunable TO-WSS were demonstrated on an SOI platform using a Vernier configured series coupled MRR. The WSS were capable of achieving a 94 nm (~C+L Band) tuning range with a power consumption of 154 mW for its full band tuning, hence demonstrating the total power consumption for a full C+L band tuning to 32.7% of that of a single ring tuning. The thermal cross talk between the rings were considerably reduced with the separated ring configuration. The proposed MRR based TO-WSS can be arranged in matrix array configurations to achieve dynamically reconfigurable add/drop WSS suitable for OADM applications in DWDM communication network with narrow channel spacing.

Series coupled triple ring resonators were designed and fabricated on an SOI platform and experimentally analysed as a thermo-optic Wavelength Selective Switch (TO-WSS). The WSS with an out of band rejection ratio >30 dB, 3 dB bandwidth <1.4 nm, pass band ripple < 0.3 dB and drop loss of 0.5 dB were obtained through the optimized design and fabrication. Among the possible detuning ring combinations analyzed, detuning a single ring adjacent to input bus-waveguide and two rings adjacent to drop line waveguide were observed to be more effective for an OFF state

with high channel extinction, low switching cross talk and low loss of OFF state. A maximum channel extinction of 22 dB, lowest switching cross talk -30 dB and a zero loss of OFF state were achieved with a single ring detuned OFF state using a switching power of 48 mW. Also parallel configuration in TO-WSS was demonstrated and its performance was compared with series configuration.

In the last part of the thesis, phase shifted vertical side wall gratings in a submicron silicon waveguide were proposed as a resonant transmission filter suitable for DWDM optical communication network. The grating resonators, which were designed to operate in the DWDM ITU grid C-band of optical communication, had shown a high free spectral range (~50 nm) and a narrow band resonant transmission ($\Delta\lambda < 0.8$ nm). The results demonstrated a wavelength tunability in the structure through changing the phase shift length or effective refractive index of the grating. Coupled cavity configurations in the grating resonator were analyzed to get high channel selectivity and a flat-top spectrum for the resonant wavelength. The -1 dB bandwidth (0.275 nm), 3 dB bandwidth (0.32 nm), and channel cross talk (-28 dB) were comparable to that of a typical DWDM wavelength filter in a 100 GHz channel spaced network. Fabrication demonstration of these grating resonators were done on an SOI wafer through electron beam lithography and promising results were obtained which are comparable to the simulation and analysis.

6.2. Major contributions

The major focus of the thesis was on the design and fabrication of wavelength filters to meet the spectral requirements and wavelength selection/routing functionalities in a Silicon-On-Insulator (SOI) platform for optical communication applications. Towards this end, MRR based TO-WSS and resonant filter using phase shifted vertical sidewall

gratings were subjected to study. Investigations into Micro Ring Resonator (MRR) based Thermo-Optic -Wavelength Selective Switches (TO-WSS) and channel add drop filters in silicon Micro Ring Resonators (MRR) has been done to get the spectral features and broad band ($\sim$ C+L band) wavelength selection/routing functionalities with low power consumption. In the grating resonator section, numerical simulation and analysis through FDTD method and fabrication through e beam lithography has been carried out to achieve the telecom grade performance parameters. From the proposed concepts and achieved significant results, the major contributions of this thesis can be summarized as below.

- Concept proposal and demonstration of SOI-MRR based TO-WSS for broad band ($\sim$ C+L Band) tunability with low thermal cross talk and low power consumption.
- Concept proposal and demonstration of series coupled silicon MRR as a TO-WSS and analysis of optimal detuning combination in the WSS for an effective OFF state.
- Research and development of phase shifted vertical side wall gratings as a band pass filter suitable for DWDM optical communication network.
- Research and development of phase shifted vertical side wall grating resonant filter as a compact and highly sensitive refractive index sensor.

6.3. Future work directions

The proposed concept and configurations can be applied for more application oriented research and further development in the future. The main areas of further investigations are explained in the following sections.

6.3.1. Fabrication and demonstration of the proposed configurations for multichannel WSS with dynamic reconfigurability

There are various configuration possibilities for the proposed two stage filter MRR TO-WSS to obtain dynamically reconfigurable channel dropping filters suitable for OADM applications.

Fig. 6-1: A 1x9 drop WSS using the proposed TO MRR

Fig. 6-2: A 1x3 OADM using the proposed TO-WSS

Fig. 6-1 shows a 1x9 drop WSS which is dynamically reconfigurable in an optical

communication network. The device can be reconfigured to a multiple channel WSS through the OFF state of the individual TO-WSS. Fig. 6-2 shows a 1x3 OADM with dynamic reconfigurability using the TO-WSS. These designs are novel in terms of their configurations, reconfigurability and mode of wavelength selectivity.

