CHAPTER 3: DESIGN AND SIMULATION OF 980/1550 nm AND 800/1310 nm UNIFORM SYMMETRIC SILICA-ON-SILICON PUMP/SIGNAL MULTIPLEXERS

3.1 Introduction

This chapter describes the design and simulation of silica-on-silicon 980/1550 nm pump/signal multiplexers for erbium doped waveguide amplifiers (EDWA) and 800/1310 nm pump/signal multiplexers for Bismuth Doped Waveguide Amplifiers (BiDWA). The Rsoft BeamPROP was used for designing and modeling these pump/signal multiplexers.

3.2 Theoretical Investigation of Directional Coupler-type Pump/Signal Multiplexers

There are several types of directional couplers, including uniform symmetric directional couplers that are employed for application in waveguide amplifiers (the couplers are called uniform as the waveguides are uniform and identical within the interactive region). This structure of uniform symmetric directional coupler is symmetric in terms of its central line which is perpendicular to the propagation direction of the z-axis. Therefore, the directional coupler is in essence an optical device comprising of two parallel symmetric waveguides [1]. For use in the waveguide amplifier, directional coupler is the lossless component as the output power is acquired solely either from bar or cross coupling. As discussed in the Chapter 2, the coupling occurs between two closely spaced waveguide which is the central region of the directional coupler. The coupling process can be described either by the CMT [2, 3] or by using the supermode theory [4].

The transmission characteristics of the uniform symmetric directional coupler can be easily expressed by the propagation matrix [5]:

$$M = \begin{bmatrix} \cos\phi & -j\sin\phi \\ -j\sin\phi & \cos\phi \end{bmatrix} \quad (3.1)$$

where ϕ is the phase term of light propagation. ϕ is also denoted as coupling strength where $\phi = \kappa L$ in which κ is the coupling coefficient and L is the total length of the central coupling region. For simplicity, the waveguide loss and bending losses at the s-bend are ignored. The bar coupling power P_1 and cross coupling power P_2 are expressed as:

$$P_1 = 1 - P_2 \quad (3.2)$$

$$P_2 = \sin^2\phi \quad (3.3)$$

From equation (3.3), a 100% cross coupling is acquired only if the coupling strength satisfy $\phi = \pi/2 + m\pi$, where $m \in N$. It is also clear to see that the output power response of the directional coupler is in a sinusoidal manner. Therefore the output power ratio can be manipulated by adjusting the coupling length L . L is the most important parameter as it determines the compactness of the devices [1]. On the other hand, the wavelength dependency can be obtained by differentiating equation (3.3) to obtain:

$$\frac{dP_2}{d\lambda} = 2\cos\phi\sin\phi\frac{d\phi}{d\lambda} \tag{3.4}$$

Equation (3.4) above shows that the factor of $\frac{dP_2}{d\lambda} = 0$ implies a 100% cross coupling directional coupler with a flattened wavelength around this maximum. The wavelength-flattened output is extended only if $\frac{d\phi}{d\lambda} = 0$, and this can be achieved with constructing very closely spaced parallel waveguides [6]. The case of when $\frac{d\phi}{d\lambda} > 0$ implies that when the wavelength is decreased, the cross coupling will also be decreased and ultimately become negligible. All the light energy will only propagate via the bar port. Similar situation will be taken place in the case of $\frac{d\phi}{d\lambda} < 0$. Hence, the wavelength response of the uniform symmetric directional coupler will also behave in a periodic manner. This is thought to be caused by κ and is considered to be almost monotonically proportional to wavelength [5]. We can conclude that the uniform symmetric directional coupler has a wavelength dependent response and this is very useful for wavelength-division multi/demultiplexers.

