CHAPTER 5: DESIGN AND SIMULATION OF SILICA-ON-SILICON HYBRID MULTIPLEXER FOR APPLICATION IN WAVEGUIDE BROADBAND AMPLIFIERS

5.1 Introduction

This chapter describes an optical chip consisting of uniform symmetric directional coupler and planar Bragg grating as part of a multiplexer module for application in waveguide broadband amplifier. In this work, the idea of add drop multiplexer is adopted. Its configuration is modified and designed as an optical chip to aim at achieving broadening amplification.

5.2 Silica-on-Silicon Hybrid Multiplexer

As already discussed in earlier chapters, the rapidly increasing demand for higher data capacities has led to innovation approaches in the area of optical amplifiers. Due to this, the design and application of a multiplexer for a waveguide amplifier can be used to overcome the heavy demands for bandwidth. In the design, the Bragg grating is employed. The unique characteristic of the Bragg grating is utilized to selectively filter out the ranges of wavelengths. Basically, two ranges of wavelengths are covered in the design: OE band (1260 - 1460 nm) and SCL band (1460 – 1625 nm). The uniform symmetric directional coupler is acted as a multiplexer also included in the design for the purpose of multiplexing. As illustrated in Figure 5.1, the directional coupler on the top is employed to multiplex the Ordinary-Extended (OE) band with 800 nm pump wavelength.

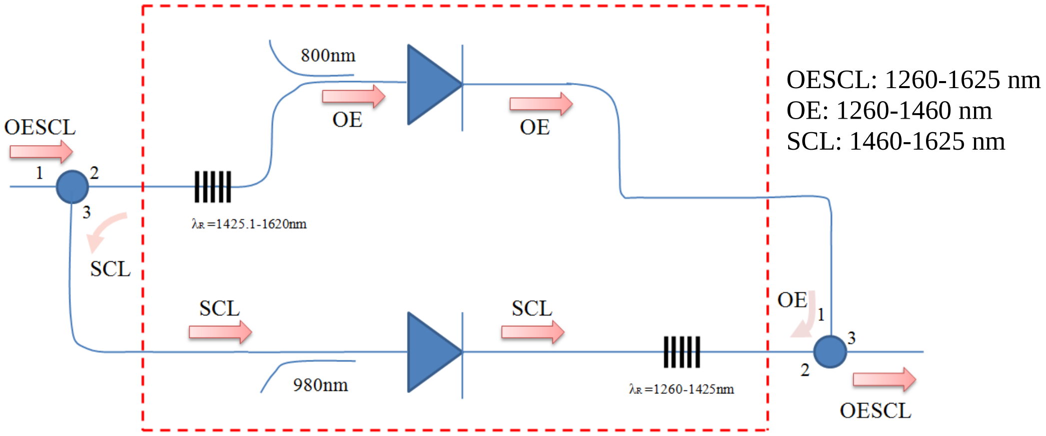


Figure 5.1: A schematic showing the physical layout of the silica-on-silicon hybrid multiplexer

It also can be seen from Figure 5.1 that the OE band passes through the Bragg grating and is then multiplex with 800nm pump wavelength. Subsequently, the OE band and the 800 nm pump wavelength will transmit into the bismuth doped amplifying region for amplification. Similarly, the coupler at the bottom serves as the multiplexing component of the Short-Conventional-Long Wavelength (SCL) band with 980 nm pump wavelength. The SCL-band is reflected from the first cascade Bragg grating and multiplex with 980 nm pump wavelength. The amplification is performed in the erbium doped amplifying region. The second Bragg grating serves to avoid the reflection of OE band to the erbium doped amplifying region. On the other hand, the fiber circulator is used to separate optical signals to travel in opposite direction. The major difference in this design to the silica-on-silicon hybrid pump/signal multiplexer design in Chapter 4 is utilization of broadband source or multiple signal wavelengths. Unlike the previous design, only 1310 nm and 1550 nm signal wavelength are employed. In this work, separate analysis for Bragg grating and directional coupler in the design as depicted in Figure 5.1 are carried out.

