Optical Add/Drop Mux-Demux Using Arrayed Waveguide Grating

MTech Thesis

By

SHUVAM BISWAS

DEPARTMENT OF ELECTRICAL ENGINEERING

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A THESIS

Submitted in partial fulfilment of the requirements for the award of the degree

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SHUVAM BISWAS

DEPARTMENT OF ELECTRICAL ENGINEERING

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **Optical ADD/DROP Mux-Demux Using Arrayed Waveguide Grating** in the partial fulfilment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY** and submitted in the **DEPARTMENT OF ELECTRICAL ENGINEERING, Indian Institute of Technology Indore,** is an authentic record of my own work carried out during the time period from June 2022 to June 2023 under the supervision of Prof. Mukesh Kumar, Professor, Indian Institute of Technology Indore.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

Shuvam Biswas
22/05/23

Signature of the student with date
(Shuvam Biswas)

This is to certify that the above statement made by the candidate is correct to the best of my/our knowledge.

(Prof. Mukesh Kumar)

SHUVAM BISWAS has successfully given his/her MTech. Oral Examination held on **May 11,2023**.

Signature(s) of Supervisor(s) of MTech. thesis
Date: 22/05/2023

Convener, DPGC
Date:

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Shuvam Biswas

Dedicated to

My Father Shri Bikash Chandra Biswas

Abstract

Optical networks are known for their high bandwidth and speed advantages, but crosstalk remains a problem. A solution to address crosstalk in optical add-drop multiplexers (OADMs) is the proposed approach using a foldback path, optical circulator, and optical switches. This creates a reconfigurable OADM with significantly reduced signal crosstalk. The design uses an N x N arrayed waveguide grating (AWG) with a loop in the optical path to reflect the signal back into the AWG. Optical switches allow for selective signal adding or dropping, while two AWGs enable reconfigurable setups for signal addition or dropping. Data transmission rates of 5 Gbps to 25 Gbps have been successfully tested, with increasing Bit Error Rates up to 0.009 at 25 Gbps. The quality factor has been analyzed using an eye diagram to ensure reliable data transmission. The eye diagram shows the signal quality visually, with the opening and closing of the eye pattern. The proposed design has a high-quality factor and eye-opening, making it a promising solution for high-speed optical networks. The incorporation of a ring resonator at the output waveguide led to a reduction in cross talk from 0.1 to 0.05. Through careful tuning of the ring resonator, we were able to successfully perform signal dropping. However, the ring resonator exhibited lower coupling efficiency, resulting in incomplete signal power drop. In contrast, the racetrack resonator demonstrated superior coupling efficiency, enabling full signal drop.

LIST OF PUBLICATIONS

Shuvam Biswas, Prem Babu, Santosh Kumar, Suresh K. Pandey, and Mukesh Kumar, “Reconfigurable Optical Add/Drop Multiplexing-Demultiplexing in Arrayed Waveguide Grating with Fold Back Technique,” **Optics Communications. June 10, 2023** (**Under Review**)

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NOMENCLATURE

ϵ	Dielectric Constant
λ	Wavelength
ω	Angular Frequency
μ	Permeability Constant
$\hbar$	Reduced Planck's Constant
β	Propagation Constant
Φ	Phase Shift
E_F	Fermi Energy Level
K_o	Free Space Wave Number
ω_p	Plasma Frequency
e	Charge of the Electron
n_e	Electron Density
m_e	Effective mass of Electron
n_{eff}	Effective Refractive Index
L	Propagation Length
α	Transmission Coefficient
Q	Quality Factor
E	Electric Field Intensity
D	Density of States

ACRONYMS

DWDM	Dense Wavelength-Division Multiplexing
PIC	Photonic Integrated Circuit
AWG	Arrayed Waveguide Grating
WDM	Wavelength Division Multiplexing
OADM	Optical Add-Drop Mux-Demux
WSS	Wavelength Selective Switch
OXC	Optical Cross Connects
LCoS	liquid-crystal-on-silicon
FPR	Free Propagation Region
FSR	Free Spectral Range
MZI	Mach– Zehnder interferometer
MEMS	Micro-Electro-Mechanical Systems
NRZ	Non-Return-to-Zero
BER	Bit Error Rate
SoTA	State-of-the-art

Chapter 1

INTRODUCTION

1.1 Integrated Photonics

The insatiable demand for high-speed data, low power consumption and computational power pushes us to make better devices. Data intensive applications like artificial intelligence and machine learning process a large amount of data in real-time and current semiconductor electronic technology, cannot fulfill these demands. Scaling down electronic device dimensions has led to significant improvement in terms of speed, power consumption, cost and footprint area. However, devices can't be further scaled down due to several short channel effects and electronics are approaching their fundamental speed and bandwidth limitations, which is an increasingly serious problem that impedes further advances in many areas of modern science and technology. Today, commercial high- performance processors offer a compute power to memory bandwidth ratio of 5–10 TDP-FLOP/Byte [1]and this shows the need to increase the bandwidth. Due to electronic interconnect delay time issues and losses, achieving quicker electronic circuits running above 10 GHz is a major challenge. Photonic devices are savior devices for such problems and light is believed to be one of the most promising possibilities for replacing electronic signals as information carriers [2]. However, photonic devices are large and bulky and do not satisfy the demand for less footprint area and integration on a single chip is not possible. The advancement in the photonics lead to a new branch called Nanophotonic. This leads to the study of controlling and guiding light beyond its diffraction limitation. Figure 1.1 shows a Photonic Integrated Circuit (PIC) depicting the integration of photonic devices on a single chip with electronics. The elements of PICs are connected via waveguides which confine and direct light. The chip elements can be both passive (for e.g., couplers, filters, and multiplexers) and active (for e.g., modulators, switches, amplifiers, and detectors) [3]–[7]. These components are integrated and fabricated onto a single substrate, which creates a compact and robust photonic device. This integration dramatically improves the performance and reliability of photonic functions while simultaneously reducing the size, weight, and power consumption. Photonic devices find applications in energy-efficient lighting, high performance computing, environmental monitoring, chemical, and biological sensing and many more [8].

1.2 Photonic devices for WDM System

Nano photonics is an emerging field of photonics that deals with the manipulation of light-matter interactions on a scale that is smaller than the wavelength of light. The plasmons, slot waveguide, and photonic crystals are the few waveguides engineered device technologies that enable us to have devices much smaller than the dimensions of wavelength [9] and the integration of nanophotonic devices can facilitate the

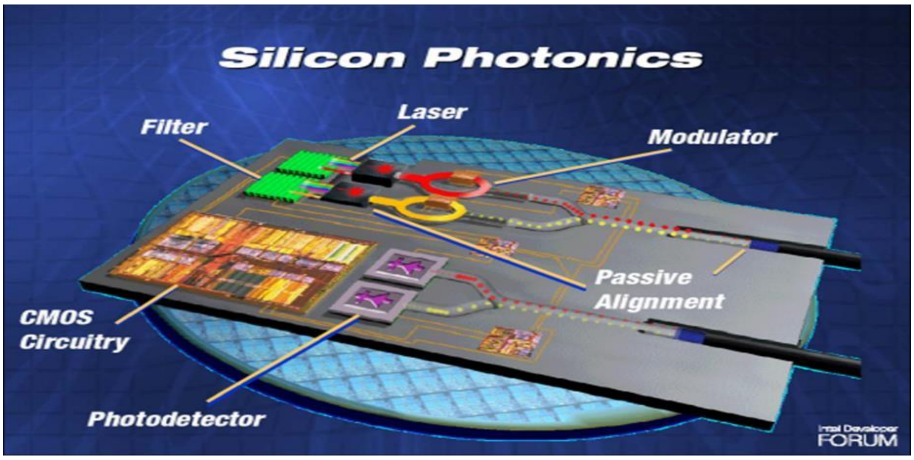


Figure 1.1 A Si photonic integrated circuit depicting the integration of photonic components with CMOS circuitry [35]

construction of a comprehensive system such as dense wavelength-division multiplexing (DWDM) in optical networks. The design of DWDM systems benefits from the utilization of various devices such as AWGs[10]–[12], fiber Bragg gratings [13], Mach-Zehnder interferometers [14], [15] etc. These devices play a crucial role in enabling the efficient and effective transmission of multiple optical signals over long distances in modern optical networks. DWDM is a photonic device technology that enables the simultaneous transmission of multiple optical signals through a single optical fiber by utilizing different wavelengths of light. It allows for high-bandwidth communication over long distances and has become an essential technology for modern optical networks. Other than that, nanophotonic devices allow for high levels of control and manipulation of light-matter interactions [16], which can result in more efficient and functional devices such as optical switches, interconnects, modulators, polarization controllers, and memory. These devices find applications in various fields including data centers, quantum computing, aeronautics, defense, biosensors, and telecommunications. The greater the light-matter interaction in these devices, the easier it is to control and manipulate light, leading to better performance and higher efficiency[17]. In today's world, optical fiber has become a crucial component in the transmission of data over long distances. However, the increasing demand for high-bandwidth communication requires larger channel capacity. If each location were to have a dedicated optical fiber, the cost would be prohibitively expensive, and the capacity of optical fibers is not infinite. To address this challenge, wavelength division multiplexing (WDM) is used, which combines signals of different colors of light and transmits them over a single optical fiber. This approach significantly increases the capacity of optical fibers, with the capacity increasing by a factor equal to the number of wavelengths used in the WDM system[18]. With this WDM system we can perform several functionalities such as add-drop, wave length selective switch etc.

1.3 Optical Add-Drop Mux-Demux (OADM)

A mostly WDM system comprises three primary components. The first component is an optical multiplexer that combines signals and transmits them through an optical fiber. The second component is a demultiplexer, which separates the combined signals received through the fiber. Finally, the third component is the optical fiber itself, which is used to transmit the combined signals over long distances. In OADM this mux and de-mux aligned back-to-back with each other connected via optical fiber. Within the flow of data, it is possible to selectively add or remove signals between the demultiplexer and multiplexer components. This allows for greater control and flexibility in managing the transmission of data in a WDM system [19] Below figure shows the clear picture how this system works. The process of dropping and adding signals to an existing communication line involves using a demultiplexer to separate the individual signals, which are then transmitted through an optical fiber. Once the signals are separated, the undesired signal can be dropped and a new signal can be added to the remaining signals. After the appropriate modifications are made, the signals are multiplexed together and transmitted through the

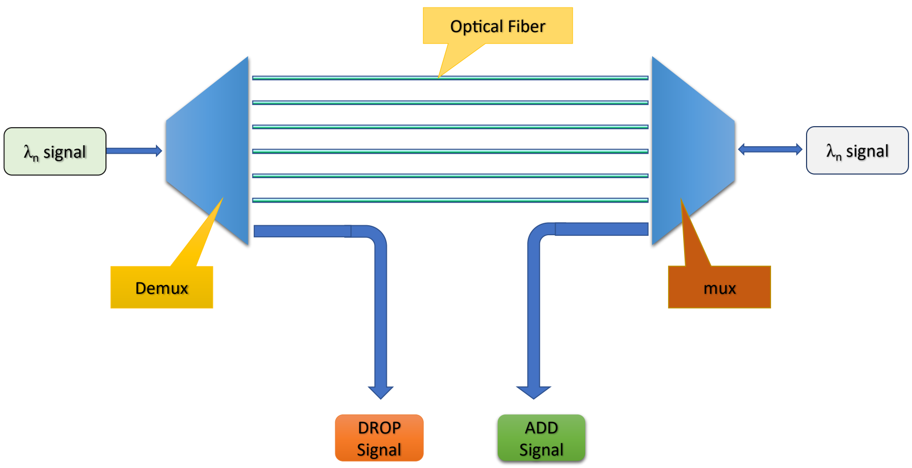


Figure 1.2 Conventional optical add-drop multiplexer demultiplexer consisting a demux, a mux and several optical fibers

communication line. This enables the manipulation of the signals within the communication line without disrupting the overall transmission process line [20]