3.3 Rsoft BeamPROP

The Rsoft BeamPROP (Version 6.0) can be utilized for producing the layout and analysis of pump/signal multiplexer throughout this work. Rsoft BeamPROP is a widely used simulation engine for the design of passive photonics devices or photonics integrated circuits. This software incorporates the advanced FD-BPM with a modern Graphical User Interface (GUI) and consists of two closely integrated elements. The main programs of the Rsoft BeamPROP are a Computer Aided Design (CAD) layout for the devices or circuits design and the control simulation feature including numerical parameters, input field, display and analysis options. This BPM-based simulation program performs the actual computational modeling and provides a graphical display of the results such as field, power distribution and other quantities interest for analysis. The CAD (Version 6.0) system allows for mode calculation and multi-variable scanning using MOST which is an automated driver for Rsoft's physics-based simulation engine [7].

3.4 980/1550 nm Uniform Symmetric Silica-on-Silicon Pump/Signal Multiplexer

To achieve a better and higher optical transmission system, optical amplifiers are required to compensate the signal loss during transmission [8]. EDFAs play a crucial step in developing the high speed and broadband optical network because of its achievement of higher gain and lower noise [9]. Moreover, EDFAs have low coupling losses, negligible polarization dependences, no inherent crosstalk between the different channels and a bandwidth of 20-40 nm. Recently, EDWA have also been extensively investigated due to their potential low cost, compact structure and the ability to be integrated with pump laser and other waveguide device such as signal/pump multiplexer into one chip. EDWAs display good performance when pumped in the 980 nm absorption band and its operation in 1550 nm band provides a lower noise figure and higher pumping efficiency [10].

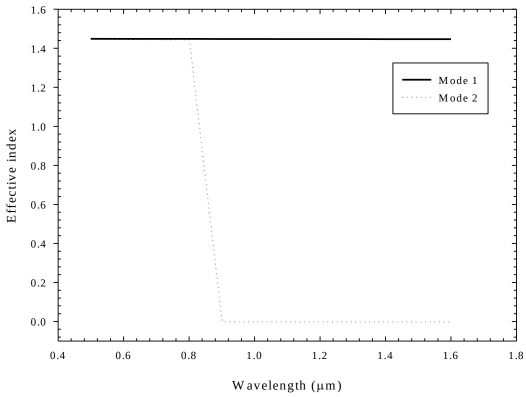
A directional coupler-type pump/signal multiplexer is used to combine light from a pump laser with the signal before amplification. A design of uniform symmetric directional coupler for 980/1550 nm based on silica-on-silicon technology which is fully integrated with EDWA is investigated. The directional coupler is an important and fundamental part in EDWA, performing the functions of splitting and combining the relevant wavelengths. It is formed by placing two waveguides in close proximity. Ideally the signal/pump multiplexer should have low loss at the pump wavelength (<0.5 dB) and at the signal wavelength (<0.3 dB), low fabrication and polarization sensitivity and a small footprint.

3.4.1 Choice of Single or Multi-Mode Waveguides

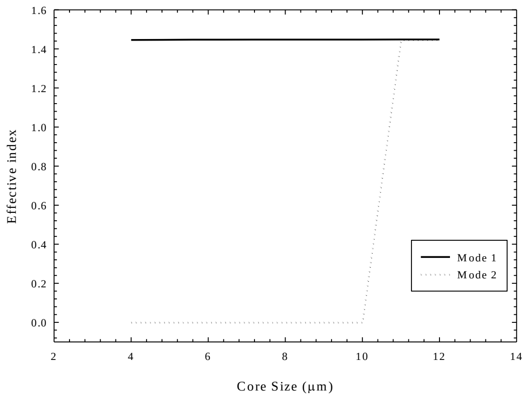
To avoid modal dispersion in the optical waveguide**,** it is necessary to use single-mode waveguide for most of the optical devices. In this regard, it was decided to work with waveguide that are single-mode at both pump wavelength and signal wavelength in our pump/signal multiplexer design. The BPM mode solving is employed to calculate the number of modes and mode cutoffs within the waveguide.

