CHAPTER 1: INTRODUCTION

1.1 Introduction

The deployment of Next Generation Network (NGN) services such as video-on-demand, video-conferencing, tele-medicine, and e-Government applications has led to a need for a significantly higher communications capacity and faster access to telecommunication networks. In this regard, NGN services therefore need broadband level connectivity in order to be able to operate efficiently. The effect of such an advancement will surely be impactful our economics and lifestyle, having seen significant changes over the last two decades from the era of dial-up internet to the lighting speeds offered by FTTH systems. The trend of internet users is also increasing, and it cannot be denied that soon even the current bandwidths will be overwhelmed. Therefore, a new generation of broadband communications, is necessary to ensure smooth communications in the future.

The technology necessary to achieve the high speed and capacity desired can be provided for by fibre optics. The emergence of optical communication networks began with the invention of the laser by Schawlow and Townes in 1958, followed closely by the work of Kao and Hockham on the first optical fiber as a high bandwidth transmission line. Subsequent practical demonstrations of low loss optical fibers (20 $dBkm^{-1}$) as a communication medium was performed by Maurer et al. in 1970 [1-2]. These inventions and demonstrations heralded the possibility of replacing the existing electrical based communications network in the 1970s, and by 1979, experts have already foreseen that optical based systems would become the backbone of the telecommunication industry [3]. At the same time, optical fibers had already begun to replace coaxial cable as a transmission medium for linking the metropolitan central offices [4] and by 1982 the United States government deregulated the telecommunication industry, leading to large-scale adoption of optical fiber networks in the telecommunications gird. Nevertheless, general confidence in optical technology increased only slowly through the 1980s due to the limitations of signal amplification and regeneration, and it was not until the introduction of the Erbium Doped Fiber Amplifier (EDFA) in 1992 that the optical communications became a mainstream technology [3, 5]. EDFAs are optical devices that permit optical signals to be amplified without conversion to electrical signals, thus avoiding the electronic bandwidth bottlenecks while at the same time enhancing the length of the transmission link. Furthermore, the EDFA is able to supply gain to signals with different wavelengths concurrently, a significant advantage over the then-used electronic regenerators. These factors enabled the EDFA to become the key element in enabling the rapid growth in the optical fiber-based high-bandwidth communication infrastructure [3, 5].

While the EDFA provided the ability for long-range networks, it was the creation of the WDM systems in the 1990s that provided the large capacity of future networks, due to its ability to transmit the different wavelengths on just a single optical fiber. The advent of World Wide Web (WWW) in 1993 sparked the exponential growth of the data traffic on the communication network and the amount of network traffic and by 2002 data traffic had already dominated over voice traffic, indicating the shifting focus of modern communications [1]. The driving force behind this development was the enormous capacity demands for the network which the conventional copper cabling transmission links could not support. Therefore, the only viable solution was provided by optical fibers to overcome the bandwidth constraints of the copper cable and allow the realization of the NGN services in the future [6, 7]. However, a drawback of this solution lay in its complexity; as the demand for capacity continued to increase, so did the complexity of the optical communications network. This is turn required more and more sophisticated optical components capable of faster switching and routing, leading to bulky and expensive components. Therefore, a new alternative has to be found so that the optical communications network would remain commercially viable.

1.2 Planar Lightwave Circuits

Planar Lightwave Circuits (PLCs), also known as Photonic Integrated Circuits or Planar Waveguide Technology are the next generation of technology designed to cater to the need for ever more complex optical components. PLCs are essentially optical chips which are connected to transmission fiber to carry out a variety of functions such as wavelength multiplexing / demultiplexing, power splitting and optical switching [3]. Although they are usually employed in fiber-optics communication networks, PLCs can also be applied to the biomedical research [8], transportation, environmental monitoring and as sensors for defense and security. The most common material technologies utilizes in PLCs are silica-on-silicon, Indium Phosphate (InP), Gallium Arsenide (GaAs), silicon-on-insulator, and polymer technology, but the dominant technology remains silica-on-silicon, due to its lower coupling loss with optical fibers (as the refractive index of silica matches with the optical fiber).