1.3.1 Wavelength Selective Switch

A wavelength selective switch (WSS) is an essential optical element used in WDM systems that allows optical signals of specific wavelengths to be switched from an input port to multiple output ports. Typically, a WSS is composed of a demultiplexer, switching elements,

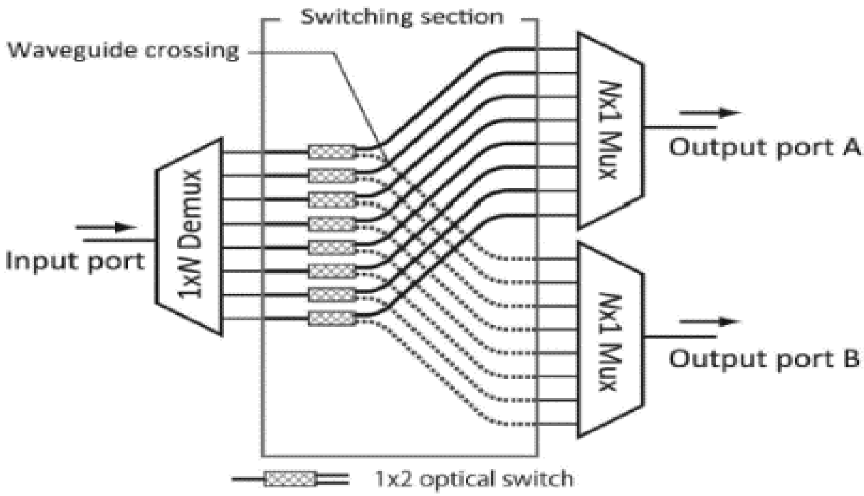


Figure 1.3 Wavelength Selective Switch with one input and two output [56]

and a multiplexer. The demultiplexer splits the inserted WDM signal into separate signals based on wavelength, which are then directed to the appropriate switching element that routes the signal to the desired output port. The signals are then multiplexed at each output port. With the use of multiple output WSSs, signals can be dropped or added in any direction based on their wavelength. This makes it possible to introduce colourless, directionless, and contention less reconfigurable optical add/drop multiplexers (CDC-ROADMs) at network nodes in WDM optical communication systems[21]. The figure 1.3 illustrates a 1x2 WSS that has one input and two outputs. When signals enter the input port, they are first demultiplexed, which separates them based on their wavelength. The resulting signals are then directed to the switching section, which transmits them to the multiplexers. In this configuration, there are two multiplexers, so the signals from all the n switches are directed to these two multiplexers. Once the signals are multiplexed, they are transmitted through the communication channel. The number of input signals that can be accommodated depends on the bandwidth of the devices being used.

1.3.2 Optical Cross Connects (OXC)

In DWDM networks, Optical Cross-connects (OXCs) are essential network elements that provide greater flexibility for network reconfiguration and improved network survivability. OXCs act as optical switches, allowing for the interconnection of optical signals between multiple input and output ports, thus enabling switching and routing capabilities[22]. The operation of an OXC can be broken down into four key steps

- Input Signals: Optical signals are received by the OXC at the input ports. These signals can be transmitted over

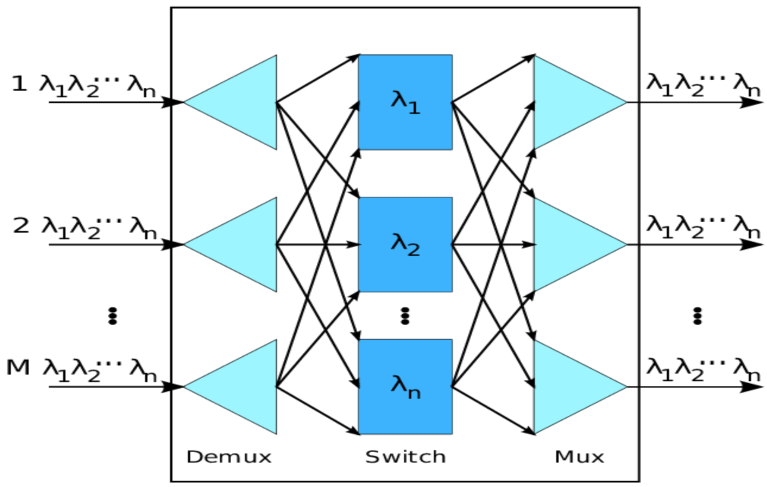


Figure 1.4 Optical cross connect architecture [22]

single-mode or multi-mode fibers and carry information such as data, voice, or video.

- Wavelength Separation: Once the optical signals are received, they are separated by wavelength using a wavelength demultiplexer. This enables individual wavelengths to be directed to the appropriate output port.

- Switching and Routing: The separated wavelengths are then directed to the appropriate switching and routing elements within the OXC. These elements can be mechanical or optical switches, micro-electro-mechanical systems (MEMS)[23], or liquid-crystal-on-silicon (LCoS) [24]devices. Output Signals switched and routed optical signals are then combined using a wavelength multiplexer and transmitted out of the output ports to their respective destinations.

1.4 Arrayed Waveguide Grating (AWG)

1.4.1 Introduction

Arrayed Waveguide Gratings (AWGs) are a type of optical multiplexer/demultiplexer that have become widely used in optical communication systems. They were first introduced in the early 1990s as a promising solution for increasing the capacity of optical fiber communication systems. Before the advent of AWGs, conventional multiplexers/demultiplexers used bulk optical elements such as prisms and gratings, which were large, expensive, and difficult to integrate with other optical components. AWGs, on the other hand, are based on planar waveguide technology, which allows for miniaturization and integration with other optical components. AWGs consist of an array of waveguides with varying lengths that are arranged in a planar structure. When light enters the AWG, it is split into different wavelengths by the waveguides, which act as narrow-band filters. The different wavelengths are then combined and sent out through a single output port, or separated into different output ports, depending on whether the AWG is being used as a multiplexer or a demultiplexer [19] One of the key advantages of AWGs is their ability to support high channel counts. AWGs can multiplex/demultiplex tens or even hundreds of channels in a single device, providing a cost-effective and space-efficient solution for high-capacity optical communication systems. Additionally, AWGs are wavelength insensitive, meaning that they can operate over a wide range of wavelengths without the need for adjustments or calibration. In summary, the introduction of AWGs marked a significant advancement in optical communication technology, offering a more efficient and cost-effective solution for optical multiplexing and demultiplexing. Their small size, high channel count, and wavelength insensitivity make them a vital component in modern optical communication systems.

1.4.2 Working Principle of AWG

The AWG-demultiplexer operates by using a waveguide array to separate a beam of light into its constituent wavelengths. As the beam enters the first Free Propagation Region (FPR), it loses its lateral confinement and becomes divergent. The beam is then coupled into the waveguide array and travels through individual waveguides towards the output aperture. To ensure that the fields in the individual waveguides arrive at the output aperture with equal phase (mod. 2π), the length of the waveguides is chosen so

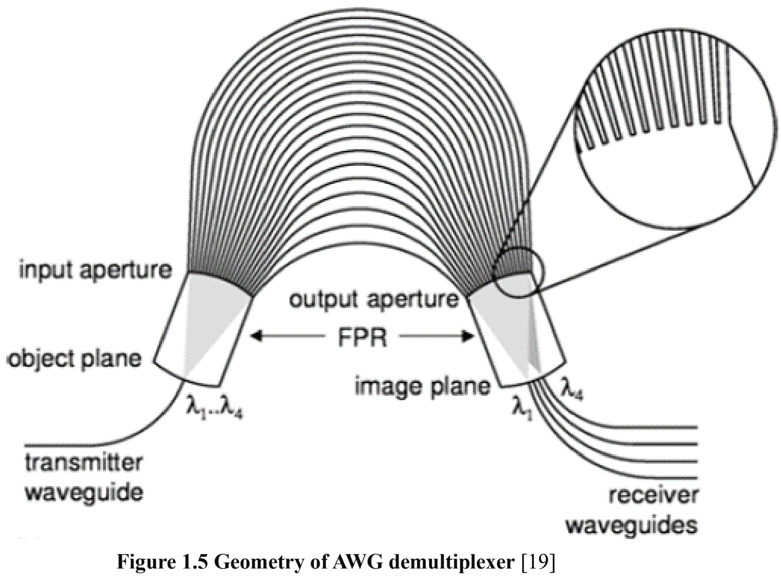


Figure 1.5 Geometry of AWG demultiplexer [19]

that the optical path length difference between adjacent waveguides equals an integer multiple of the central wavelength of the demultiplexer. This allows the field distribution at the input aperture to be reproduced at the output aperture, transforming the divergent beam into a convergent one with equal amplitude and phase distribution. The input field at the object plane gives rise to a corresponding image at the center of the image plane. By linearly increasing the lengths of the array waveguides, the spatial separation of different wavelengths is obtained, introducing a wavelength-dependent tilt of the outgoing beam. Overall, this process allows for efficient and precise separation of different wavelengths in a beam of light.

In an AWG, the focusing of fields propagating through the waveguides is achieved by ensuring that the length difference (ΔL) between adjacent waveguides is an integer(m) multiple of the wavelength of the light.

$$\Delta \mathrm{L} = \mathrm{m}.\frac{\lambda \mathrm{c}}{\mathrm{neff}} \qquad \mathbf{(1.1)}$$

This condition ensures that the fields arrive at the output aperture with the same phase, resulting in constructive interference and a clear output signal.[19] In other words, the precise alignment of the waveguides allows for efficient and accurate wavelength separation. The integer $\boldsymbol{m}$ is called the diffraction order of the array, $\boldsymbol{\lambda c}$ is the center wavelength and $\boldsymbol{n_{eff}}$ is the effective-refractive-index of the guided mode . In an AWG, the array of waveguides behaves like a lens, with object and image planes located at a distance a Ra from the array apertures. The focal line, which defines the image plane, follows a circular path with a radius (Ra/2) equal to half of the distance between the object and image planes. Transmitter and receiver waveguides should be located on this line to ensure optimal performance. This geometry is similar to a Rowland-type mounting, which is commonly used in spectroscopy to achieve high-resolution imaging. The precise alignment of the waveguides in the AWG ensures that the incoming beam is efficiently separated into its constituent wavelengths and focused onto the image plane. This makes the AWG a valuable tool in a wide range of optical

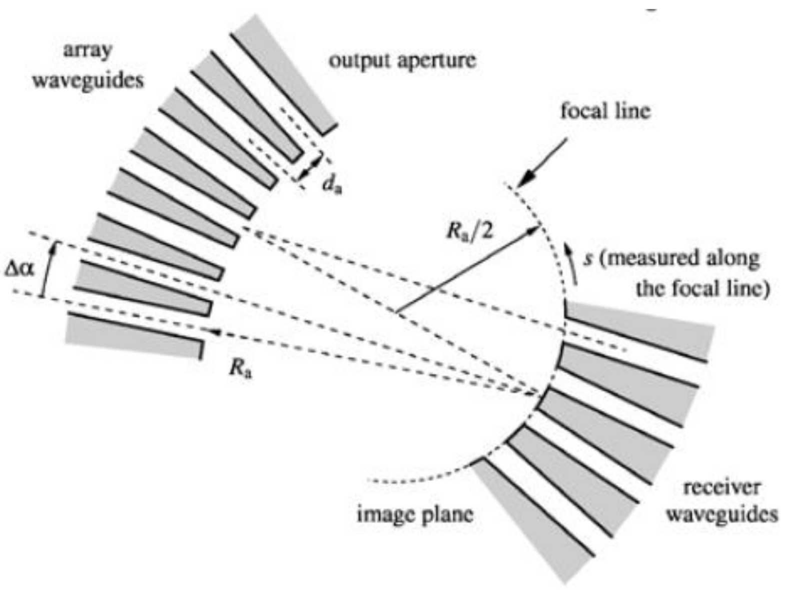


Figure 1.6 Design Geometry in AWG free propagation region [19]

applications, including telecommunications and spectroscopy. The length increment, denoted by ΔL, in the

waveguide array of an AWG introduces a phase difference between adjacent waveguides. This phase difference is given by the equation:

$$\Delta \phi = \beta \Delta L \qquad \textbf{(1.2)}$$

where λ is the wavelength of the light and $\boldsymbol{\beta = 2\pi\nu\frac{neff}{c}}$ which is the Propagation constant, **ν=c/λ** is frequency of the propagation wave and ***c*** is the light speed in free space.