For a rectangular step index core with index difference (delta) Δn =0.004 and waveguide height and width of 8 μm, Figure 3.1(a) shows that 980 nm pump wavelength and 1550 nm signal wavelength are single-mode waveguide on the conditions as stated above. It is depicted that the waveguide can support fundamental mode (mode 1) of wavelengths from 0.5 μm to 1.6 μm. Meanwhile, it is noted that the sudden drop to zero for higher order mode (mode 2). The higher order mode is cutoff for wavelength longer than 0.9 μm. The BPM mode solver was unable to record the value for the effective index of the mode when a mode goes beyond the cutoff at some point. Thus, for wavelengths longer than

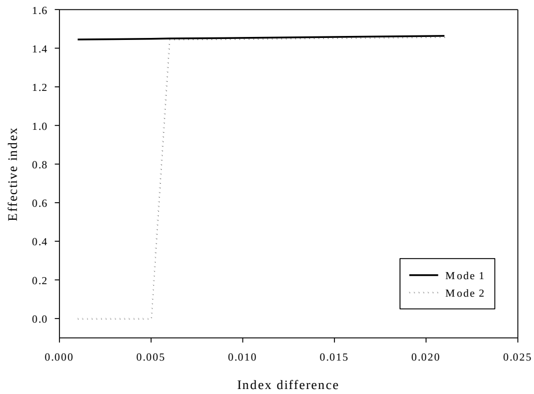
0.9 μm is considered a single-mode waveguide in a condition stated earlier. Similar investigations for the waveguide core size and refractive index difference between core and cladding (delta) are carried out. For the case of waveguide core size, it can be seen that the higher order mode is cutoff for core size smaller than 10 μm as illustrated in Figure 3.1(b). This investigation is carried out under the conditions of wavelength 1550 nm and delta Δn =0.004. In Figure 3.1(c), there is only fundamental mode existing within the waveguide for index difference less than 0.005 when wavelength and core size are fixed as 1550 nm and 8 μm x 8 μm, respectively.



(a)



(b)



(c)

Figure 3.1: BPM mode solver showing the single/multi mode propagation within the waveguide with respect to (a) wavelength, (b) core size and (c) index difference.

3.4.2 Structures for 980/1550 nm Uniform Symmetric Silica-on-Silicon Pump/Signal Multiplexer

The physical layout of the 980/1550 nm uniform symmetric silica-on-silicon directional coupler is illustrated in Figure 3.2.