5.3 GratingMOD

GratingMod developed by the Rsoft using the BeamPROP interface to design and simulation for both fiber and integrated waveguide. It has a wide variety of grating applications including, but not limited to, fiber Bragg grating devices, dispersion compensators, narrow band and broadband filters. The software is based on the CMT algorithm for fast simulation as well as sophisticated multiple mode algorithms for advanced applications. Multiple types of grating profiles and apodization types are included in the GratingMOD package. It is a user-friendly and the theory behind calculation performed by the software is easy to understand. GratingMOD is utilized for simulation and analyzing the grating profile throughout this work.

5.4 Bragg Gratings

A Bragg grating is an optical wavelength filter which is created by a periodic variation in the effective index of a waveguide. A propagating light reflection takes place at each change of the refractive index. The repeated changes of the refractive index lead to the multiple light reflection. Therefore at the particular wavelength or Bragg wavelength, all reflected lights are in phase and add constructively. The reflected light is governed by the period of index modulation. Reflected light at other wavelength does not add constructively and are cancelled out. As a result these wavelengths are transmitted via the grating [1, 2]. The mechanism as stated above can be described using the following equation [1]:

$$\lambda_B = 2n_{eff}\Lambda \tag{5.1}$$

where λ_B is the Bragg wavelength, Λ is the grating period and n_{eff} is the effective index of the waveguide. Equation (5.1) is known as Bragg condition and it can be derived using the principles of energy and momentum conservation. However, the relation above does not provide any information about the bandwidth of the filter response and the strength of the reflection. The CMT can be used to predict this information. The derivation of CMT is not provided here. Instead, readers are directed to the following publications [3, 4]. Based on the CMT, the variation of reflectivity of a grating is given by:

$$r = \frac{\sinh^2(L\sqrt{\kappa^2 - \hat{\sigma}^2})}{\cosh^2(L\sqrt{\kappa^2 - \hat{\sigma}^2}) - \frac{\hat{\sigma}^2}{\kappa^2}} \tag{5.2}$$

where L is the length of the grating while κ and $\hat{\sigma}$ are coupling coefficients. The maximum reflectivity can be calculated as:

$$r_{\max} = \tanh^2(\kappa L) \tag{5.3}$$

The bandwidth of the uniform grating can be defined as the first minimum either side of maximum reflectivity peak or is expressed as:

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta n_{eff}}{n_{eff}} \sqrt{1 + \left(\frac{\lambda_B}{\Delta n_{eff} L} \right)} \tag{5.4}$$

If considering very small index perturbations where $\Delta n_{eff} << \frac{\lambda_B}{L}$, the equation 5.4 reduces to:

$$\frac{\Delta\lambda}{\lambda} \rightarrow \frac{\lambda_B}{n_{eff} L} \tag{5.5}$$

whereas for strong grating case, the equation reduces to:

$$\frac{\Delta\lambda}{\lambda} \rightarrow \frac{\Delta n_{eff}}{n_{eff}} \tag{5.6}$$

We use the unique characteristic of Bragg grating as explained above to design the broadband filter which is an important element in this multiplexer for waveguide amplifier.

5.5 Structures of Silica-On-Silicon Hybrid Multiplexer for Applications in Waveguide Broadband Amplifiers

The two-dimensional physical layout of the planar Bragg grating on silica-on-silicon in application of multiplexer for waveguide broadband amplifiers chip is illustrated in Figure 5.1. The chip is consists of two cascade planar Bragg grating, two uniform symmetric directional couplers, two circulator and two amplifying regions. For each cascade planar Bragg grating is serves as wavelengths filtering in the ranges of 1250 - 1460 nm and 1460 – 1620 nm respectively. Two uniform symmetric directional couplers with two different combination of wavelength (980 nm/SCL-band and 800 nm/OE band) are employed. However, for the design of 980 nm/SCL-band and 800nm/OE band couplers, the couplers design which are optimized for 1550 nm and 1350 nm, respectively.