6.3.2. Incorporation of multiple ring resonators in the proposed two stage configuration of TO-WSS to obtain a flat top spectrum and a higher out of band rejection ratio.

The observed channel selectivity (~15 dB) and spectral shape in the experimentally proven TO-WSS has to be improved. The spectral shape has to be improved from Lorentzian to a box like response with a flat-top spectrum to get the increased signal stability in the WSS. This can be done through coupled ring resonators at each stage of the WSS. The series coupled triple ring resonators and their optimal detuning combination as demonstrated in chapter 2 can be applied into the proposed design to achieve high channel isolation and a flat-top spectrum for the TO-WSS.

6.3.3. Improving the fabrication of the silicon waveguide grating resonators to reduce the spectral noise, Fabry- Perot oscillation effect and the propagation loss.

The fabrication of the waveguide grating resonator should be improved to reduce the propagation loss and spectral noise. This can be done by adopting methods to reduce the side wall roughness of the waveguide and reducing the stitching errors in the e-beam litho patterning.

6.3.4. Resonant wavelength tuning in the phase shifted grating resonant filter.

The resonant wavelength of the designed grating resonators are highly sensitive to the effective index variation inside the phase shifted waveguide. Wavelength tuning can be done in the grating resonators through an applied thermal tuning or carrier injection based plasma dispersion effect. This effect can be applied for obtaining a compact silicon based modulator or tunable wavelength filter fabrication.

6.3.5. Fabrication and characterization of channel dropping filter with phase shifted grating assisted MRR for single wavelength selection.

The grating resonators can be used in a micro ring resonator connected configuration as illustrated in the appendix A to obtain a channel dropping filter with single wavelength selection functionality. The fabrication and characterization of the proposed configuration to achieve the functionality can be one of the future directions.

6.3.6. Experimental verification of label free biosensor chip using fabricated phase shifted vertical side wall gratings.

The fabricated phase shifted vertical side wall gratings with a good spectral response can be employed in a chip device as shown in Fig. A.1(Please see section A.2 in the AppendixA) to obtain a highly sensitive label free biosensor for the detection of biomolecules such as protein, antibody, DNA etc,. One of the future work directions can be the fabrication and experimental validation of the proposed biosensor configuration. The proposed configuration in biosensor chip with a high sensitivity ($\Delta n_{\min}=5 \times 10^{-5}$) and compact dimension is highly suitable for multi-analytes detection

through a sensor array configuration.

The device fabrication includes PDMS layer fabrication having micro fluidic reservoir and channels for sample injection and fluid delivery. This method will offer a reusable biosensor chip in which PDMS cladding layer can be removed and replaced after single use. The sensor configuration shown in Fig. 6-3 can be highly parallel in terms of sensing different targeted analytes through the construction of opto-fluidic sensor array. The input would be a broad band laser source to deliver light source for each grating sensor point. Each grating sensor will be associated with a micro fluidic channel for the sample delivery. The sensor output will be a series of sharp resonance peak corresponding to each grating. Any change in the effective index of the grating sensor due to bulk refractive index change or surface chemistry will result into the corresponding change in the output spectrum (as a wavelength shift or intensity variation), which can be detected as a sensor signal.

Fig. 6-3: Schematic diagram of the proposed sensor array for multi-analytes detection using phase shifted vertical side wall gratings.

The proposed concepts and illustrated configuration/systems in this thesis are expected to find potential applications with improved performance in high tech arenas such as micro electronics, optical communication and lab-on-a-chip devices.

Appendix

Appendix A

Phase shifted grating resonant filters as a highly compact refractive index sensor

A.1. Introduction.

The phase shifted vertical side wall grating designed has a spectral characteristic suitable for refractive index sensing applications. The resonant transmission peak would allow an easy interrogation of the sensor through a wavelength shift measurement or intensity measurement method. A sensor configuration is designed with a micro fluidic channel across the resonant grating and the structure is analyzed for its refractive index sensitivity and detection limit (DL).

A.2. Sensing principle and detection limit (DL).

Fig A.1 shows the schematic diagram of the proposed integrated biosensor based on phase shifted vertical side wall gratings. The beam of light from a tunable laser is coupled to the grating from one end and the output light is coupled out from the other end for the spectrum analysis. The cladding layer is modified with a micro fluidic channel across the grating structure, so that the structure imitates a biosensor in a lab-on-a-chip like device. The width of the micro channel corresponds to the length of the two phase shifted grating, which is approximately 13 μm . A fluid of refractive index n_{Clad} is assumed to be flowing through the channel.