The phase difference plays a crucial role in determining the wavelength-dependent tilt of the outgoing beam, which allows for efficient and accurate separation of different wavelengths. By carefully designing the length increment, it is possible to achieve high spectral resolution and excellent performance in various optical applications. When the input wavelength of an AWG is changed such that the phase difference between adjacent waveguides increases by a multiple of 2π, the response of the AWG remains the same. This periodic behavior is due to the fact that the AWG is designed such that the optical path length difference between adjacent waveguides is equal to an integer multiple of the wavelength of the light. The period of this periodic response in the frequency domain is referred to as the Free Spectral Range (FSR).

$$FSR = \frac{\nu}{m}\left(\frac{neff}{ng}\right) \qquad (\mathbf{1.3})$$

The FSR is defined as the frequency difference between two adjacent peaks in the transmission spectrum of the AWG. It represents the range of wavelengths over which the AWG can separate the different spectral components of an input signal. The FSR is a key parameter in the design and performance of AWGs, as it determines the resolution and accuracy of wavelength separation. By adjusting the design parameters of the AWG, it is possible to optimize the FSR and achieve high spectral resolution and accuracy in various optical applications[19]

1.4.3 Arrayed Waveguide Grating (AWG) Applications

Arrayed Waveguide Gratings (AWGs) are devices widely used in optical communications and spectroscopy applications. AWGs use an array of waveguides to separate an input signal into its constituent wavelengths, allowing for high-resolution and accurate analysis of optical signals [19]. One of the key applications of AWGs is in wavelength division multiplexing (WDM) systems [10], [12]. In WDM systems, multiple signals of different wavelengths are transmitted simultaneously over a single optical fiber. AWGs are used to separate the different wavelengths at the receiving end of the fiber, allowing for the recovery of the original signals. AWGs are also commonly used in spectroscopy applications, where they can be used to analyse the composition of a sample based on its spectral signature. In this application, the AWG separates the different wavelengths in the sample's spectrum, which are then detected and analysed. AWGs offer high spectral resolution and accuracy, making them a valuable tool in a wide range of spectroscopy applications. Another important application of AWGs is in optical sensing, where they can be used to detect changes in the optical properties of a material or environment. By monitoring changes in the transmission spectrum of an AWG, it is possible to detect changes in the refractive index, temperature, or other environmental parameters. In addition to these applications, AWGs are also used in a variety of other optical systems, including optical amplifiers, optical filters, and optical switches [25] With their high performance, versatility, and reliability, AWGs have become an essential component in many modern optical systems. In summary, AWGs are a key technology in optical communications, spectroscopy, sensing, and other optical applications. With their ability to separate and analyse different wavelengths with high resolution and accuracy, AWGs have revolutionized the field of optical engineering and enabled a wide range of new technologies and applications.

1.4.4 State-of-the-art AWG

PARAMTER	SPECIFICATION (VALUES)	
	Flat Top	Gaussian
Channel Spacing	100,50 Ghz	100 Ghz
Channel umber	96	48
Insertion Loss	<7 dB	<4.5 dB
Isolation (adjacent channel)	>22 dB	>25 dB
Polarization Dependent Loss	0.5	<0.5 dB
Return Loss	>40 dB	>40 dB
Operating Temperature	-10 ~+65 °C	-5 ~+65 °C

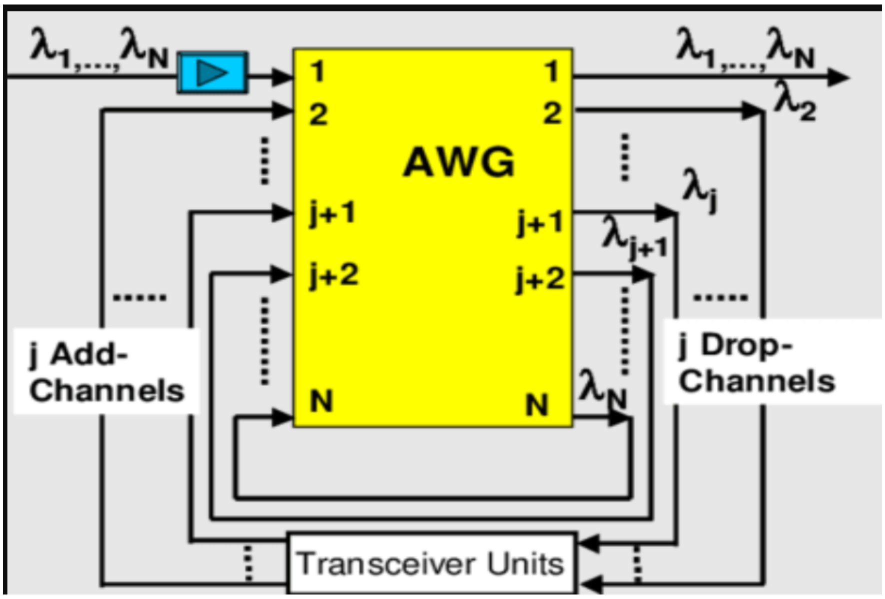
Table 1.1 AWG device parameters for flat-top and gaussian Technology [26], [27]

1.5 Applications of AWG in WDM System

Arrayed Waveguide Gratings (AWGs) are widely used in WDM systems as passive demultiplexers to separate the incoming signals into their constituent wavelengths [10]

1.5.1 Add Drop MUX – DEMUX

AWGs can be used as Add/Drop Mux Demux (ADMD) devices, which allow the extraction or insertion of individual channels at specific wavelengths while leaving the other channels undisturbed. An ADMD device typically consists of a multiplexer (MUX) and a demultiplexer



(DEMUX) connected by a set of waveguides that form a ring resonator.

Figure 1.7 Architecture of AWG OADM [57]

The AWG acts as the demultiplexer and separates the incoming signal into its constituent wavelengths. A switch can be used to select the desired wavelength channel for drop or add, and the AWG acts as the multiplexer to combine the remaining channels for onward transmission [28]

1.5.2 Wavelength Router

AWGs can also be used as N x N cross-connects in WDM systems, where N is the number of channels. N x N AWGs are used to route signals between different input and output ports, enabling wavelength-based routing of optical signals in the network. These devices have a

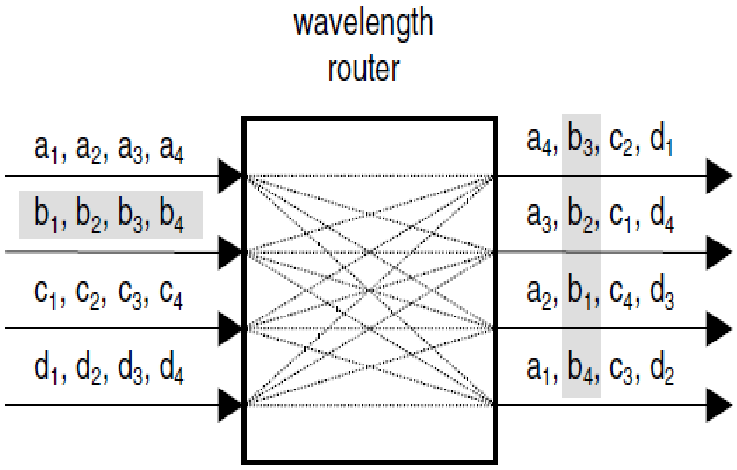


Figure 1.8 architecture of the wavelength router [25]

large number of input and output ports, which can be interconnected to form complex routing networks [29]

1.5.3 Wavelength Selective Switch (WSS)

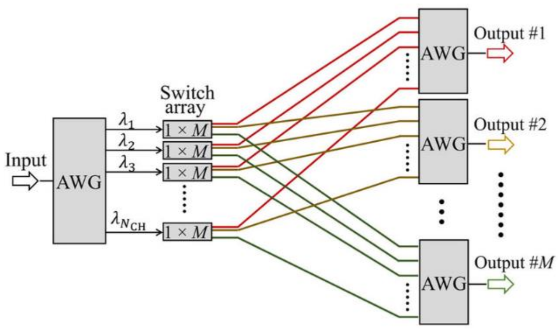


Figure 1.9 Wavelength selective switch architecture with AWG [58]

In addition, AWGs are also used in Wavelength Selective Switches (WSS), which are devices that enable dynamic reconfiguration of the wavelength channels in a WDM network. A WSS typically consists of an N x N AWG and a set of MEMS (Micro-Electro-Mechanical Systems) mirrors that can be individually controlled to route the incoming channels to different output ports [30]

1.6 Ring Resonator and its Application

Optical communication has progressively replaced electrical transmission over the last many decades. Tolerance to electromagnetic interference, minimum channel losses for large data speeds across long distances and high bandwidth capabilities per cable are all advantages of optical signalling over electrical transmission[31]. The benefits of photonics over electronics become obvious for smaller and smaller distances as communication bandwidth requirements continue to rise. Despite the multiple obstacles that short-reach electrical interconnects encounter, optics has typically remained absent from this sector because of the large number of optical components required per chip and their associated bulkiness. Passive silicon waveguide architectures, particularly wavelength selective devices and ring resonators, have demonstrated an extraordinary reduction in waveguide footprint [32], [33]. Photonic waveguides can have bend radii of less than 5 μm because of the large n_{eff} contrast between silicon and its oxide (or air), allowing for incredibly compact rings. Ring resonators are crucial to the growth of silicon photonics because they enable on-chip integration of photonic devices.

1.6.1 Introduction to Ring Resonator

Integrated ring resonators have evolved in integrated photonics in recent years and have made their way into a variety of applications.

MRR is a resonant cavity formed by a waveguide coiled around in a ring. The ring resonators use a parallel coupling waveguide to couple light from a straight waveguide to a circular shaped waveguide [34]. The distance between the interaction length and the ring is kept such that the desired frequency can be coupled into the ring. For optical

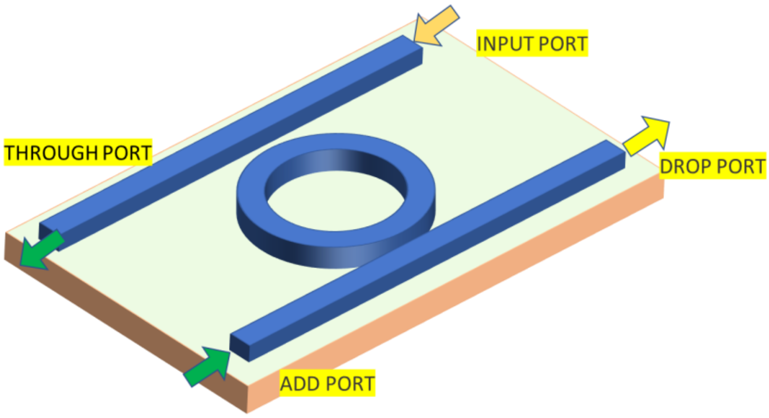


Figure 1.10 Basic Structure of micro ring resonator

feedback, integrated ring resonators don't need facets or gratings, making them ideal for monolithic integration with other components. A basic structure of the micro ring resonator is as depicted in Figure 1.10. MRRs find applications in optical sensors, filters, switches, optical amplifiers, routers and optical sources. The ring resonator is a key building block of a DWDM link. Unlike conventional WDM multiplexers, which use clunky arrayed waveguide gratings [33], that are hundreds of micrometers on a side, ring radii in DWDM links are on the order of 5 µm, allowing thousands of MRRs to be packed onto a single die.