Generally, PLCs are a planar arrangement waveguide on a substrate. In the case of silica-based PLCs, they are fabricated on a silicon or fused silica substrate by the combination of Flame Hydrolysis Deposition (FHD) and Inductively Coupled Plasma (ICP) techniques. The process begins with a deposited oxide layer as lower cladding followed by deposited core layer with slightly higher index. High temperature annealing is done after each deposition process to ensure low optical loss. The circuit patterns are formed with photolithography and ICP etch, and subsequently the upper oxide layer which has a lower index is deposited to embed the circuits. Alternatively, the circuits' pattern can be formed by UV writing. The wafer is then heated to high temperature for consolidation [9 to 12]. Of the many materials used in the fabrication of PLC devices, silica-based PLCs have received the most attention as a result of their low propagation loss, low coupling loss and reflection. Silica-based PLCs has the same refractive index and mode field diameter as conventional single mode fiber, and its excellent physical and chemical stability means that it can withstand the endface polishing necessary for coupling [13]. This makes silica-based PLCs a very commercially viable component, as the cost and simplicity of manufacturing the component provides a good profit margin.

The rapid growth in network traffic (internet traffic) has led to the need for enormous capacity photonics network system such as Dense Wavelength Division Multiplexing (DWDM) and Optical Time Division Multiplexing (OTDM) systems. These advanced networks require various types of highly functional photonics components such as optical switches, power splitters, wavelength selectors for optical cross-connects and WDM-routing systems [14]. Various types of optical signal processing systems with ultra-high speed (exceeding that of the electrical speed limit) and low power consumption will be needed to support the potential enormous capacity of future photonics networks [15]. In this regard, silica-based PLCs have emerged to be the promising candidate to realize highly functional and cost-effective components for large capacity photonic network. This technology has the ability to combine passive devices such as wavelength multiplexer and active device like semiconductor optical amplifier on PLC chip [16], providing a significant advantage in the size and cost of the system.

1.3 Integrated Photonics

In the 1970s, Miller [17] foresaw that integrated optics devices offer long term stability and eradicate the alignment issue inherent in bulk or fiber-based optics. It is therefore not surprising that the concept was quickly adopted in the bid to produce multi functional optical chips. In addition, the widespread use of photonics network has accelerated the development of various kinds of integrated photonics modules. The dominant material platform for optically passive functionalities is silica. Furthermore, active functionalities such as amplification and lasing are acquired by incorporating the glass matrix with rare earth materials. Combining both passive and active functionalities on a single chip would lead to more compact and cost effective devices.

In general, integrated photonics are grouped into 2 categories: monolithic integration and hybrid integration. Monolithic integration refers to a process in which all the components including the light source, waveguide and multiplexer are integrated on the same chip [18]. This overcomes the coupling problem between various kinds of components from different materials. Hybrid integration on the other hand is accomplished by assembling different optical components together from various materials onto one common platform. Common hybrid components are those from III–V compound light sources that are attached onto silica or polymer platforms [18]. The drawback, however, of hybrid integration is the bond holding the various optical components in different materials are subject to misalignment owing to the thermal expansion and vibration [19].

To reduce the high conversion cost of transferring data from the optical domain to the electronic domain in optical network, “all-optical” networks needs to be implemented [20]. “All-optical” here refers to a system where there are no electronic components applied on the optical network. This creates a win-lose situation; all-optical systems offer a significant advantage in terms of the speed and capacity of the system, but as the size and complexity of the network increases the more pervasive usage of optical components would result in almost exponentially higher costs. A solution is at hand; the replacement of bulky discrete optical components and interconnections in an integrated form will result in much lower manufacturing costs of photonics systems [21], thus allowing for more complex systems to be deployed without creating a significant dent in the budget.

Comparing Electronic Integrated Circuits (EICs) to Photonics Integrated Circuits (PICs), EICs commonly integrate millions of components, whereas PICs only integrate a few number of components, at most in the region of hundreds of components, owing to the strong nonlinear effects and shorter wavelength of electrons. This is the main reason that EICs can facilitate the far denser integration of components as compared to PICs. However, if a photon is made a carrier, then the high signal bandwidth can be reached [3], and thus integrating various optical devices on the single chip have become the ultimate goal for producing monolithic integrated optical device. It is here that the next stage of development for integrated devices becomes visible; the optical amplifier. Integrated optical amplifiers will become a critical component to overcome the losses that will accumulate in the PIC as more and more devices are embedded, resulting in high insertion loss.