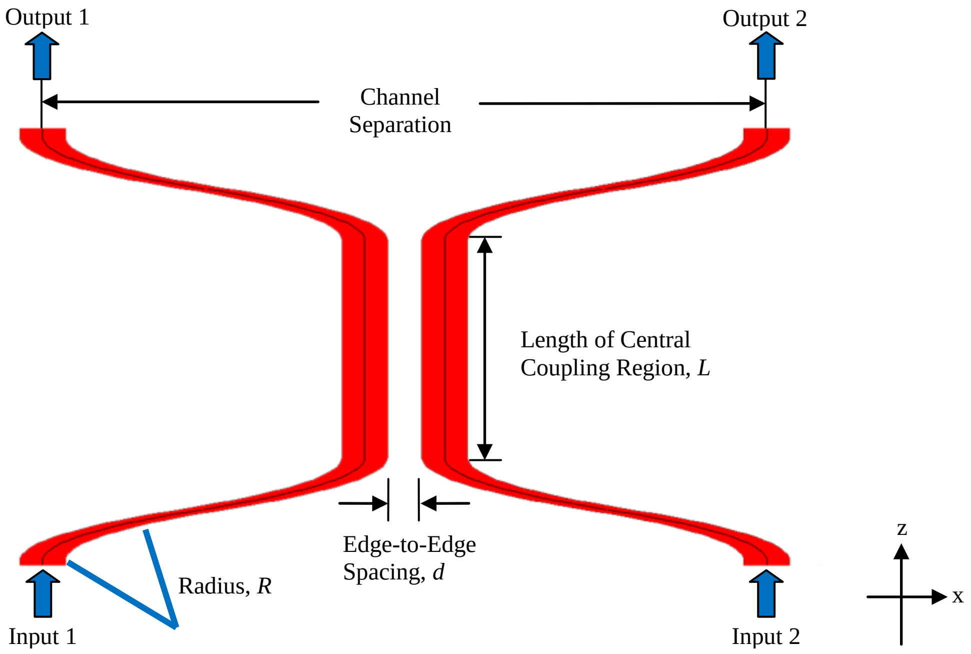


Figure 3.2: A schematic showing the physical layout of the designed 980/1550 nm uniform symmetric silica-on-silicon pump/signal multiplexer

The multiplexer is formed by placing two parallel straight waveguides in close proximity to one another. The directional coupler also comprises of four diverging waveguides, two at the input end and two at the output end. The diverging waveguides are made up of two arc bends with a curvature radius, *R*. The edge-to-edge spacing between two adjacent waveguides is represented by the variable *d*. The length of central coupling region is where the coupling process take place is set as *L*.

As mentioned in the previous chapter, the buried waveguide type is used throughout this work. The rectangular core cross-section of the planar waveguide utilized in this design is 8 μm $\times$8 μm. The core of the directional coupler is sandwiched between upper and under cladding layers with slightly lower refractive index as indicated in Figure 3.3. The refractive index of core and cladding are selected to be 1.449 and 1.445, respectively. This directional coupler has a refractive index difference, Δ of 0.28% which is approximated from equation below:

$$\Delta = \frac{(n_{co} - n_{cl})}{n_{co}} \approx \frac{(n_{co}{}^2 - n_{cl}{}^2)}{2n_{co}{}^2} \tag{3.5}$$

where n_{co} and n_{cl} are core index and cladding index respectively [11]. In the design, the radius, R of diverging waveguide is fixed at 25 mm. The 25 mm radius is selected due to its bending and transition losses are minimal. If the extremely low curvature radius is utilized, the mode could not support within the waveguide and its power would leakage to the cladding. On the other hand, the device dimension is larger if larger curvature radius is employed. Figure 3.3 shows Cross-section and refractive index profiles of the 980/1550 nm uniform symmetric silica-on-silicon pump/signal multiplexer.

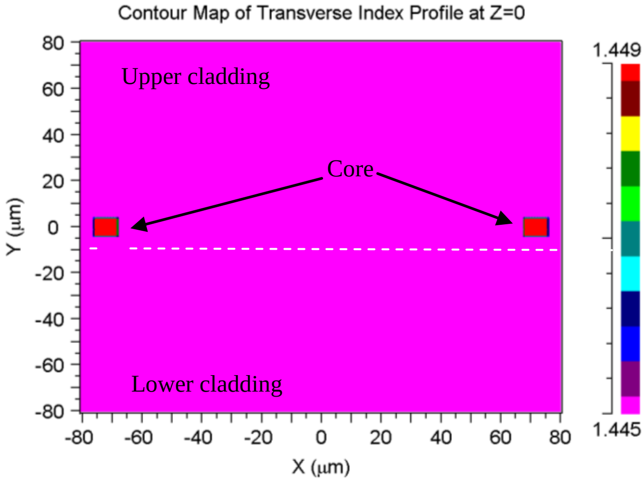


Figure 3.3: Cross-section and refractive index profiles of the 980/1550 nm uniform symmetric silica-on-silicon pump/signal multiplexer.

The 25 mm radius is appropriate for low refractive index difference (Δ = 0.3%). The curved paths cannot have too small radius of curvature, otherwise significant bend loss would occur [6]. The separation between the two inputs (channel separation) has to be set as 125 μm. This is because the inputs need to be directly coupled to a fiber having a diameter of 125 μm. Similarly, the separation between the output arms also needs to be 125 μm apart. Table 3.1 shows the parameters of the directional coupler utilized for the design.