1.6.2 Application Of Ring Resonator

Ring resonators have wide range of applications as shown in Figure 1.11. Ring resonators have been primarily investigated to be implemented as optical add–drop filters in optical networks. Several optical filter designs have been proposed and realized in semiconductors like purely passive devices, ring resonators with integrated gain sections and devices made out of active material. Optical filters need to be tunable in order to be deployed in optical networks and when it comes to ring resonators, the resonances of the ring resonator filter can be easily tuned. The researchers offer numerous manufactured devices that can be used for flexible dispersion compensation using ring resonators [35]. A square frequency response is essential in wavelength division multiplexing (WDM) applications. By combining a modified Mach– Zehnder interferometer (MZI) with a ring resonator, periodic multiplexers and demultiplexers with a flat passband and a large rejection region can be achieved. Ring resonators

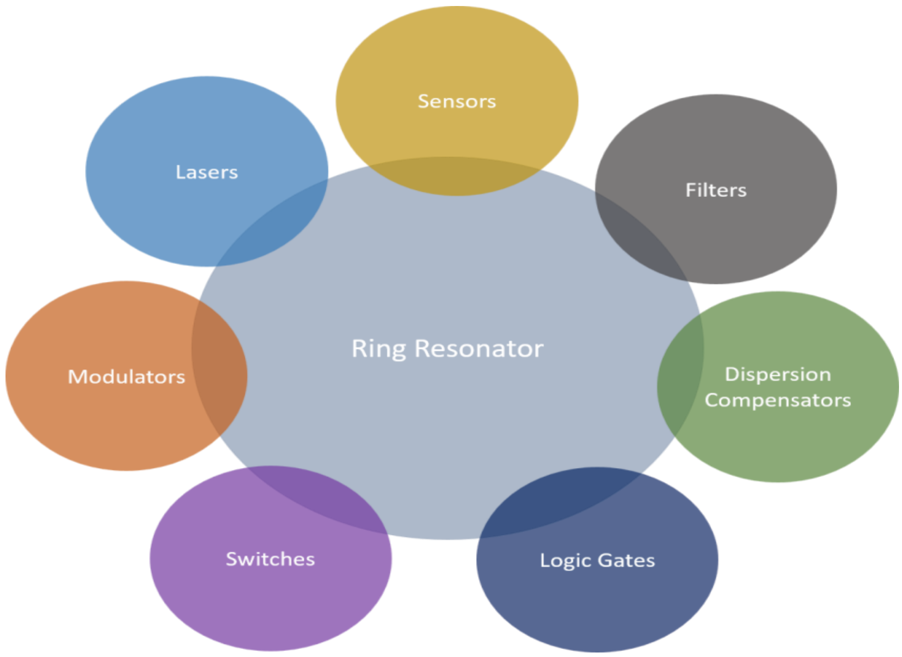


Figure 1.11 Different application of ring resonator

with very small radii have been developed thanks to advances in fabrication technique, allowing these elements to be used as modulators as well as logic gates and switching devices in optical signal processing systems [36]. Finally, as a latest technological movement known as Bio photonics emerges, MRRs have resurfaced in the form of sensors in this new field.

1.7 Organization of the Thesis

The thesis is organized in five chapters starting with an introduction and literature survey, one chapter consisting of the original research work followed by the conclusion and the future scope.

Chapter 2 Literature Survey: This literature review covers AWG with loop back, fold back, ADD DROP mux-demux configurations. AWG with loop back improves performance in multiplexing and routing. AWG with fold back reduces the device footprint. ADD DROP mux-demux combines AWG and WSS for dynamic routing. Crosstalk, bandwidth, and performance optimization are discussed.

Chapter 3 AWG Based OADM: Chapter three presents a proposed design for an OADM (Optical Add-Drop Multiplexer) and discusses its operation with the aid of optical circulators and switches. The design facilitates the routing, addition, and dropping of signals

Chapter 4 AWG with Ring Resonator: This chapter discusses the proposed design of AWG utilizing the ringreosnator. The design helps to improve the AWG crosstalk, and perform the drop operation. Due to less coupling efficiency race track resonator shows improved result than ring resonator.

Chapter 5 Conclusion and Future Scope: This chapter outlines the thesis and briefly discusses the future scope of the project.

Chapter 2

LITERATURE REVIEW

2.1 Introduction To literature view

The ever-increasing demand for network bandwidth has led to the emergence of optical networks such as optical local area networks and wavelength-division-multiplexing (WDM). These networks offer several advantages over traditional electronic networks, such as higher data rates, lower power consumption, and longer transmission distances. As a result, optical networks are becoming increasingly popular in various applications, including telecommunications, data centers, and high-performance computing. Among the popular integrated-photonics devices used in optical networks, the N x N arrayed waveguide grating (AWG) is particularly useful in WDM due to its ability to multiplex and demultiplex multiple channels within a single device. An AWG can separate a broadband optical signal into its individual frequency components, which can then be routed to different output ports. Similarly, an AWG can combine multiple signals at different wavelengths into a single output port. To enable optical dropping and adding of signals in WDM networks, various techniques have been demonstrated. One such technique involves using fiber Bragg gratings, which can reflect light at specific wavelengths, enabling the selective addition or removal of optical signals. Another technique involves using Si wire waveguides, which can be configured to drop or add signals at specific wavelengths. Multiple Mach-Zehnder interferometers and micro-ring resonators have also been demonstrated for this purpose. However, optical add-drop multiplexers (OADMs) using AWG are particularly attractive due to their advantages in terms of integration and robustness in fabrication. An OADM can be constructed using a conventional approach that involves using a 1 x N arrayed waveguide grating (AWG) demultiplexer, an N x 1 AWG multiplexer, and N optical fibers. This configuration allows for the selective addition or removal of optical signals using the appropriate signal processing equipment. However, the successful operation of this OADM is dependent on the precise alignment of channel wavelengths between the demultiplexer and multiplexer AWGs since they must function together as a pair. This limits the flexibility of the OADM and makes it difficult to accommodate changes in the network. In a conventional N x N AWG, N signals at the output port correspond to the frequency of the input. However, since the output is on the opposite side of the input, crosstalk is present. Crosstalk refers to the interference between adjacent channels, which can lead to signal distortion and degradation. Several OADMs using three AWGs and AWG with a loopback path have been proposed to overcome this limitation. In a three AWG OADM, three AWGs are used instead of two. The first AWG is used as a demultiplexer, the second as a multiplexer, and the third as a filter to remove the crosstalk signals. This configuration eliminates the need for precise wavelength alignment and allows for greater flexibility in the network. However, the use of three AWGs increases the size and complexity of the OADM, making it less attractive for some applications. Another approach is to use an AWG with a loopback path. In this configuration, the output port of the AWG is connected to the input port via a loopback path. This allows the crosstalk signals to be cancelled out by interference with their own reflections, improving signal quality. This configuration also simplifies the OADM design and reduces its size. However, AWGs with loopback paths have limitations in terms of the number of channels they can support and the level of crosstalk reduction they can achieve. Moreover, the loopback path introduces additional losses and phase errors, which can degrade the signal quality. To overcome these limitations, a new approach using a modified AWG with a loopback path and an additional output port has been proposed.

2.2 Review of AWG with Loop Back

The demand for higher data handling capabilities in WDM systems can be met by utilizing arrayed waveguide gratings (AWGs), which offer reduced crosstalk using various methodologies. Several research papers have explored the use of AWGs with loop back and fold back paths, many research papers have introduced the use of these methodologies for the implementation of signal add-drop functionality in WDM systems which will be discussed in this section.

Yoshiaki Tachikawa et.al-1996 [37]**:** This paper shows a 32x32 AWG multiplexer chip with 0.8nm channel spacing was fabricated using planar light wave circuit (PLC) technologies. It was used in the configuration of an integrated-optic AWG multiplexer with loop-back paths, which demonstrated an add-drop multiplexer (ADM), network access terminal, and wavelength channel selector for dense-WDM ring or bus networks. The device had low insertion loss of 3.9dB and low interchannel crosstalk of less than -28dB.

Xinyi Wang et.al-2020 [38]**:** The study presents a loopback arrayed waveguide grating (AWG) that can serve as a multi-tap finite-impulse-response (FIR) RF filter. Each delay channel provides a feedforward replica of the RF signal, and the bandwidth and center frequency of the filter can be tuned by adjusting the number of delay channels and time interval. The loopback AWG performs spectrum slicing and wavelength-selective delay, simplifying the light source requirement for the FIR filter.

Hideaki Asakura et.al-2015 [39] In this paper a Compact 17-channel 1x2 wavelength-selective switch using silicon wire waveguides and AWG with loopback has 200-GHz spacing. Chip size is 2.8mm x 6.5mm, with minimum and maximum loss of 21dB and 26dB, and crosstalk of -21dB and -2dB, respectively.

Osamu Ishida et.al-1994[40] Proposing an optimized configuration for a 2x2 switch based on an AWG multiplexer, using fold-back optical paths for significant crosstalk reduction and loss-imbalance equalization. The switch with a 16x16 multiplexer demonstrates coherent crosstalk of less than -30 dB and a reduction in loss-difference, extending the number of nodes in all-optical FDM networks.

2.3 Review on AWG with Fold Back

AWG is good in the foldback method because it can reduce crosstalk and improve signal integrity by using the same side waveguide for both input and output, resulting in a coherent signal with low loss and low inter-channel crosstalk. Additionally, the feedback loop can provide precise wavelength selection and tuning, making it useful for various applications in dense WDM systems and RF signal processing.

H. Takahashi et.al-1994 [41] A recent study explored an AWG with a fold-back path that prevents direct light transmission to the output waveguide. The experiment achieved an insertion loss of 10 dB and a crosstalk/signal ratio of -20 dB. Interestingly, the study demonstrated that the crosstalk/signal ratio reduced, indicating that the fold-back path method is effective in reducing unwanted signal interference in optical communication systems

Borja Vidal et.al-2003 [42]This study presents a new optical delay line (ODL) utilizing a fold-back configuration of an arrayed-waveguide grating (AWG), which offers improved crosstalk and loss-imbalance compared to the loop-back AWG-based ODL. The experimental results demonstrate the ability to achieve highly precise delays over a broad modulation bandwidth (2-18 GHz) using a single AWG.

Fumi Nakamura et.al 2021 [43] A novel 1xM wavelength selective switch using interleavers, 1xM optical switches, and AWGs in a fold-back configuration is presented. It has fewer waveguide crossings, reducing excess crosstalk and loss. A 20-channel, 1x2 silicon WSS with

200-GHz spacing demonstrated an insertion loss of 29.6 dB and extinction ratio of 10.9 dB.

Fumi Nakamura et.al-2018 [44] A novel 20-channel 1x2 wavelength selective switch (WSS) was designed using silicon photonics. It features 1x4 interleavers, arrayed-waveguide gratings (AWGs) connected to fold-back waveguides, and 1x2 optical Mach-Zehnder interferometer switches. The WSS has fewer waveguide crossings than conventional configurations.

2.4 Review on Optical Add-Drop Mux-Demux

Kwanil Lee et.al-2007 [45] A new optical add-drop multiplexer has been proposed for optical transport networks, which utilizes an arrayed waveguide grating. By incorporating circulators in the coupled fold-back paths between demultiplexed channels, the loss margin and crosstalk performances are enhanced.

Po-Tsung Wu et.al-2019 [46] This paper presents a reconfigurable optical add/drop multiplexer (ROADM) that utilizes arrayed waveguide gratings (AWGs) and optical switches (SWs). With SWs integrated into the ROADM, network managers can add/drop specific optical wavelength channels without disrupting other channels. Other channels bypass the add/drop function and are directed to the output port. Our proposed ROADM simplifies the add/drop process, permits multichannel input, and enhances flexibility, scalability, and affordability compared to previous ROADM designs. It is a promising solution for next-generation networks.

Edwin J. Klein, et.al-2005 [47] We present a compact and reconfigurable four-channel optical add-drop multiplexer (OADM) suitable for access networks. Our OADM is based on vertically coupled microring resonators (MRs) made of Si3N4-SiO2 materials, which can be thermally tuned across the full free-spectral range of 4.18 nm. The OADM occupies a small footprint of 0.25 mm2 and each individual MR has a 3-dB bandwidth of 50 GHz, making it a promising candidate for high-speed optical communication systems.