The sensor sensitivity and detection limit is calculated through wavelength shift

measurement and intensity measurement approach. For a sensor based on wavelength shift measurement, a high Q -factor and a high transmittivity is desirable for its resonant transmission.

Fig. A.1: The schematic picture of an integrated biosensor based on phase shifted vertical side wall grating.

For a wavelength shift measurement method, the minimum detectable refractive index of the sensor is expressed as

$$\Delta n_{\min} = \frac{m}{2\Lambda} \left(\frac{\partial n_{\text{eff}}}{\partial n_{\text{clad}}} \right)^{-1} \Delta \lambda_{\min} \quad (1)$$

Where, the Bragg condition $\lambda_B = \frac{2n_{\text{eff}} \Lambda}{m}$ is used to approximate the resonance condition, as the quarter wave phase shift produces a resonance effect exactly at the Bragg wavelength. $\Delta \lambda_{\min}$ is the spectral resolution of the sensor that can be measured using an external instrument. The cladding fluid refractive index is varied from 1.325 to 1.336 and the output spectrum is analyzed. The combined spectrum is shown in Fig. A.2(a). The effective index variation obtained as in Fig.A.2 (b) gives the slope of

$$\frac{\partial n_{\text{eff}}}{\partial n_{\text{clad}}} = 0.1389. \text{ Considering the fact that the smallest shift that can be measurable}$$

is one fifteenth of the of the peak width, the grating with a grating length $L_{\text{out}} = 14 \Lambda$ will offer a smallest spectral resolution of $\Delta \lambda_{\min} = 7.33 \text{ pm}$. Hence the minimum detectable bulk refractive index change is calculated from Eqn (1) as $\Delta n_{\min} = 8.1 \times 10^{-5}$

RIU. The same detection limit can also be calculated from the sensitivity(S) of the sensor using the equation $\Delta n_{\min} = \frac{R}{S}$ [171], where $R = \Delta \lambda_{\min} = 7.33$ pm is the sensor resolution and $S = \frac{\Delta \lambda}{\Delta n} = 90$ nm /RIU is the sensor sensitivity, giving a DL of $\Delta n_{\min} = 8.1 \times 10^{-5}$ RIU. Where the sensor sensitivity S to the bulk refractive index change is calculated by measuring the spectral shift $\Delta \lambda$ with a change Δn in cladding fluid refractive index.

Fig. A.2: (a) Spectral response of TPG filter for different channel fluid refractive indices. (b) Variation in effective index of the grating with respect to channel fluid refractive index. (c) Normalized transmission of the resonant peak with respect to change in the fluid refractive index.

For an intensity measurement approach the transmitted power has to be measured at a particular resonant wavelength for a change in cladding fluid refractive index. Here, one of the resonance wavelengths is set as a reference wavelength and the change in power is measured with respect to change in cladding fluid refractive index n_{clad} . Fig A.2(c) shows the normalized transmission with respect to the change in refractive index of the cladding fluid. The grating with two phase shifts is used in the analysis

and it has given a sharp line shape in the spectrum improving the sensitivity considerably.

Considering the power change as a function of cladding refractive index change the minimum detectable refractive index change can be defined as [172]

$$\Delta n_{\min} = \frac{\partial n_{\text{clad}}}{\partial \lambda_B} \frac{\partial \lambda}{\partial P} \Delta P_{\min} \quad (2)$$

Where $\frac{\partial \lambda}{\partial P}$ is calculated from the transmission spectrum of two phase shifted grating

as 0.4134 nm and $\frac{\partial n_{\text{clad}}}{\partial \lambda_B} = \frac{1}{S} = 0.0111 \text{ nm}^{-1}$.

$\Delta P_{\min}$ is power measurement resolution which is the minimum detectable change in optical power, which depends on many things especially laser power fluctuation and dark current noise of the photo detector. Considering a power measurement resolution of 1%, the minimum detectable refractive index change is calculated from Eqn (2) as $4.59 \times 10^{-5} \text{ RIU}$.

The detection limit is also calculated using the power sensitivity which is defined by [173].

$$S = \frac{1}{P} \frac{\partial P}{\partial n} \quad (3)$$

Where, P is the normalized transmitted power at the reference wavelength λ_r .

The average slope $\frac{\partial P}{\partial n}$ is calculated from the Fig.A.2(c) as 184.51 giving a power

sensitivity of $S = 184.51$. With a power measurement resolution $R = \Delta P_{\min} = 1\%$ the

detection limit is calculated as $\Delta n_{\min} = \frac{R}{S} = 5.43 \times 10^{-5} \text{ RIU}$.