The rectangular core cross-section of the planar waveguide utilized in the design is 4.5 μm × 4.5 μm. The core of the planar waveguide is sandwiched between upper and under cladding layers with lower refractive index. The refractive index of core and cladding are selected to be 1.464 and 1.445 respectively. The planar waveguide has a refractive index difference, Δ of 1.3%. For the coupler design, the curvature radius is set as 2 mm. For the cascade Bragg grating design, the modulation depth is fixed at 1.469. The acquirement of length of the grating and the period of each wavelength are discussed in the Section 5.4. The reflectivity of the each wavelength is set as around 99%. Table 5.1 shows the parameters of the silica-on-silicon hybrid multiplexer which will be utilize for the design.

Table 5.1: Parameters of silica-on-silicon hybrid multiplexer

Parameter	Values
Core dimension	4.5 μm × 4.5 μm
Refractive index of core, n_{core}	1.464 at 1550 nm
Refractive index of cladding, $n_{cladding}$	1.445 at 1550 nm
Refractive index difference, Δ	1.3%
Curvature radius, R	2 mm
Channel separation	<125 μm
Modulation depth	1.469
Maximum reflectivity	~ 99%

5.6 Simulation Results of Silica-On-Silicon Hybrid Multiplexer for Applications in Waveguide Broadband Amplifiers

Before the discussion of the simulation results, it is necessary to first elaborate the possible chip fabrication method. There are two possible ways to fabricate the chip. The first method is through the conventional CMOS process which is deposited by Flame Hydrolysis Method (FHD) and the chip is patterned via photolithographic and etching process. However, this option is costly and time consuming. An alternative method is using UV-writing system. To obtain a small form of devices, we utilized both sets of approaches. Initially, the under cladding and core layers are deposited using FHD, and then patterned by photolithographic and etching process. The grating structure was defined using UV-writing. In this work, the design parameter will be based on the constraint of the UV-writing. Thus index modulating grating on planar waveguide is applied on the following design instead of relief grating.

Owing to different devices being integrated into the chip, separate simulations were carried out. In this section, the simulation results are divided into two parts. The first part is the result of simulation on the grating structure on the chip whereas the second part is simulation outcome from the uniform symmetric directional coupler.

5.6.1 Simulation Results of Bragg Grating

The Bragg grating design was performed using Rsoft BeamPROP interface and validated via GratingMOD. In the simulation, two-dimensional structure was utilized and sinusoidal profile was adopted as illustrated in Figure 5.2. The Gaussian mode was selected as a launch field and the sScalar field was chosen owing to low polarization sensitivity of the grating structure (please refer equation (3.6)).