Shipeng Wang et.al-2017 [48] We introduce a silicon-based on-chip reconfigurable optical add-drop multiplexer (ROADM) designed for hybrid wavelength-division-multiplexing-mode-division-multiplexing systems. Our proposed ROADM comprises a four-channel mode demultiplexer, four wavelength-selective thermos optic switches utilizing micro ring resonators, and a four-channel mode multiplexer. This ROADM enables adding or dropping a wavelength channel of any mode to or from the multimode bus waveguide with an excess loss of 2-5 dB and an extinction ratio of approximately 20 dB across a wavelength range of 1525-1555 nm.

2.5 Research Objectives

After doing the deep literature survey on the past works related to AWG with loop back, AWG with fold back path and ADD DROP mux-demux I found the following area of improvement and worked through that. Following are the objectives of the research work carried out for this thesis

1. To utilize the Fold Back path in AWG for add drop functionality
2. To design the ROADM with the help of optical circulators and optical switch using fold back method
3. To analyse the Bit error rate and eye diagram for different functionality
4. To analyse the output spectrum with incorporation of ring resonator at the output of AWG.
5. To perform drop operation at the output of the AWG utilizing the ringreosnator.

Chapter 3

AWG BASED OPTICAL ADD-DROP MULTIPLEXER-DEMULTIPLEXER

3.1 Optical Switches

An optical switch is a device used to selectively control the routing of optical signals by manipulating their paths. The cross-bar and bar mode optical switches are two commonly used types of optical switches in telecommunication and data center applications. The cross-bar optical switch consists of a grid of waveguides arranged in a matrix [49] The input and output waveguides are perpendicular to each other and intersect at each waveguide junction. The switching function is performed by the electro-optic effect, which is achieved by applying an electric field across the waveguide junctions. When a signal is input into the waveguide, the electric field can change the index of refraction, causing the signal to either cross to an output waveguide or be reflected back. The bar-mode optical switch, also known as a 2x2 optical switch, consists of two parallel waveguides that are brought into close proximity, but not touching as shown in figure 3.1 (a). The waveguides are separated by a small gap that can be filled with a material whose index of refraction can be varied by an external control signal. By applying a control signal, the refractive index of the gap material changes, causing the light signal to be guided to either the through port or the cross port. The switching mechanism can be either mechanical or non-mechanical, such as using electro-optic or thermo-optic effects. When the switch is in the bar mode, the input signal is allowed to pass straight through to the output port. But when it is switched to the cross mode, the input signal is directed to the other output port, resulting in a change in the signal path.

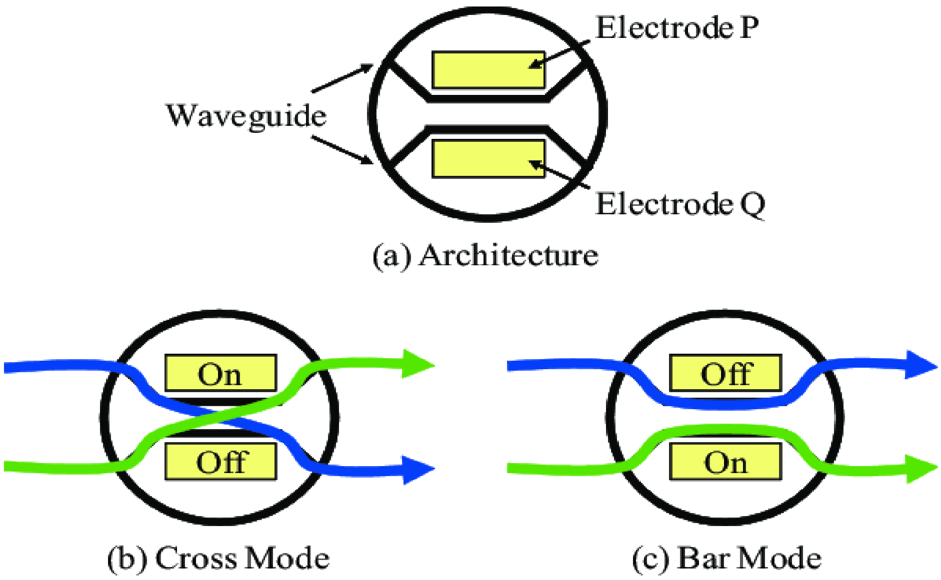


Figure 3.1 Optical circulator internal architecture

Both cross-bar and bar-mode optical switches are widely used [50] in optical networks for their fast-switching speed, low insertion loss, and high extinction ratio. The choice of which type of switch to use depends on the specific application requirements, such as the number of input and output ports, the speed of the switching operation, and the desired level of control over the switch operation [51]

3.1.1 Key-Performance Parameters of Optical Switches

There are several figures of merit that decide the performance of an optical switch and some of those are listed as extinction ratio, optical bandwidth, insertion loss, device footprint and power consumption. Extinction Ratio: It is one of the foremost vital figures of merit for an optical switch. It is defined as the ratio of two intensities: Imax-the intensity transmitted when the switch is in ON state and Imin is -the intensity transmitted when the switch is in OFF state. It is represented in decibels and expressed as: 10log (I max / I min). A large extinction ratio is desirable. Optical Bandwidth: It refers to the useful operational wavelength range of the device. A wide optical bandwidth is preferred. Ring resonators provide optical switching over a large bandwidth as their resonance wavelengths are easily tunable. Insertion Loss: It considers the optical power lost when the switch is added into the photonic circuit. It is a passive loss which comprises reflection, absorption, and mode coupling losses. Device Footprint: It is the footprint area occupied by the switch. Device footprint area should be as minimum as possible. Ring resonators with small radii have less device footprint hence making it suitable for on-chip nanophotonic applications. Switching Power: This parameter becomes particularly important when optical interconnects are considered. It is the amount of power consumed for switching the optical signal on and off.

3.2 Optical Circulators

Optical circulators are passive devices that allow light to propagate in only one direction through a fiber-optic system. They are typically three-port devices that are designed to be used in fiber-optic communication systems.

In an optical circulator, light enters from port 1 and is directed to port 2. Light entering from port 2 is directed to port 3, and light entering from port 3 is directed back to port 1 [52]. This one-way flow of light is achieved by using Faraday rotation, a phenomenon in which the polarization of light is rotated as it passes through a magnetic field. [53]

Optical circulators are used in a variety of applications, including in

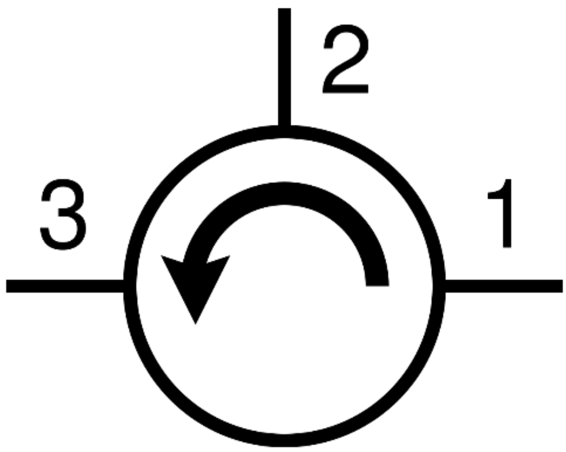


Figure 3.2 Optical Circulator diagram

fiber-optic communication systems to route signals and in fiber-optic sensors to detect changes in temperature, strain, and other physical parameters. They are also used in fiber-optic gyroscopes, which are used for navigation in airplanes and other vehicles.

3.3 Proposed Design of ROADM

3.3.1 NxN AWG Routing Behavior

An arrayed waveguide grating (AWG) is an optical device that has both multiplexing and demultiplexing properties. It is widely used in optical communication systems to combine or separate multiple wavelength channels in optical fibers. An AWG of N×N can demultiplex signals in a different way at the output side when N signals are fed into the input ports through different input ports. For example, when 8 signals are fed into input port 1 of an AWG, they are demultiplexed and distributed to port 1 onwards. However, if the same 8 signals are fed into input port 2, then signals 2 to 8 will be demultiplexed and distributed to ports 1 to 7, while signal 1 will be demultiplexed and distributed to port 8. This behaviour is due to the way the waveguides in the AWG are designed and arranged.

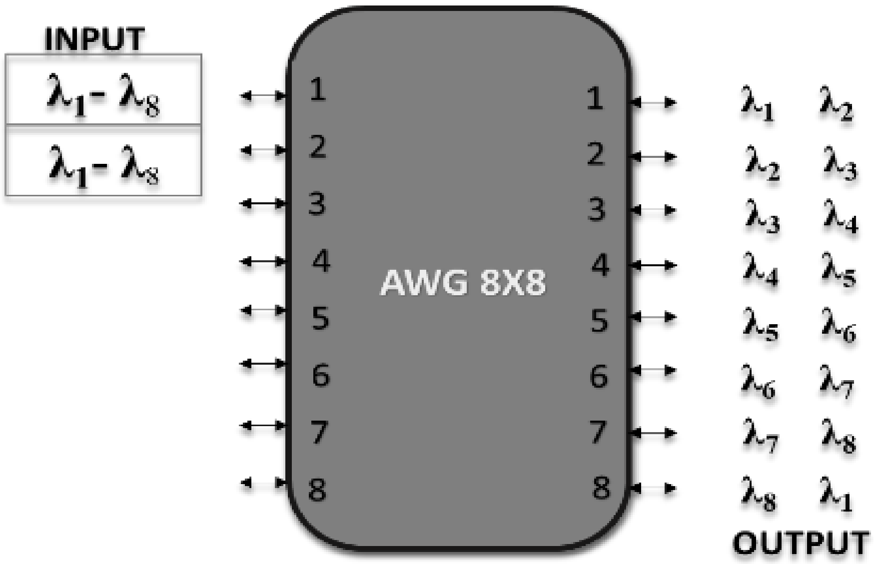


Figure 3.3 Routing behaviour for 8X8 AWG

3.3.2 AWG With Fold Back Method

AWG (Arrayed Waveguide Grating) Foldback is a technique used to improve the performance of an optical add-drop multiplexer (OADM) based on an AWG. In a traditional AWG-based OADM, some channels may experience higher loss or crosstalk due to the channel spacing, causing degradation in the signal quality.

AWG Foldback solves this problem by adding a circulator and a foldback waveguide to the OADM. The circulator allows the signal to be sent back to the AWG for further processing instead of going straight to the output, while the foldback waveguide guides the signal to a different part of the AWG. This effectively doubles the channel spacing

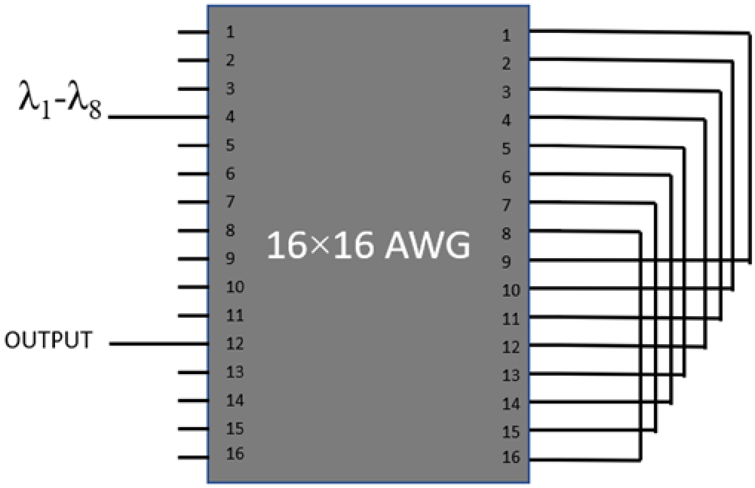


Figure 3.4 16X16 AWG with foldback path configuration

and reduces the effects of crosstalk resulting in improved loss margin and crosstalk performance. The fold-back method, depicted in above figure is used in 16×16 AWGs. In this method, eight signals ranging from λ1 to λ8 are fed through port 4 and are demultiplexed at the output ports 9 to 16. The fold-back method works by connecting R_{i+8} to R_i, effectively folding the output ports back towards the input ports. As a result, all eight signals are guided back from port 1 to port 8. The output ports are located on the same side as the input ports, preventing crosstalk light from directly reaching the output ports [54]. This method is commonly used in AWGs for its ability to efficiently demultiplex multiple signals without crosstalk interference.