The detection range for refractive index change would be larger for wavelength shift measurement method as the resonance peak can be shifted over the wide stop band

(1335nm to 1589 nm). From the spectral shift measurement observed in our structure, this range suggests a possible detection range of approximately 2.8 RIU change. The intensity measurement approach is limited for measuring refractive index change by the one spectral peak used in the measurement. As the resonance peak has a sharp edge and the intensity comes down very fast with small refractive index change the calculation shows that only a range of less than 0.01 RIU change would be able to measure with one resonance peak. However the intensity measurement approach has advantages over wavelength shift measurement, in terms of comparatively good sensitivity with less stringent requirement for detector resolution and high intensity spectrum obtained outside.

Table.A.1 shows a comparison of the phase shifted grating sensor parameters with some of the silicon based structures such as Mach-Zehnder interferometer, ring resonator and surface corrugated Bragg grating.

<i>Parameter</i>	<i>Mach-Zehnder interferometer [174]</i>	<i>Ring resonator [175]</i>	<i>Surface Corrugated Bragg grating[176]</i>	<i>Proposed Phase-shifted vertical side wall grating</i>
<i>Δn_{min}</i>	7×10^{-6}	7×10^{-5}	1×10^{-4}	5×10^{-5}
<i>Dimension</i>	L= 30 mm	Ring Radius= 5 μ m (Area=100 μ m ²)	L=173 μ m	L=13 μ m

Table.A.1. Parameter comparison of some of the silicon based sensor structures.

The proposed grating resonator based refractive index would find significant advantage over other commonly used silicon waveguide structures such as Mach-

Zehnder Interferometer, ring resonator, etc, when deployed in a biosensing environment. The Mach-Zehnder based structure has got complexity in structure with a long length and 3 dB couplers, so that the structure is less suitable large number integration in micro fluidic or multi analyte detection setups. For a ring resonator based structure the free spectral range is very small and is limited by the ring radius. The dimension of the surface corrugated Bragg grating is larger than our structure by one order of magnitude and the structure needs stringent requirements for a single mode waveguide design and fabrication. The grating resonator is highly compact making them suitable high mass sensitivity and for high density integration. The other advantage of this compact phase shifted grating based sensor would be the possibility for arranging the sensor points in an array format to get a multi analyte sensor with multiplexed detection possibility. More details about this sensor configuration and sensing principles are explained in the future work direction of the thesis.

Appendix B

Channel dropping filter with grating assisted MRR for single wavelength selection

B.1. Introduction.

For channel dropping filter (CDF) based on a MRR, the spectral response at the output is periodic and hence supports a large number of resonances with a separation between them given by the Free Spectral Range (FSR). A good filter in an optical communication channel should be able to filter out only one unique resonant wavelength out of a broad band of input given to it, i.e., a filter in C-band require an FSR of at least 30 nm for better performance. Usually a MRR based multi channel filters are implemented by designing bus waveguide connected to sequentially arranged rings with small difference in their radius so that they differ in their FSR[177, 178]. The major challenges in this procedure are in the design and fabrication of rings with exact radius with little fabrication imperfection and accurate waveguide-ring coupling to get the accurate FSR. To get a flat top spectrum, multiple rings has to be used, which increases the fabrication challenges further [56, 149]. Also proper design for the ring-ring couplers and optimization in effective refractive indices are required to avoid the Coupling Induced Frequency Shift (CIFS) which distorts the shape of the output spectrum considerably[179].

Here the design and simulation of Single MRR channel dropping filter

connected top grating resonators is illustrated to get a narrow band, high transmission and a flat-top spectrum for the filtered channel.

B.2. Filter design and spectral behaviour

The schematic of the single wavelength selection filter is shown in Fig. B.1 (a). The structure consists of a single MRR with grating resonant filters connected at the drop port. The grating resonators are designed with Silicon-On-Insulator (SOI) strip waveguide vertical side wall gratings. The structure parameters are shown in Fig.B.1 (a). Where W is the waveguide width and ΔW is the grating etch depth inscribed into the vertical side wall of the waveguide, n_1 and n_2 are the effective refractive indices of the waveguide in the grating region and waveguide region, respectively.