1.4 Optical Amplifiers

With the advent of the Neodymium Doped Fiber Amplifier (NDFA) in 1964 by E. Snitzer, followed by the practical demonstration of the EDFA in late 1980s at Southampton University [22], a great transformation in the field of optical communications took place. No longer was optical communication networks bound to the limitations of electronics regenerators and electrical bandwidths, now fully optical networks with high speed and large capacities could be realized. The reason for this: the optical amplifier. The optical amplifier is a device to boost an optical signal without need to first convert it to electrical signal, making it very advantageous. Optical amplifiers can be classified into two main categories: fiber-based amplifier and planar optical amplifier. The more commonly used fiber-based amplifier in current optical communication network is the EDFA, which utilizes an Erbium Doped Fiber (EDF) as a gain medium to amplify an optical signal. A typical EDFA module consists of many discrete parts which are usually fiber-based and were manually spliced during the final assembly. However, the labor costs required for the assembly is expensive even though the cost of single device and material has dropped extensively in recent years [23]. By replacing the EDFA with a planar optical amplifier, numerous steps of assembly can be eliminated. On the other hand, planar optical amplifier which is build on the planar glass waveguide offer lower production costs and the prospects of integration with other components such as directional coupler and isolator [24].

Planar optical amplifier e.g. Erbium-Doped Waveguide Amplifiers (EDWAs) essentially operates same principle as EDFA. It may seem there is straightforward conversion in concept of the EDFA to EDWA. Nevertheless, in scaling down the device dimension from length of gain medium of EDFA to EDWA, the concentration of the erbium need to increase in order to achieve same amount of gain. The physical process becomes important in planar amplifier [25]. There are several materials that are suitable in producing EDWA such as polymer, silica on insulator and silica on silicon. However, the dominant material apply in making of EDWA is silica on silicon due to its low coupling loss. As with the EDFA, the EDWA use the rare earth erbium ions as the active element and mainly used to compensate the loss in splitters, multiplexers, and other device [26]. It also serves as a pre-amplifier for active device such as detectors [25]. The incorporation of an active gain element into the particular area is via selective area solution doping [27].

Typically, EDWAs compose of a pump laser, a pump/signal multiplexer (WDM) and an amplifying medium (spiral). Amplification is obtained by optically pumping (via the pump laser) the erbium ions through the pump/signal directional coupler in order to generate a population inversion. Stimulated emission is induced by an incoming optical signal (via pump/signal multiplexer) which results in optical amplification. The importance of pump/signal directional coupler will be elaborated in next section.

1.5 Pump/Signal Multiplexer

Pump/signal multiplexers (MUXs), which are also known as Wavelength Division Multiplexers (WDMs) are the basic building block of optical amplifiers and are used to multiplex both the pump and signal wavelengths into amplifying medium. The Pump/signal MUX plays a significant role in designing a highly efficient optical amplifier, and in order to get a high efficiency optical amplifier, the pump/signal MUX should have low loss of less than 0.5dB at the pump wavelength and less than 0.3 dB at the signal wavelength, low fabrication and polarization sensitivity and a relatively small size. The size is very important in the design of the optical device as space on the wafer is limited, and the tiny size also minimized the signal loss and absorption in the MUX [28].

There are several design that have been considered to multiplex two widely spaced wavelengths (typically, the pump and signal wavelengths are usually have a large gap between them, such as in the case of EDFAs where the pump wavelength is 980 nm and the signal wavelength is 1550 nm). For instance, the uniform symmetric directional coupler (US DC) is a frequently used pump/signal multiplexer in both fiber-based and planar-based optical devices [29] as well as curved waveguide couplers as a signal/pump MUX are also presented [30, 31]. However, the dimension of the curve waveguide coupler is relative large at more than 30 mm, making it unsuitable for building photonics integrated circuits. Other possible coupler designs include the multimode interference coupler, asymmetric Y-branch splitter and a filter with discrete delays.

In this work, the architecture of selected pump/signal MUX designs will be introduced. Here the 2 uniform symmetric directional couplers are placed parallel in order to multiplex the 1310 and 1550 nm signal wavelengths respectively using 2 different pump sources at 800 and 980 nm. At the same time, a hybrid pump/signal multiplexer and a new grating and directional coupler architecture are also numerical analyzed.