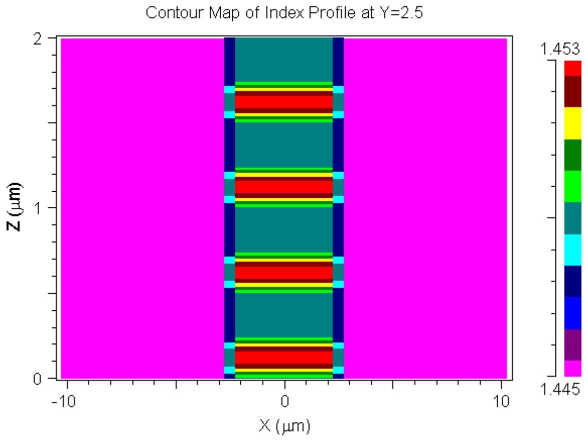
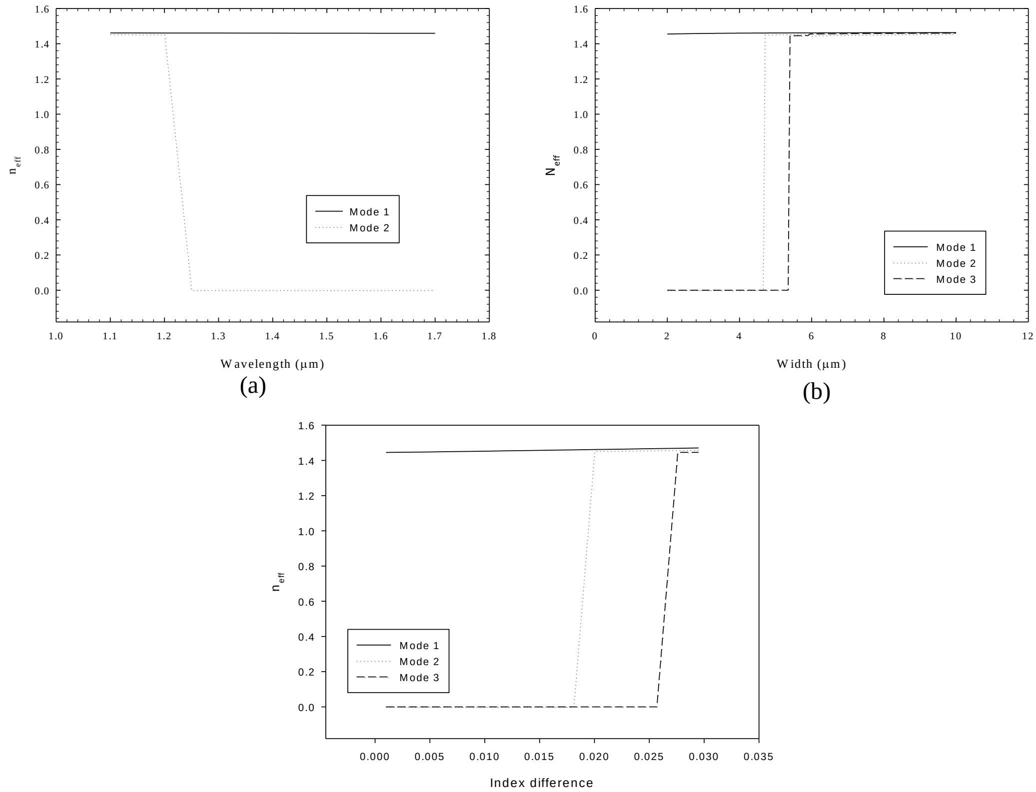


Figure 5.2: Two-dimensional sinusoidal bragg grating profile (top view)

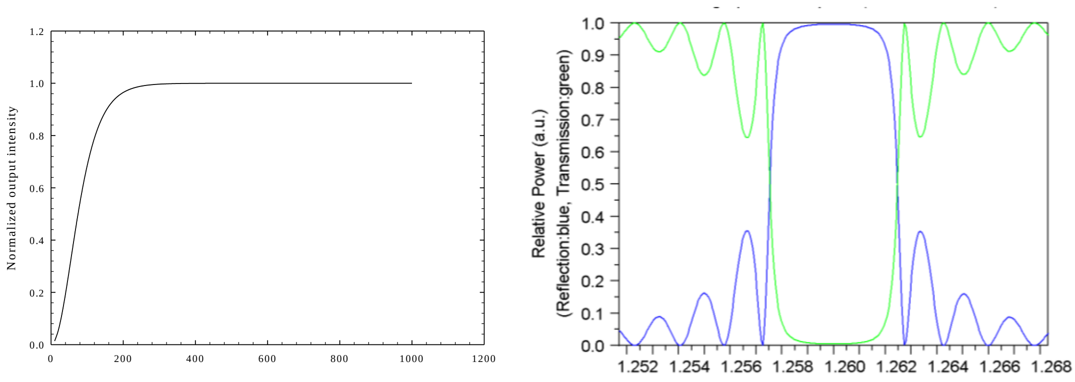
In this research the waveguide is taken as single modal at signal wavelengths in the range of 1260 - 1620 nm. Thus, it is necessary to carry out the mode calculation by solving the BPM mode. In Figure 5.3 (a), it is clear that the waveguide can only support fundamental mode (mode 1) at signal wavelengths from 1.26 μm onward at a delta of 0.019 and waveguide width of 4.5 μm. This means that the higher order modes are cutoff for signal wavelengths longer than 1.26 μm and similar analysis for waveguide width and delta were carried out. For the case of waveguide widths, it can be seen that the higher order modes are cutoff for waveguide width smaller than 4.5 μm as illustrated in Figure 5.3 (b). This analysis is under the condition of wavelength of 1.26 μm and delta of 0.019. Meanwhile, in Figure 5.3 (c), there is only fundamental mode supported by the waveguide for delta less than 0.019 in the condition of wavelength of 1.26 μm and waveguide width of 4.5 μm. Consequently, the waveguide parameters utilized in subsequent simulations allow for only fundamental mode.