Table 3.1: Parameters for the 980/1550 nm uniform symmetric silica-on-silicon pump/signal multiplexer

Parameter	Values
Core dimension	$8\mu m \times 8\mu m$
Refractive index of core, n_{core}	1.449 at 1550nm
Refractive index of cladding, $n_{cladding}$	1.445 at 1550nm
Refractive index difference, Δ	0.28%
curvature radius, *R*	25mm
channel separation	125μm

The next section provides the simulation results of the 980/1550nm uniform symmetric silica-on-silicon pump/signal multiplexer based on the parameters as given in Table 3.1.

3.4.3 Simulation Results of 980/1550 nm Uniform Symmetric Silica-on-Silicon Pump/Signal Multiplexer

To check the feasibility of the design, 3D Beam Propagation Method (BPM) was employed to simulate the light propagation in the 980/1550 nm uniform symmetric silica-on-silicon pump/signal multiplexer. The design of the 980/1550 nm directional coupler was carried out using BeamPROP (Version 6.0), a commercial software developed by RSoft which utilize Finite Difference technique to calculate field distribution across a waveguide. In the BPM modeling, a step index profile was assumed. Automatic tilt was utilized for BPM launch and monitor, and full transparent boundary condition was implemented. Gaussian mode was chosen for the launch field and the launch power monitor calculates the overlap integral between the calculated fields at certain positions along the waveguide and the input field.

An important characteristic of optical devices is polarization sensitivity. If the effective index of the two polarization states is different, the waveguide is said to be birefringence:

$$\Delta n_{eff} = n_{eff}^{TE} - n_{eff}^{TM} \tag{3.6}$$

where n_{eff}^{TE} and n_{eff}^{TM} represent effective index of TE mode and TM mode respectively. From calculations of the BPM mode solver, for 8 μm x 8 μm planar straight waveguide with refractive index difference Δ = 0.28% and 980 nm and 1550 nm as the excitation wavelengths, the birefringence is negligible. For the case of 980 nm excitation wavelength, an effective index of 1.448 for n_{eff}^{TE} and n_{eff}^{TM} are obtained, while for the 1550 nm excitation wavelength, an effective index of 1.447 for n_{eff}^{TE} and n_{eff}^{TM} are acquired. It can be deduced from the obtained indices that the waveguide has low polarization sensitivity. Hence the scalar mode is utilized in the simulation and we can conclude that for low refractive index difference waveguide, the polarization effect is negligible.

Once the basic directional coupler design has been characterized, investigation into the effect of length of central coupling region, *L* and edge-to-edge spacing, *d* are carried out. These parameters determine the normalized output intensity for 980 nm and 1550 nm wavelengths. To ensure both wavelengths propagate into the same output, the simulation of length of central coupling region and edge-to-edge spacing are executed by using Rsoft BeamPROP to determine the region of highest normalized output intensity. Figure 3.4 shows the variation of length of the central coupling region, *L* to edge-to-edge spacing, *d* for 980 nm and 1550 nm.