3.3.3 Functionality of Add / drop Multiplexer-Demultiplexer

The foldback method is a highly effective way to control signals for dropping and adding in optical communication systems. This method utilizes pairs of Optical Circulators (OC) and Switches (SW) to achieve this control. When signals are transmitted without additional functions, all switches are set to the bar mode. However, when specific signals need to be dropped or added, the corresponding switch is set to the cross mode.

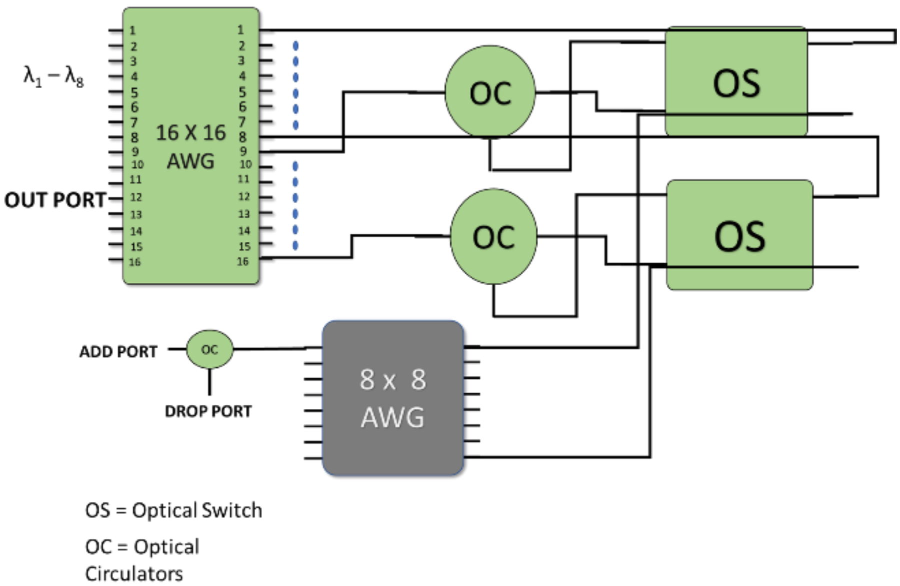


Figure 3.5 Proposed design for OADM

For example, if λ1 and λ2 need to be dropped, switches 1 and 2 are set to the cross mode. The dropped signal will be visible at the output AWG .To evaluate the effectiveness of this design, simulations were conducted using the FDTD-based method. This method allowed us to analyze and verify the performance of the proposed design, and make necessary adjustments to improve its efficiency.

Overall, the foldback method with OC and OS pairs is a reliable technique for controlling signals in optical communication systems as shown in figure 3.5. It provides a practical solution for managing optical signals in complex networks, ensuring efficient and reliable data transmission.

3.4 Results and Discussion

Figure 3.6(a) displayed the spectrum of the input signal from the CW laser is displayed with a power level of 0 db. 8 signals are fed to the design with a starting frequency of 193.1 THz and frequency spacing of 100 GHz When the optical switch is in the bar state, the signal remains unchanged, with no loss or manipulation occurring. Since the OS are in the bar mode, the incoming signal is first demultiplexed, and then passes through the OC and OS components. Subsequently, it is multiplexed again and finally appears at the output port. This can be seen in Figure 3.6(b), where the output signal has the same amplitude as the input signal. This is due to the fact that the simulation was set with no insertion loss, meaning that the same signal strength is maintained at output. Similarly, During the drop process, the cross mode was activated for optical switches SW3, SW5, and SW6. As a result, the signals 193.3 THz ,193.5 THz and 193.6 THz were properly separated, with the designated signals being dropped at the drop port and the remaining signals appearing at the output port. The spectrums after the drop operation can be seen in figures 3.6(c) and 3.6(d), which illustrate the signals at both the output and drop ports. The proposed ROADM was proven to be effective in the drop process by successfully dropping the signal wavelengths λ3, λ5, and λ6 at the drop port. Furthermore, wavelengths can be added back to the network through the add process, as shown in Fig. 3.6 (e) at the output port we are only inputting four signals with frequencies of 193.1 THz, 193.2

THz, 193.3 THz, and 193.8 THz. To add the 6th signal, we will set the corresponding optical switch (SW6) to the

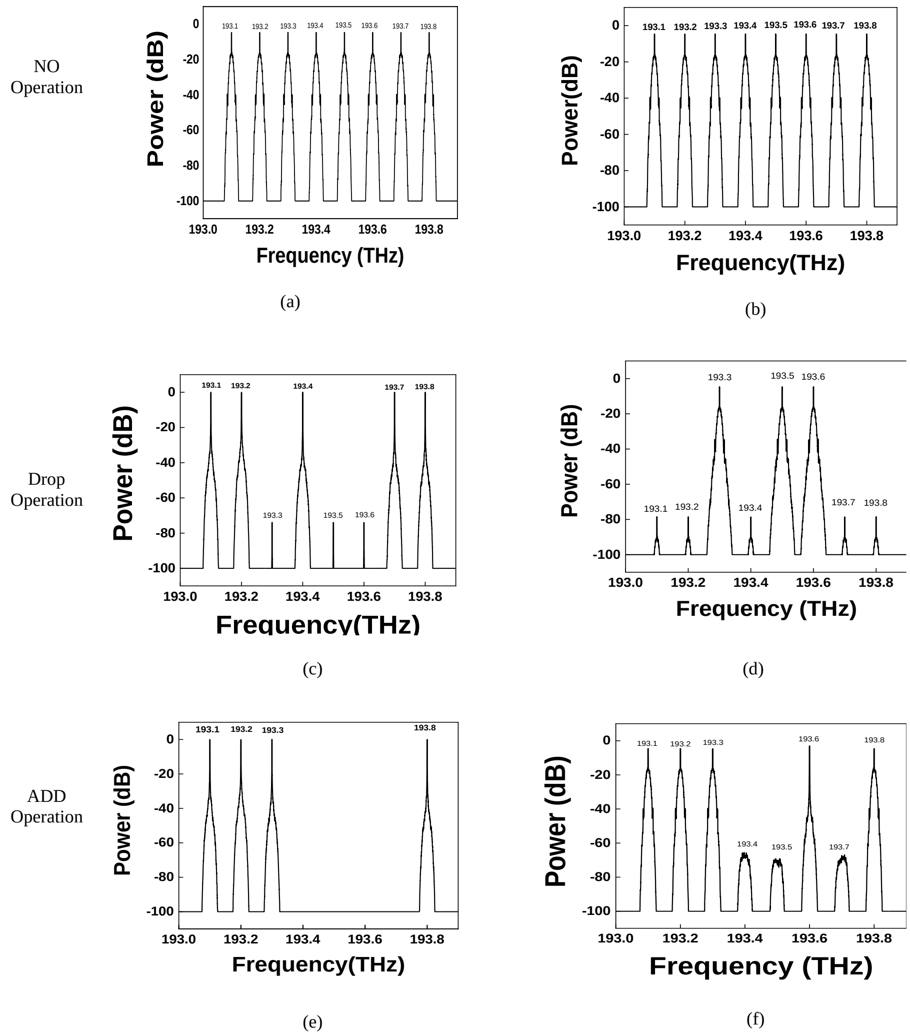


Figure 3.6 (a) The input spectrum consists of eight signals that originate from a continuous wave (CW) laser. The signals span a frequency range from 193.1 to 193.8, with a frequency spacing of 100 GHz. (b) The output spectrum includes all eight signals starting from 193.1 THz to 193.8 THz. Fig (c) After performing the drop operation on the output port, the resulting spectrum consisted of the remaining signals. Specifically, the signals at 193.3THz, 193.5THz, and 193.6THz were dropped by setting the corresponding optical switch to cross mode. (d) The signal spectrum after the drop operation showed that the dropped signals appeared at the drop port. (e) There are four signals at the input port, with frequencies of $193.1\ THz$, $193.2\ THz$, $193.3\ THz$, and $193.8THz$. (f) After adding a signal with a frequency of $193.6THz$ through the add operation, which involved setting the corresponding Optical Switch (OS) in cross mode, the spectrum of signals at the output port was obtained

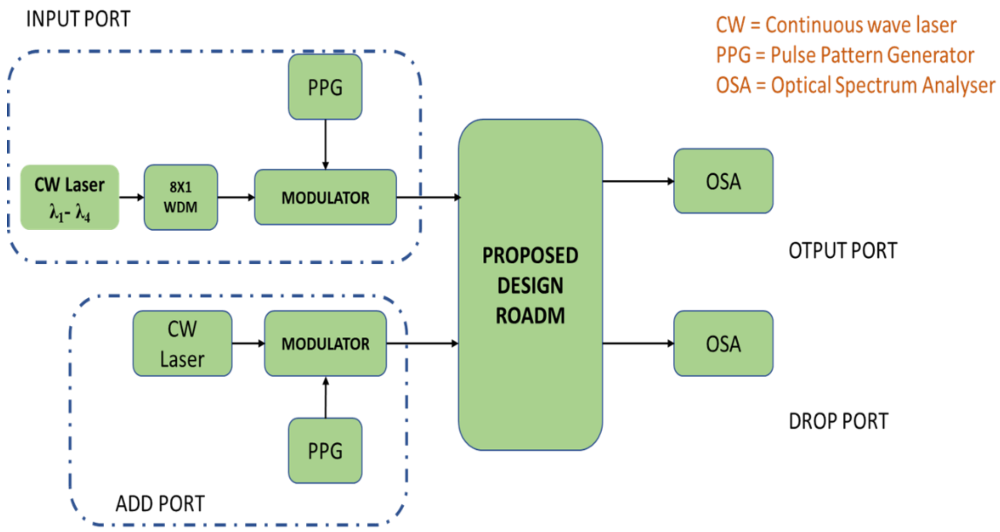


Figure 3.7 Block diagram for the data transmission components

cross mode. This approach enables us to observe the 6th signal at the output. To transmit data, we created random data sequence using a Non-Return-to-Zero (NRZ) pseudorandom bit generator. We then generated an optical signal by combining a Continuous Wave (CW) laser with WDM and sent it to a modulator to modulate the generated data. Finally, we sent the modulated signal to the proposed ROADM for further transmission. To add signals through the ROADM's, add port, we use the same methodology as described above to generate a modulated signal. This involves creating a random data sequence using a Non-Return-to-Zero (NRZ) pseudorandom bit generator, generating an optical signal using a CW laser combined with WDM, modulating the generated data onto the optical signal using a modulator, and then sending the modulated signal through the add port of the ROADM for further transmission. Based on the information provided in Figure 3.8, it can be observed While dropping that as the speed of data transmission increases, the eye-opening reduces, making the design more susceptible to noise. At a speed of 5 $Gbps$, the eye-opening is good enough to detect bits and is less transparent to noise. However, at a speed of 15Gbps, the eye-opening reduces, and the jitter starts to increase, with a reduction in quality factor to 10.78. This makes the design more prone

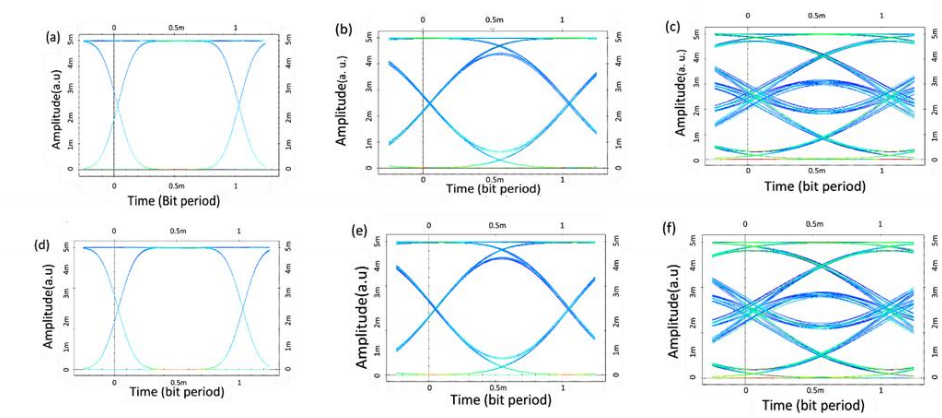


Figure 3.8 (a)-(c) shows the eye diagram for the dropping process at the transmission speed of 5 $Gbps$, 15 $Gbps$, and 25 $Gbps$, respectively. (d)-(f) shows the eye diagram for the adding process at the transmission speed of 5 $Gbps$, 15 $Gbps$, and 25 $Gbps$, respectively

to noise, which increases the bit error rate (BER). When the speed is increased to 25 $Gbps$ eye-opening reduces significantly to the point where it becomes difficult to detect bits, and the jitter increases more than the previous speed. As a result, the design has less noise margin, and the BER increases In Figure 10, we observe that as the speed of the design increases, it becomes more susceptible to noise, leading to an increase in BER, a decrease in Quality Factor, and an increase. in jitter visibility However, if we use the single channel dropping or adding operator, we can achieve a Quality Factor of nearly 771. This suggests that as we increase the number of channels being dropped or added, the Quality Factor decreases.