(a) (b) (c)

Figure 5.3: BPM mode solver showing the single/multi mode propagation within the waveguide with respect to (a) wavelength, (b) width and (c) index difference.

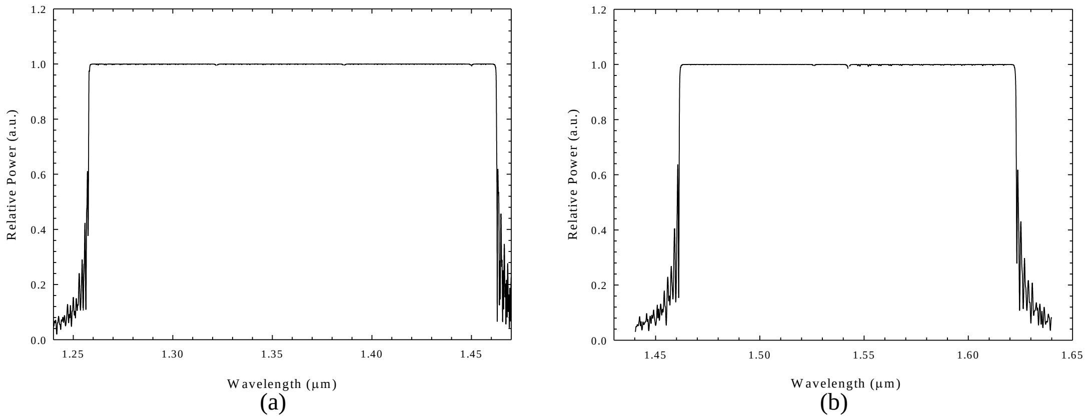
The single wavelength Bragg simulation was carried out initially instead of a simulation with multiple wavelengths. In this work, the Bragg wavelength λ_B of 1.26 µm was chosen It is because λ_B =1.26 µm is a shorter wavelength in O band. Initially, the investigation into reflectivity of the Bragg grating with respect to grating length was executed. Our aim here is to obtain at least 99.9% reflectivity. In Figure 5.4 (a), it is worth noting that the Bragg grating accomplish at least 99.9% reflectivity at grating length longer than 355 µm. We performed further simulation at fixed grating length of 355 µm. From the simulation results in Figure 5.4 (b), it is observed that there is 99.9% reflectivity at the peak of 1.26 µm and the spectral FWHM at 1.26 µm is 4.73 nm.



(a) (b)

Figure 5.4: (a) The graph showing that normalized output intensity as a function of grating length and (b) the transmission and reflection profile of a Bragg grating structure at Bragg wavelength 1.26 μm.