Fig.B.1: (a) Schematic diagram showing different structure parameters of the proposed CDF with grating resonators at the drop and add port. (b) Cross sectional view of the SOI strip waveguide and TE mode intensity distribution

The ring resonator radius was set to $R=10\mu\text{m}$ with a bus-ring coupling gap of 50 nm. A Silicon-On-Insulator (SOI) strip waveguide with area of cross section of 400×250 nm with air cladding is assumed in the simulation to get single mode propagation for

TE wave input (Fig.B.1 (b)). The structures were simulated using Finite Difference Time Domain (FDTD) method [165]. A broad band Gaussian modulated continuous wave at a wavelength of 1.55 μm and spectral bandwidth of 281nm was given as input. A mesh grid size of 5 nm and timestep size of $\Delta t = 1.2 \times 10^{-17}\text{s}$ were used in the simulation.

Fig. B.2. Transmission spectrum at the drop and through port of the OADM showing the stop band and single wavelength transmission at drop port. Inset shows the magnified resonant transmission at Bragg wavelength.

Fig.B.2 shows the spectral response of the filter. The drop port is characterized by a wide stop band for broad band of MRR resonant wavelength except for the given grating resonant wavelength. The stop band from 1.47 μm to 1.63 μm corresponds to an FSR of ~ 160 nm for the dropped channel. The drop channel wavelength has a band rejection (BR) of 26.3 dB at the through-port and drop loss (DL) of < 3 dB at the drop-port. The suppression of side band wavelengths adjacent to the resonant wavelength, termed as side band rejection (SBR) is observed to be 19.8dB. The channel selectivity

is calculated from -1dB and -10dB band width as, $S = \frac{(\Delta\lambda)_{-1dB}}{(\Delta\lambda)_{-10dB}}$, = 0.178.

B.3. Spectral response of the channel dropping filter with optimized multiple phase shifted grating resonant filters

The Single Phase Shifted (SPG) resonant filter at the drop port of configuration in Fig.1 is replaced with optimized double phase shifted grating (DPG) and Triple Phase Shifted Grating (TPG) resonant filters. The structure features of the optimized grating resonators are given by $\Lambda=323\text{nm}$, $\Delta W=150\text{nm}$, $D=60\%$, $L_{\text{out}}=20\Lambda$, $L_{\text{in}}=40\Lambda$. The spectral response was improved in their channel selectivity(S) and side band rejection (SBR) and spectral shape considerably. Fig.B.3 and Fig.B.4 shows the drop/through response obtained for Double Phase shifted Grating CDF (DPGCDF) and Triple Phase shifted Grating CDF (TPGCDF), respectively.

Fig. B.3. Transmission spectrum at the drop/ through port of the DPGCDF. Inset shows the magnified central region showing the dropped channel (black) and through port dips (red)

The BR and SBR are improved from 26.3 dB to 35.2 dB and 19.8 dB to 53.2 dB when a SPGOADM is converted into a DPGCDF. A considerable improvement in the channel selectivity ($S=0.698$) is also observed for a TPGCDF. The spectral shape is observed to be flat-top in these multiple phase shifted grating CDF. The dropped channel from the MRR has undergone a multiple cavity resonance at the grating

resonators leading to high channel selectivity. The final dropped channel band width and spectral shape is solely determined by the grating resonators. Hence even if a strong bus-ring coupler is used (leading to a broader dropped channel through RR), a narrow band resonance can be achieved in the filter through grating resonators. TableB.1 shows a comparison in values of the spectral parameters of Single Phase shifted Grating CDF (SPGCDF) with DPGCDF and TPGCDF.

Fig. B.3. Transmission spectrum at the drop /through port of the TPGCDF. Inset shows the magnified central region showing the dropped channel (black) and through port dip (red).

Parameter	SPG	DPG	TPG
<i>DL</i> (dB)	< 3	< 3	< 3
<i>BR</i> (dB)	26.3	32.1	35.2
<i>SBR</i> (dB)	19.8	28.3	53.2
<i>(Δλ)_{-1dB}</i> (nm)	1.07	1.14	1.3
<i>(Δλ)_{-10dB}</i> (nm)	6	2.1	1.86
<i>S</i>	0.178	0.543	0.698

Table.B.1. Comparison of CDF spectral parameters with different grating resonant filters

B.4. Summary

A single mirroring resonator with higher radius has been used to demonstrate CDF with an ultra high FSR, high channel selectivity and a flat top spectrum through a grating resonator connected configuration. The high FSR for the device is achieved through the suppression of the non desired resonance wavelengths in the RR using the band gap effect of grating resonators. The obtained high FSR ($1.47\mu\text{m}-1.630\mu\text{m}=155\text{nm}$) is in the DWDM ITU grid which can cover all the channels in the C to L band ($1.52\mu\text{m}-1.63\mu\text{m}$) of optical communication network. The grating resonators are designed and analyzed with phase shifted vertical side wall gratings to achieve a high Q -factor along with a high transmission and a flat top spectrum so that the spectral response in the CDF can be improved. Better channel selectivity (0.698), high through-port band rejection (35.2dB), high drop-port side band rejection (53.2dB) and a flat top spectrum is obtained in the proposed CDF through the use of optimized multiple phase shifted grating resonators. The other advantages are, a single RR of higher radius can be used and the reconfiguration and channel selection in the CDF can be done by varying the phase shift length or effective refractive index of the grating resonators, rather than the ring radius.