3.5 Summary

In this work a ROADM design is proposed with an AWG with the incorporation of the fold back method to reduce crosstalk. The system configuration enabled dynamic signal dropping and adding using OC and OS, allowing for dynamically dropping and adding of multiple signals. However, it was observed that the output port received a relatively low power of around -70 dB after dropping a signal. During data transmission, increasing the speed from $5Gbps$ to $25Gbps$ for signal dropping and adding led to a decrease in Quality Factor and an increase in noise although the bit error rate was less than 0.009. Interestingly, the Quality Factor was found to be higher for single channel dropping/adding compared to multiple signal dropping. It was also noted that the use of only two AWGs for the add and drop function makes the system more compact, and the fold back method shows promising potential for future WDM systems.

Chapter 4

AWG WITH RING RESONATOR

4.1 Introduction

Within the structure of an NxN AWG, there are several key components. These include the input waveguide, the free propagation region (FPR), the arrayed waveguide, and the output waveguide. The number of signals being utilized determines the configuration of the output waveguides. When a signal is injected through the input waveguide, it propagates through the FPR region before entering the arrayed waveguide. Finally, the signal is directed towards the output waveguide, where it is focused and guided accordingly. In an ideal scenario, an AWG should be able to focus each signal separately without any interference. However, in practice, this is not always achieved and we encounter a phenomenon known as crosstalk as shown in figure 4.1. Crosstalk occurs when a portion of the power from one channel signal leaks into adjacent channels, resulting in a degradation of AWG performance. This can lead to signal interference and reduced signal quality, impacting the overall performance of the system. Measures

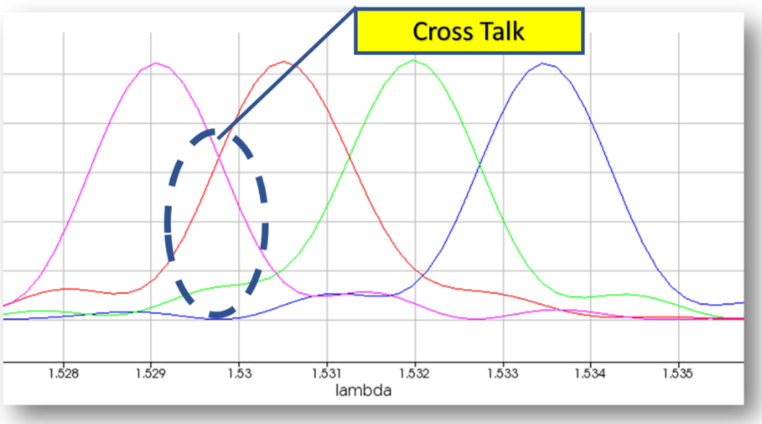


Figure 4.1 Output Spectrum of the 1x4 AWG

need to be taken to minimize crosstalk and optimize the performance of the AWG in order to ensure accurate and reliable signal transmission.

4.1.1 Proposed Structure of AWG With Ring Resonator

In the designed structure, the output side of the Arrayed Waveguide Grating (AWG) focuses each signal onto its respective waveguide. The proposed modification involves integrating a Ring Resonator (RR) at each output waveguide. These individual ring resonators are engineered to selectively accept the resonant signals, enhancing the overall performance of the system.

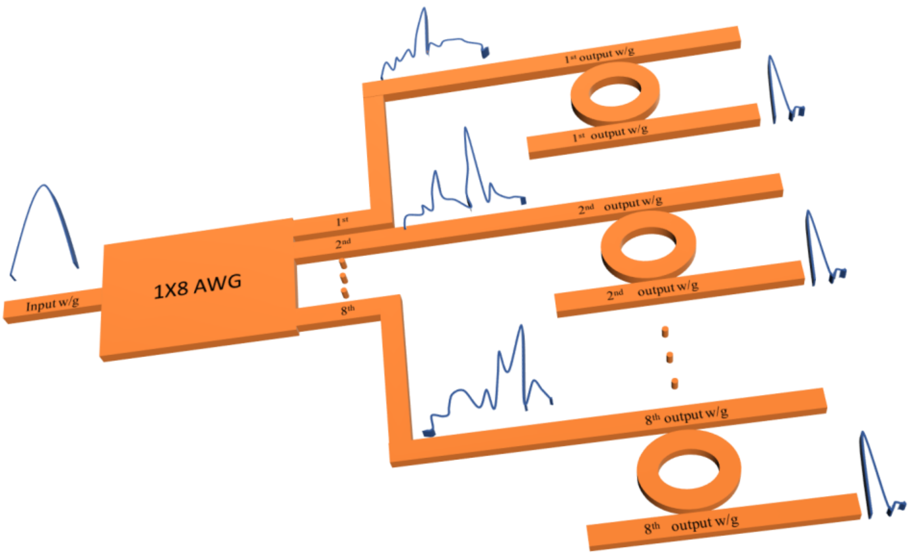


Figure 4.2 Proposed architecture of 1x8 AWG with ring resonator at each output waveguide

4.1.2 Working of the Device

The working of the device involves various steps as shown in figure 4.3.

Step 1: A broadband source will be utilized at the input waveguide of AWG with a center wavelength of 1550nm to provide input to AWG.

Step 2: Signal from input waveguide of AWG travel through its input side FPR region follow by travel in Array waveguides and demultiplexed at the output FSR to have different wavelength at each of output waveguide of AWG.

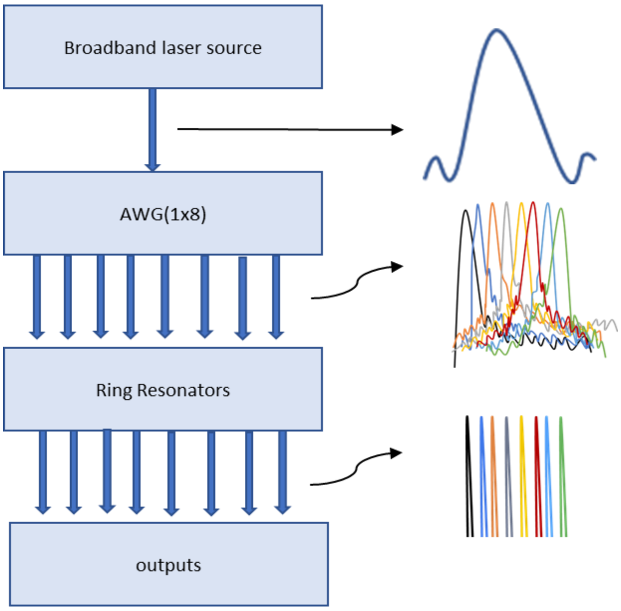


Figure 4.3 Block Diagram of the working of the proposed design

Step 3: Although the signal which appears at the output waveguide of AWG have some crosstalk. To reduce this crosstalk, we introduced ring along with the waveguide which in turn help us to achieve reduction in cross talk.

4.2 Modeling of Ring Resonator

The fundamental setup of a ring resonator is depicted in Figure 3.3, where a ring resonator of radius r is coupled unidirectionally with a waveguide. The optical signal is introduced at the Input port (In) and interacts with the ring resonator, which selectively couples certain

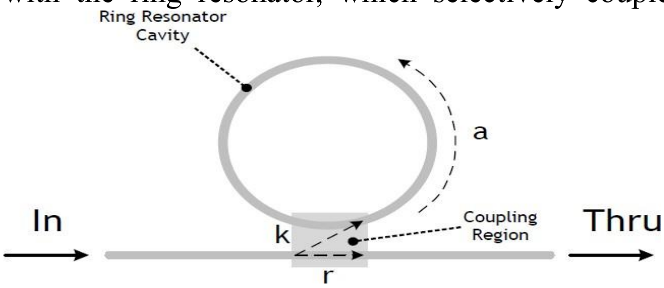


Figure 4.4 Microring resonator coupled to a bus waveguide through a coupling region [51]

wavelengths based on its resonant characteristics. The remaining light, which is not coupled, is collected at the Throughput port (Thru). The MRR's input port to through port transmission coefficient [55], α is specified by equation (3.1)

$$a = \frac{I_{thru}}{I_{in}} = \frac{a^2 - 2arcos(\varphi) + r^2}{1 - 2arcos(\varphi) + a^2r^2} \qquad (4.1)$$

where 'a' represents the MRR transmission for one roundtrip, 'r' denotes the bus waveguide's self-coupling, 'k' represents cross-coupling between the bus waveguide and the MRR. $r^2 + k^2 = 1$ as r^2, k^2 are the power splitting ratios of the coupler for a lossless coupling region.

The intensities at the input port and through port are I_{input} and I_{thru}. The quantity Φ is equal to the microring waveguide's single-pass phase shift, which is specified by $\Phi = \beta L$. β is the propagation constant, which is equal to $2\pi n_{eff} L/\lambda$, and L is the microring's round-trip distance. Effective refractive index is n_{eff}. When Φ is a multiple of 2π, the ring is in resonance. For a set of resonant wavelengths, λ0 this condition [55] is met.

$$\lambda_0 = \frac{n_{eff}L}{m} \qquad (4.2)$$

where m = 1,2,3………………

The transfer characteristics of the ring resonator are as shown in Figure 3.4. From in-port to through-port, MRR connected to a bus waveguide functions as a notch filter. Wavelengths that are not on resonance pass by the resonator, whereas wavelengths that are near to the λo's are caught, and the resonances are periodic in nature. The gap between resonances is called as the free spectral range (FSR) as shown in Figure. and is given by equation (4.3)

$$FSR = \frac{\lambda^2}{n_g L} \qquad (4.3)$$

where ng is the group index, that accounts for the silicon waveguide's dispersion. When on resonance, equation (4.1) reduces to

(4.4)

$$\alpha(\lambda_0) = 1 - A = \frac{a^2 - 2ar + r^2}{1 - 2ar + a^2r^2} = \frac{(a-r)^2}{1 - 2ar + a^2r^2}$$

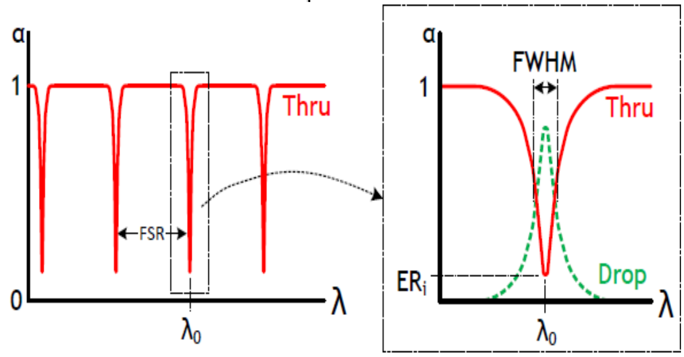


Figure 4.5 The optical transfer characteristics of a MRR that is resonant at λ0 [51]

Once the ring is critically coupled, r = a and α(λ0) = 0 i.e., the power coupled from the bus guide equals the rate of decay of energy owing to losses in the ring. Substituting this condition in equation (4.4) we get

$$\alpha(\lambda_0) = \frac{(a-a)^2}{1 - 2a^2 + a^2a^2} = 0 \quad (4.5)$$

As a result, for a MRR to have the maximum extinction in its response, it must be critically coupled. However, because 'a' depends on the MRR loss, which is a result of various factors, 'r' and 'k' can be varied by adjusting the separation distance between the waveguide and MRR to tweak the percentage of evanescent wave coupling [55].