As given in equation (5.5), the reflectivity bandwidth increased for longer wavelengths. Hence, it can be attributed to the reflectivity bandwidth that the spectral FWHM is more than 4.73 nm when shifting to the longer wavelengths. The procedures as stated above are repeated from signal wavelength of 1.26 μm until 1.62 μm. However, to minimize the simulation consumption time, the latter simulations were carried out by varying the signal wavelength starting from 1.26 μm with 4 nm intervals. For each wavelength, separate length of grating and period were utilized. Consequently, separate cascaded Bragg grating structures with different Bragg wavelengths were combined. Figure 5.5 shows the simulation results.



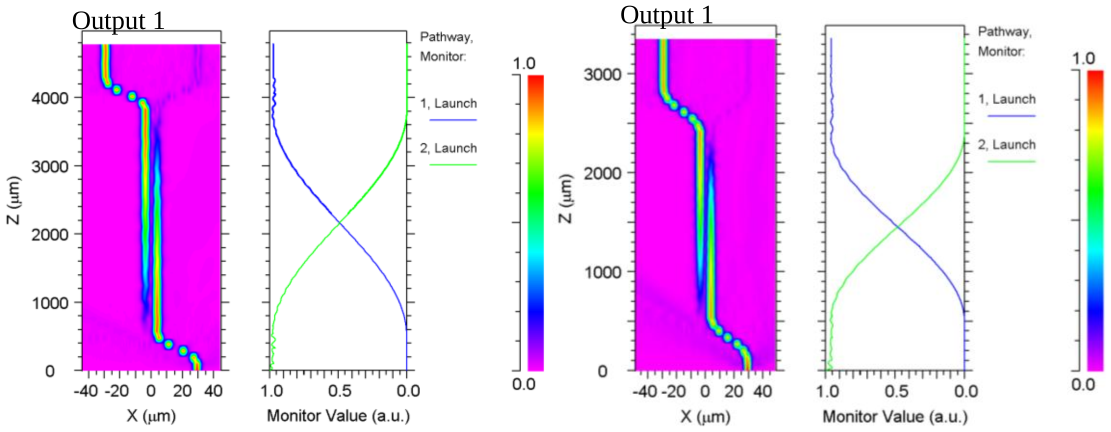
(a) (b)

Figure 5.5: The broadband spectral (reflection profile) in the range of (a) 1.260 - 1.462 μm and (b) 1.4621 - 1.6200 μm.

From the simulation results shown in Figure 5.5, the two cascade Bragg gratings structure display 99.9% reflectivity and broadband spectral from (a) 1.260 - 1.462 µm and (b) 1.4621 -1.620 µm, respectively. The broadband spectral FWHM in the range of 1.260 - 1.462 µm is around 208 nm whereas the spectral FWHM in the range of 1.4621 - 1.6200 µm is around 164 nm. This wavelength flattened output allows the reflection of multiple signal wavelengths concurrently with low loss and propagating into respective amplifying regions.

5.6.2 Simulation Results of Uniform Symmetric-Typed Directional Coupler

The procedures of designing the uniform symmetric directional coupler in this work were similar in the previous design. There are two different wavelength combinations uniform symmetric directional couplers were designed: (i) 800/1350 nm and (ii) 980/1550 nm. The validation of the design is executed by 2D FD-BPM using BeamPROP. The optimal design parameters fulfilling both power throughput for (i) 800/1350 nm and (ii) 980/1550 nm would correspond to edge-to-edge spacing, *d* of 3 μm and length of central coupling region, *L* of (i) 3280 μm and (ii) 1850 μm, respectively. Figures 5.6 (a) and 5.6 (b) show the transmission evolution along the uniform symmetric directional coupler for 1350 nm and 1550 nm signals wavelength, respectively.



(a) (b)

Figure 5.6: BPM simulation showing the transmission of uniform symmetric directional coupler for (a) 1350 nm and (b) 1550 nm.