Appendix C

Taper couplers for coupling between laser and silicon waveguide with large allowable tolerance

C.1. Introduction

The design of efficient couplers, that couple an external element (source /detector) and waveguide, is a challenging issue as far as the development of submicron waveguide based devices is concerned. A taper coupler with multimode input and single mode output is presented for coupling between edge emitting laser diode and silicon waveguide. The tapered coupler structure is optimized and tolerance for laser diode placement is studied. A typical coupling efficiency of -2 dB is achieved from laser diode to silicon waveguide. With tolerance of $\pm 4 \mu\text{m}$ laterally or vertically, the variation of the coupling efficiency is about 3 dB. The tolerance is large compared with other methods. Tilting angle at laser diode and the small gap between tapered coupler and silicon waveguide also affect the overall coupling. From our studies, horizontal and vertical offsets are more critical for laser diode placement in order to have a good coupling. The new design can be applied to photonics packaging because it will make passive assembly easier by having larger tolerance for packaging compared with the conventional method with lens.

C.2. Taper coupler design and simulation for laser and silicon waveguide coupling

A taper coupler with mode size matching at both sides will convert the mode from one waveguide to another waveguide. But the mode size converter needs to be aligned with the both the waveguides precisely, as otherwise, most of the light will be lost [180, 181]. In order to achieve a more generous tolerance for passive alignment in low cost assembly, a taper coupler with relative large input opening is designed to couple the light from laser diode to silicon waveguide. In order to make the fabrication simpler, the coupler is designed to have symmetric lateral taper and pseudo-vertical taper shape. The laser diode active waveguide faces the centre of the entrance facet of taper coupler. Figure C.1 shows the top view, cross-sectional views and isoparametric view of the designed tapered coupler structure. The design of the coupler includes considerations of assembly. Considering the placement of laser diode will be at least a distance from the taper coupler, the laser beam will diverge to a beam spot of several micrometers diameter. Thus, we designed the opening at input side to be $12\mu\text{m} \times 12\mu\text{m}$ which is larger than the laser diode mode size. Considering the divergence angle of 32 degree, the distance between the laser diode and the taper coupler should be less than $21\mu\text{m}$. This helps in coupling the light into the coupler even if the laser diode has a few micrometers displacement. Higher order modes will be lost during the propagation through the coupler. However, most of the light will be coupled into the waveguide by design optimization. The taper coupler has two layers to form the pseudo-vertical tapering structure as depicted in Fig.C.1 (b). The bottom layer is $11\mu\text{m}$ thick and top layer is $1\mu\text{m}$ thick. The length of the bottom layer is optimized so that most of the light will be coupled into the top layer. The output end of the taper coupler tapers down to $1\mu\text{m} \times 1\mu\text{m}$ whose fundamental mode matches with propagation

constant of the mode in silicon waveguide. The length of the coupler is 1.7 mm. The length of the top layer is optimized to achieve the best coupling between the taper coupler and silicon waveguide. Figure C.2 shows the horizontal vertical slice of the light propagation from laser diode to a silicon waveguide through taper coupler. By using such a taper coupler, a typical -2dB coupling efficiency is achieved.

Fig. C.1. Taper coupler between laser diode and silicon waveguide (a) top view
 (b) side view(c) isoparametric view.

Fig. C.2. Light propagation from laser diode to silicon waveguide through taper coupler (a)horizontal slice (b)vertical slice.

C.3. Laser diode tolerance study during design

To study the possible tolerance values of laser diode placement, simulation studies were carried out by shifting the input to the tapered coupler in both horizontal and vertical positions. The placement tolerances were studied from $-4\text{ }\mu\text{m}$ to $+4\text{ }\mu\text{m}$ offset laterally and from $-4\text{ }\mu\text{m}$ to $+4\text{ }\mu\text{m}$ vertically. The coupling efficiency varies from -1.9 dB to -5 dB within $\pm 4\text{ }\mu\text{m}$ lateral offset (Fig. C.3 (a)), which means the variation is about 3 dB . The coupling variation is less than 3 dB when the vertical position of the laser waveguide offsets from $-4\text{ }\mu\text{m}$ to $+4\text{ }\mu\text{m}$ (Fig. C.3 (b)). In these two sets of simulations, we assume there is not tilting at the active waveguide of laser diode relative to the optical axis of taper coupler and silicon waveguide.