4.3 Results and Discussion

In the simulation, a 1x4 Arrayed Waveguide Grating (AWG) is used with a broadband source cantered at a wavelength of 1550nm and a frequency spacing of 100GHz. The Finite-Difference Time-Domain (FDTD) method is employed to model and analyse the behaviour of the AWG. Figure 4.6(a) depicts the AWG output when no ring resonator has incorporated inside the design. The signal crosstalk level is more than 0.15. Figure 4.6 (b) depicts as we inserted the ring resonator the crosstalk level reduced to less than 0.1. Now due to insertion of the waveguide at the add port the signal which was resonating inside the ring can now be transferred to drop the signal. Figure 4.7 shows that the one signal has been dropped from the output of the AWG. Although the signal power 0.1 is still remaining in the waveguide.

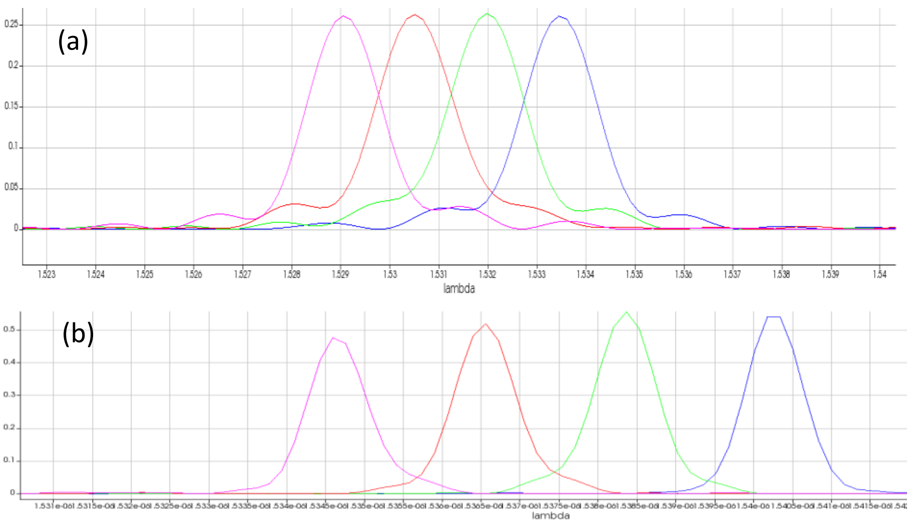


Figure 4.6 Spectrum at the output of the 1x4 AWG (a) spectrum without microring resonator (b) spectrum with microring resonator

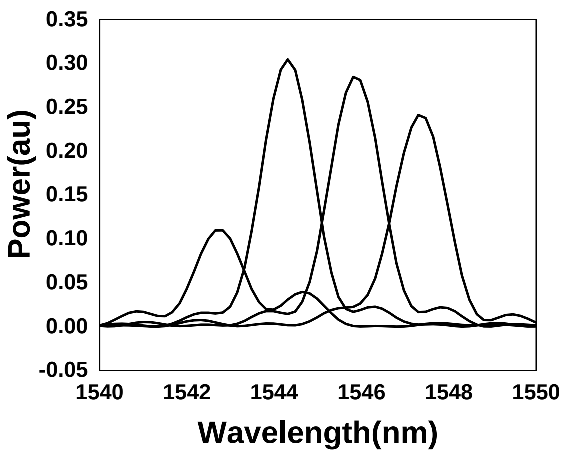


Figure 4.7 Output spectrum at the output of 1x4 AWG with ring resonator

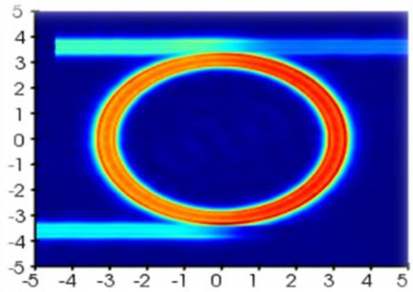


Figure 4.8 Electric field profile of the ring resonator

The figure 4.8 illustrates the propagation of the electric field within a ring resonator. One characteristic of ring resonators is their relatively short coupling length, which results in lower coupling efficiency. In contrast, racetrack resonators have longer coupled lengths that are determined by their coupling coefficients. Due to this extended coupling length, racetrack resonators have demonstrated higher power

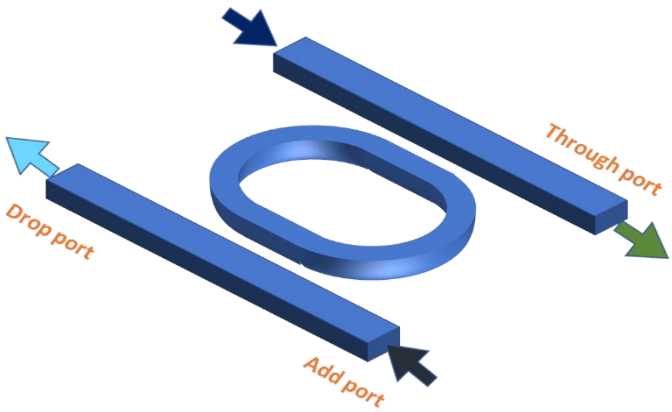


Figure 4.9 Schematic of the racetrack resonator

coupling capabilities within the resonator. The shorter coupling length of ring resonators limits their ability to efficiently couple power into and out of the resonator. On the other hand, racetrack resonators benefit from the longer coupling length, allowing for improved power transfer between the resonator and the external waveguides. This longer coupling length enables racetrack resonators to couple a greater amount of power inside the resonator, enhancing their overall performance. The coupling efficiency plays a crucial role in determining the amount of power that can be effectively coupled into the resonator. The racetrack resonator's larger coupling length facilitates a more efficient transfer of power, making it a preferred choice in applications where maximizing power coupling is essential. However, it's important to consider the trade-offs between coupling efficiency, device size, and other design requirements when selecting between ring resonators and racetrack resonators for specific applications. The provided figure depicts the insertion of a racetrack resonator, which results in enhanced power coupling and improved signal dropping capabilities. When a racetrack resonator is inserted into the optical system, it facilitates a more efficient transfer of power between the input and output waveguides.

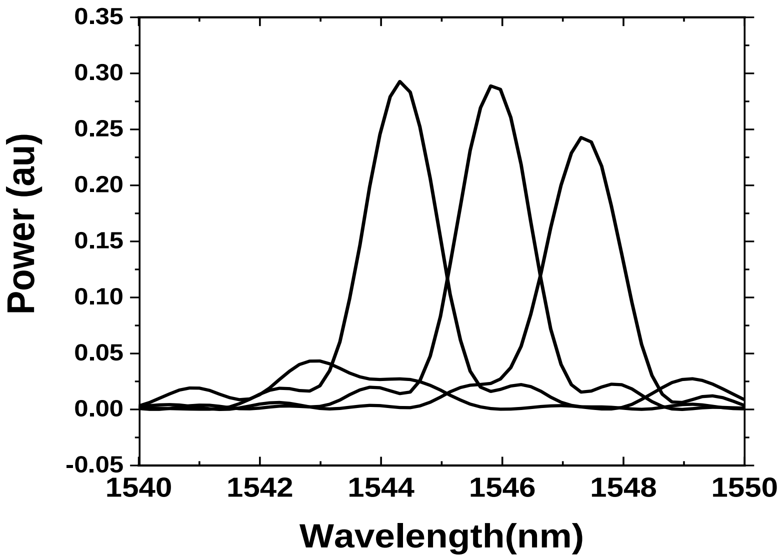


Figure 4.10 Spectrum at the output of 1x4 AWG with racetrack resonator

By introducing the racetrack resonator, the power coupling between the input and output waveguides is increased, allowing for a more effective drop of the desired signal. The enhanced coupling length provided by the racetrack resonator enables a better interaction between the resonator and the incident light, leading to improved signal dropping performance. The racetrack resonator's design and longer coupling length allow it to capture and direct a greater portion of the input signal into the resonator structure. This ensures that the signal, which may not have been fully dropped without the resonator, is now properly dropped and redirected as intended. Overall, the insertion of a racetrack resonator enhances the power coupling and improves the signal dropping capabilities within the optical system. It optimizes the interaction between the input and output waveguides, enabling efficient signal manipulation and transmission.

4.4 Summary

In this study, a ring resonator was integrated into the output waveguide of the AWG, resulting in a significant reduction in crosstalk to 0.05. The ring resonator effectively dropped the resonance signal, although a small amount of power (0.1 au) remained in the waveguide, potentially impacting device efficiency. This was attributed to the limited coupling area of the ring resonator, leading to lower coupling efficiency. In contrast, the race track resonator, with its larger coupling area, exhibited improved coupling efficiency. By replacing the ring resonator with the race track resonator, the dropping power was significantly enhanced, resulting in a more efficient signal drop. This finding highlights the importance of coupling efficiency in achieving effective signal manipulation in photonic devices.

Chapter 5

CONCLUSION AND FUTURE SCOPE

The demand for smaller, more efficient chips has risen with the increasing volume of data. Photonics chips and wavelength-division multiplexing (WDM) systems offer faster transmission rates. Optical add-drop multiplexers (OADMs) play a crucial role in routing signals between MAN networks. By integrating OADMs into network architectures, the growing bandwidth requirements can be met. The pursuit of smaller chip designs aims to handle large data volumes while maintaining compact form factors. These advancements in photonics chips and WDM systems revolutionize data transfer capabilities, enabling efficient communication between MAN networks. The major contribution of the thesis is summarized as follows:

- First a routing network consisting OC and OS is used in the foldback path of the AWG. Each individual signal will be folded back thorough this routing network. Based on the status of the optical switch the signal will be pass or perform add-drop functionality. Using the OC OS, we can also perform the ROADM

- To perform the data transmission, we first generated a pseudo random bit sequence then modulated with the help of signal coming from CW laser. The modulated signal is then transferred to the AWG. AWG demultiplex the signal and sends thought the routing network.

- By analyzing the eye diagrams, we have observed a notable trend. As the data transmission speed increases from 5 $Gbps$ to 25 $Gbps$, we have observed a reduction in the eye height and a significant decrease in the quality factor. This decrease in the quality factor indicates that the reliability of bit determination becomes more challenging at higher transmission speeds. More importantly bit-error-rate increases up to 0.009

- The output signal of an AWG typically exhibits crosstalk, which refers to the unintended transfer of signals between different channels. However, by incorporating a ring resonator into the system, we can achieve a significant reduction in crosstalk, typically around 0.1. While the ring resonator effectively drops a portion of the signal, it is important to note that it may not be able to fully eliminate the signal power due to its lower coupling efficiency. In contrast, the racetrack resonator offers a distinct advantage in terms of power coupling efficiency. With its longer coupling length, the racetrack resonator can more effectively drop the signal, resulting in a complete removal of the desired signal from the output. This characteristic of the racetrack resonator makes it a more suitable choice when the objective is to fully drop the signal and minimize crosstalk.

Although, the proposed OADM is designed to achieve better noise reduction and lesser crosstalk. Indeed, there remain several future possibilities to further accomplish and extend the objective of the thesis. Following are the future scope for the presented work:

- As WDM system are famous the WSS is one of the applications in WDM. By modifying the routing network this device can be used to perform the wavelength selective switch.
- Optical cross connects (OXC) is a device by which we can perform signal switching. Similarly using this OADM routing network one can modify and can perform the OXC characteristic

- AWG that has been analyzed is Si-based only, we can introduce Si-ITO heterojunction-based AWG to have an electrically tunable output AWG device.

- Si-ITO based ring modulator can also be introduced at the AWG's output waveguide utilizing the concept of modulation at various wavelengths for a same modulating signal which gave a way for development of optical SIMO device.

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