The right-hand side of each transmission revolution shows the launch field power monitor. It can be seen that both signal wavelengths suffer low loss during transmission. However, it is also shown that there is little residual power at the bar output. As discussed in the earlier chapter, uniform symmetric directional coupler is a wavelength sensitive device. Therefore, it is difficult to obtain wavelength flattened output for uniform symmetric directional coupler. In Figure 5.7, it is observed that a Gaussian profile is acquired for both couplers.

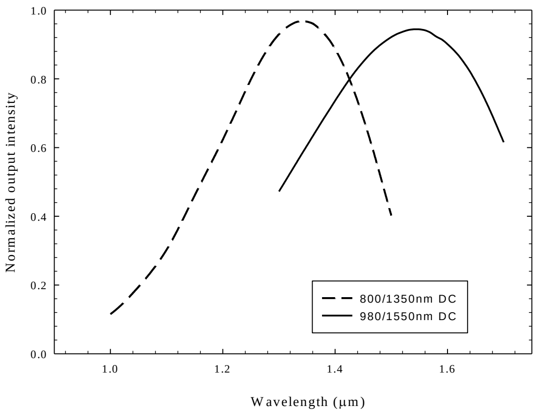


Figure 5.7: The graph showing output intensity as a function of wavelength from 800/1350 nm (dash line) and 980/1550 nm (solid line).

The output intensity decreases gradually at both sides of the center wavelength which is 1350 nm and 1550 nm, respectively. For these couplers, they are unable to attain minimum 93% power remaining (0.3 dB loss) at output port 1 (left-hand side) for every signal wavelength. However, this coupler can be only achieved at least 80% power remaining (1 dB loss) at output port 1 if only if the signal wavelengths propagate into 800/1350nm coupler is in the range of 1.260 - 1.425 μm instead of 1.260 - 1.462 μm. Meanwhile the signal wavelengths transmitted into 980/1550 nm coupler is from 1.4251 μm until 1.6200 μm. To accomplish at least 80% powers remaining at output port 1, the reflected wavelengths from the first cascade Bragg grating are from 1.4251 μm until 1.6200 μm. As such, the reflected wavelengths from the second cascade Bragg grating to be in the range of 1.260 - 1.425 μm.

5.7 Discussion

In this work, we have designed an optical chip which integrated several devices on a standard 4 inch wafer to perform certain functions. The function here is amplification. The chip is called waveguide amplifier. However, in this design, we focus on the pump/signal multiplexing and transmission/reflection of signal wavelength on the chip using Bragg grating. The amplifying regions are assumed low loss. The design of the amplifying region could be long straight channel or spiral. The major advantage of the design in this chapter over the previous chapters is it allowed broadband sources to couple into the chip in order to overcome bandwidth constraint. The Bragg grating is utilized to split the broadband source to propagate into two different directional couplers. The Bragg gratings provide the broad wavelength flattening output with at least 99.9% power reflection as illustrated in Figure 5.5. The broad spectral obtained from Bragg grating is unable to be attained from other devices like directional couple. This is the main reason that Bragg gratings are employed in the design. The uniform symmetric directional coupler is utilized because of its low insertion loss.

To fabricate the chip, two step fabrications are required: UV-writing process and conventional CMOS process. Hence, the time consuming and risk of the process has been increased. Besides, the optical circulator is excluded from chip. It is because the facilities available here could not produce the waveguide circulator. On the other hand, from the simulation results of the uniform symmetric directional coupler shows a wavelength non-flattened output and the output intensity reduces gradually at both sides of center wavelength. Most of the signal wavelengths are not fully transferred or 100% coupled from input port to desire output port and they are suffered not more than 1dB loss. The residual power is propagated to adjacent output port. This thought to be caused by the uniform symmetric directional coupler is a wavelength sensitive device. In conclusion, the drawbacks of the design need to verify through experiments. However, the main advantage of the design is allowing broadband source (1260-1625 µm) to carry out the amplifications on the same chip in order to achieve higher data capacity and bandwidth

5.8 Reference

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