Fig. C.3. Coupling efficiency versus (a) lateral offset (b) vertical offset (c) tilting angle.

It's also possible that the laser diode is tilted relative to the optical axis of tapered coupler and silicon waveguide.

Fig. C.4. Top view of a taper coupler with later tilting laser diode and a silicon waveguide.

The coupling property at tilting condition is studied. The schematic configuration of tilting between laser diode and coupler is shown in Fig. C.4. The coupling efficiency results over a range of tilting angle are presented in Fig.B.3. (c). When there is a deliberate tilt of ± 2 degrees, the coupling efficiency improves from -1.9dB to -2.8dB. Hence, the coupling efficiency variation due to tilting of laser diode is less than 1dB. Figure 10 shows the light propagation from laser diode to silicon waveguide through taper coupler with 2 degree tilting at laser diode. It can be seen that the modes are launched asymmetrically in tapered coupler. The light propagation is very similar to horizontal offset of laser diode.

C.4. Summary

In this work a coupler is designed for coupling the light from laser diode to silicon waveguide with large alignment tolerances. The coupler has a pseudo vertical tapered structure. Laterally, it has a linear taper. The input aperture is much larger than the size

of the laser waveguide cross-section. The tapered coupler provides single mode output and matches the mode propagation constant with that in silicon waveguide. The tapered coupler can be fabricated on the same substrate with the silicon waveguide through the silicon micro-fabrication process. The misalignment between the silicon waveguide and taper coupler can be very small since this is controlled by high precision silicon optical bench patterning processes. The coupler relaxes the laser diode placement accuracies and eliminates the need for a coupling lens. Design Studies showed that the tolerance between the laser diode and taper coupler can be more than $\pm 4\mu\text{m}$ misalignment at xy, and more than ± 2 degree tilting angle tolerance. The laser to silicon waveguide coupling tolerances is greatly improved and passive alignment for laser diode and silicon waveguide becomes possible. The technology is suitable for functional integration for silicon photonics. Important results are summarized as followings:

1. A taper coupler is designed for larger tolerance laser diode and silicon waveguide light coupling;
2. The optimized structure can achieve -2dB coupling efficiency by simulation;
3. With $\pm 4\mu\text{m}$ laser diode offset, the coupling efficiency varies only 3dB;
4. ± 2 degree tilting at the laser diode varies the coupling efficiency by only 1dB.

Appendix D

Finite Difference Time Domain Method (FDTD)

D.1. Introduction

The FDTD method involves solution of Maxwell's equation rigorously, without any theoretical restrictions or approximations. This method can be widely used integrated optics design as a wave propagation technique. Many physical effects in a complex structure can be simulated through this method with the direct solution of the Maxwell's curl equations. The Finite Difference Time Domain (FDTD) method has been extensively applied for the design of complicate microwave and RF devices having a dimension comparable to the wavelength of operation. FDTD plays same role as the commonly used Beam Propagation Method (BPM) .The BPM simulation method is used in a waveguide structure having a slow variation along the propagation direction, no back reflections and less divergence in the beam propagation. Even though the BPM method is highly developed in its performance it is not a suitable tool for modeling high-index contrast structures. A high index contrast structure is characterized by strong confinement of light and rapid changes along the direction of propagation. FDTD method is the best suited method for this kind of waveguide structures.

D.2. The FDTD algorithm

The FDTD method solves the full vector Maxwell's equations without any approximations other than the replacement of differential equation with finite differences. The simulation space is divided into meshes, usually having a rectangular shape. With an initial field applied to the domain, the code is updated at every time steps with the electric and magnetic field evolving according to the Yee's algorithm[182].The algorithm solves both electric field and magnetic field in time and space using the coupled Maxwell's curl equations

$$\nabla \times E = -\frac{\partial}{\partial t} \mu H \quad \nabla \times H = -\frac{\partial}{\partial t} \epsilon E \quad (1)$$

Fig.D.1 shows the position of electric and magnetic field components in a cubic unit cell of Yee space lattice. Every E (H) component is surrounded by four circulating H (E) components.

Fig. D.1 Yee cell with electric and magnetic field

D.3. Two dimensional (2-D) FDTD algorithms

The 3-D FDTD simulation is very demanding in terms of time and memory

requirements. So it is often preferred to perform the calculation in 2-D domain. The 2-D structure is derived from the initial 3-D structure. Here the variation of the field along one direction of the structure is neglected so that whole Maxwell's equations are decoupled into two systems of equations.