1.6 Device Design and Modeling

With the maturity of today's photonics technology, the design of photonics devices, especially that of integrated photonic devices becomes more complex and requires the use of dedicated numerical algorithms and related software for accurate simulation. In the case of the more advanced device designs such as Arrayed Waveguide Gratings (AWGs), which includes the introduction of an arbitrarily shaped optical waveguide, the basic model is unable to simulate the complex structure effectively, leading to incomplete and inaccurate models [32]. This results from the complexity of the new design, as well as the necessity for the incorporation of other physical models. Hence, for this purpose, different modeling techniques have been developed to meet the different analysis requirements of various photonics devices as well as to overcome the limitations of the previous models. A good example of this is the need to use numerous analytic and semi-analytic approaches to solve a wave equation built to compute eigen-modes and study the light evolution within photonics devices. However, these troublesome and tedious calculations can be reduced using methods such as the Finite Difference Beam Propagation Method (FDBPM), which is a popular approach for modes calculation and the description of field propagation in the complex structure [33].

The need for numerical modeling and device simulation lies in the fact that the fabrication of devices is a complex and long process; a typical fabrication of a photonics device would involve a multi-step process that takes several days. Therefore, any mistake in the design will only be discovered after a significant investment of funding, time and resources, and therefore the numerical simulation or device modeling should be carried out prior to fabrication to ensure an efficient device design and reduce the overall cost and time of device development. Even though there are lots of user-friendly computational tools for modeling and simulation available in the market, these tools are useless without an adequate understanding of the behavior of the photonics device and a solid background in the physics and mathematicss behind the graphical user interface is prerequisite for a complete interpretation of the simulation results [34]. Therefore, in this work, the use of the Rsoft BeamPROP is utilized to simulate the photonics devices while numerical simulations are carried out using 3D FDBPM. A full description of the physical and mathematical models that are used to develop this model is also discussed.

1.7 Objectives of the Thesis

The work in the research concerns mainly the design and simulation of a pump/signal multiplexer on a silica-on-silicon platform. The pump/signal multiplexer is an essential building block for waveguide amplifier and is used to multiplex and de-multiplex the pump and signal wavelength simultaneously. The effectiveness of the optical amplifier would decrease significantly without efficient multiplexing, and thus the achievement of 100% (no loss) coupling and the highest transmission power for both the pump and signal wavelengths at the desired output would be main focus of this work. The study is limited to the design of a pump/signal multiplexer in an EDWA and also a Bismuth Doped Waveguide Amplifier (BDWA). The objective of this work is to develop an optical chip capable of increasing the number of incoming wavelengths, thus overcoming the constraints of bandwidth. Specifically, the objectives and motivations of the research are:

1. To investigate and study the characteristics of pump/signal multiplexer (uniform symmetric directional coupler).
2. To obtain compact pump/signal multiplexer (uniform symmetric directional coupler) on silica-on-silicon platform.
3. To develop an optical chip for allowing higher data capacities.

4. To design a multiplexing system for application in waveguide broadband amplifier.

The next section provides the scope of the thesis.

1.8 Scope of Thesis

This thesis is separated into six chapters, with Chapter 2 describing the theoretical treatment of waveguide, the waveguide analysis method, and several designs and models of silica-based PLC pump/signal multiplexer. Also included in Chapter 2 is the coupled mode theory and FD-BPM which will be explained in detail. Chapter 3 provides the discussion on the design and simulation of the individual 980/1550 nm and 800/1310 nm uniform symmetric silica-based PLC pump/signal multiplexer, while Chapter 4 presents the design and simulation of a hybrid pump/signal multiplexer and used for application in broadband amplifier. The design combines two individual pump/signal multiplexers into one circuit which consists of 980/1550 nm and 800/1310 nm pump/signal multiplexer. Subsequently, Chapter 5 describes the design and simulation of an optical chip which consisting of planar Bragg grating and a uniform symmetric directional coupler as part of a multiplexer for applications in a proposed ultra broad band amplifier. Finally, Chapter 6 concludes the thesis.

1.9 References

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