TE Fields (E_x, E_y, H_z)

$$\frac{\partial E_x}{\partial t} = \frac{1}{\varepsilon} \left(\frac{\partial H_z}{\partial y} - \sigma E_x \right) \quad (2)$$

$$\frac{\partial E_y}{\partial t} = \frac{1}{\varepsilon} \left(\frac{\partial H_z}{\partial x} - \sigma E_y \right) \quad (3)$$

$$\frac{\partial H_z}{\partial t} = \frac{1}{\mu} \left(\frac{\partial E_x}{\partial y} - \frac{\partial E_y}{\partial x} - \sigma^* H_z \right) \quad (4)$$

Fig. D.2 Yee cell space lattice in 2-D case: (a) TE (b) TM

TM fields (E_x, H_x, H_y)

$$\frac{\partial H_x}{\partial t} = \frac{1}{\mu} \left(-\frac{\partial E_z}{\partial y} - \sigma H_x \right) \quad (5)$$

$$\frac{\partial H_y}{\partial t} = \frac{1}{\mu} \left(-\frac{\partial E_z}{\partial x} - \sigma H_y \right) \quad (6)$$

$$\frac{\partial E_z}{\partial t} = \frac{1}{\varepsilon} \left(\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} - \sigma^* E_z \right) \quad (7)$$

And the discretization is analogous to the 3D case. But now the field and material

properties are given by 2D matrices. The Yee cell is modified in 2D as shown in Fig.D.2.

D.4. Numerical parameter requirements in FDTD

In order for proper implementation of FDTD algorithms, following numerical parameters should be specified accurately. The following section outlines the definition of these parameters.

D.4.1. Spatial and temporal grid

During the discretization process care should be taken to choose a proper time steps Δt relative to the spatial steps Δx , Δy , Δz , Otherwise the stability of the algorithm will be disturbed in the simulation.

It can be shown that the stability of the algorithm is dependent on the following relationship.

$$c\Delta t \leq \frac{1}{\sqrt{\frac{1}{(\Delta x)^2} + \frac{1}{(\Delta y)^2} + \frac{1}{(\Delta z)^2}}} \quad (8)$$

Eqn(2.4) is known as Courant –Friedrich-Levy (CFL) criterion.

In the case of a 2-D simulation the stability condition (2.4) is modified as

$$c\Delta t \leq \frac{1}{\sqrt{\frac{1}{(\Delta x)^2} + \frac{1}{(\Delta y)^2}}} \quad (9)$$

In the case $\Delta x = \Delta y = \Delta$, reduces to

$$\Delta t \leq \frac{\Delta}{c\sqrt{2}} \quad (10)$$

D.4.2. Boundary Conditions

An unbounded geometry is usually simulated numerically by considering a finite computational domain. The proper choice of boundary condition is very crucial in this type of simulation. The finite difference equations must be modified at the boundaries such that a very low back reflection is observed at the boundaries. One of the technique to implement an Absorbing Boundary Condition (ABC)[183, 184]. This boundary condition allows the waves to leave the computational domain using one way wave equations. But the field will still suffer unwanted back reflections. These reflections back into the computational domain will contaminate the simulation result and will lead to instability. A new approach was developed by Berenger [185] which is known as Perfectly Matched Layer (PML) . The Perfectly Matched Layer (PML) boundary conditions have the best performance. This boundary condition reduces the back reflections to a large extend from all the angle of incidence.

D.5. Summary

The fundamentals of FDTD method of numerical simulation is presented in this appendix. The computational process in FDTD method is relatively simple, which uses only addition, subtraction, and multiplication. The technique is extremely versatile because it is inherently full-vectorial without limitations on optical effects such as direction of propagation, index contrast, or backward reflections. The FDTD method is time-tested and stable, and can efficiently handle material dispersion and nonlinearities. Also, because it is based in the time-domain, it can cover a wide frequency range with a single simulation run. Furthermore, FDTD lends itself to cluster computing. This allows the computational demand for a single problem to be

shared among several computers on a network, and permits researchers to simulate problems otherwise impossible on a single computer. The FDTD method is computationally demanding, requiring a fairly dense grid of points at which all three vector components of both the **E** and **H** fields must be maintained. For example with a grid size of 5 nm , a grating device of 10 μm in length required a CPU time of ~20 minutes for 2-D simulation and two and half days for 3-D simulation using a PC with memory capacity 8GB. A full three-dimensional simulation of some fairly mundane problems like a simple, planar, evanescent splitter can be near impossible. Such devices are usually long (20 to 30 mm) and would require a computer with terabytes of memory, notwithstanding an impossibly long simulation time.

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