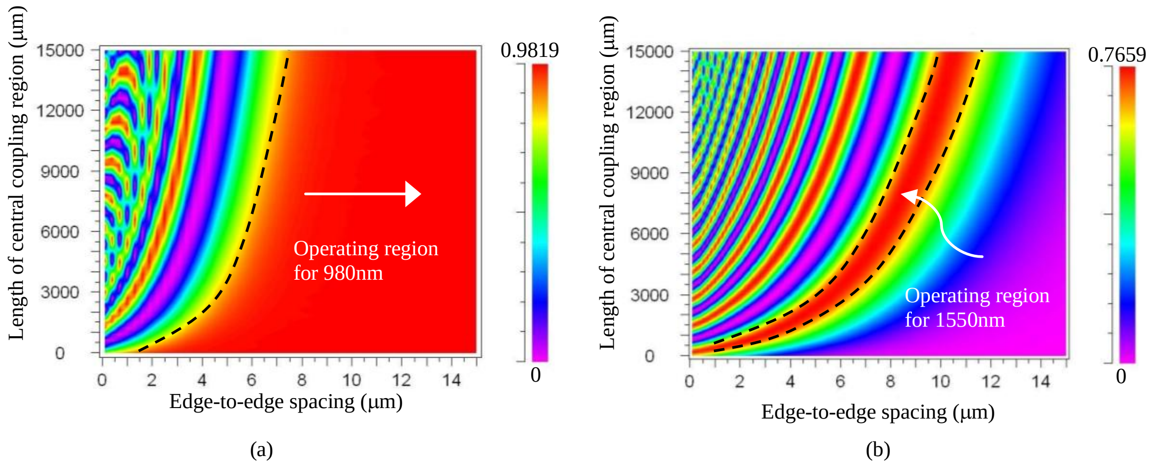


Figure 3.4: The graph showing variation of length of central coupling region, *L* to edge-to-edge spacing, *d* for (a) 980 nm and (b) 1550 nm

In Figure 3.4, the red portions indicate the highest output intensity at output 1. The highest normalized output intensities for 980 nm and 1550nm are 98% and 77% respectively. To ensure that the 980 and 1550 nm signals propagate to the same output, the coupler parameters that generate the characteristics highlighted by the red portion on the graph were used again in following simulation. Figure 3.4 provides a rough indication for selecting the length of central coupling region and the edge-to-edge spacing. When a horizontal line is drawn in both Figure 3.4 (a) and (b) for each length of central coupling region, we observe that the length of the central coupling region produces the highest normalized output intensity in a periodic manner. However, the focus is on the length of central coupling region, *L* which is at 6000 μm. The lengths of central coupling region of more than 6000 μm will result in making the device larger. However, the fabrication techniques may not be fulfilled for smaller length of central coupling region because of the small tolerance in highest output intensity region. Figures 3.5 to 3.8 show the normalized output intensity as a function of the edge-to-edge spacing for the simulation

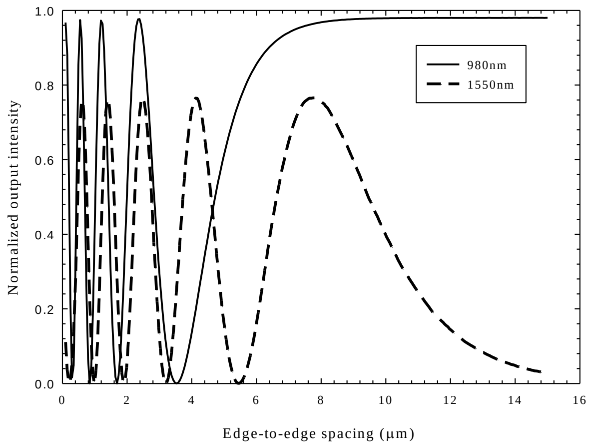


Figure 3.5: Graph showing normalized output intensity as a function of the edge-to-edge spacing. (Length of central coupling region is fixed at *L*=6000 μm)

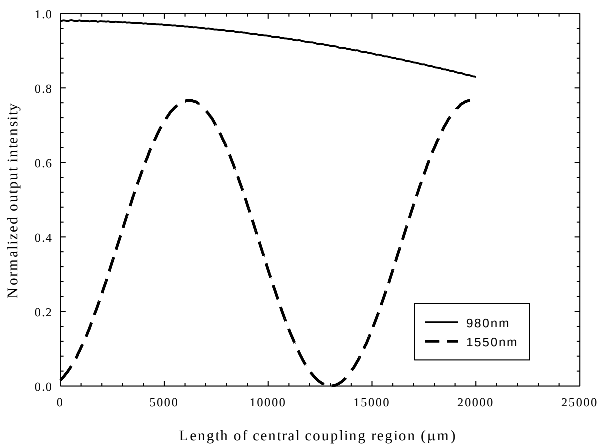


Figure 3.6: Graph showing output intensity as a function of the length of central coupling region. (Edge-to-edge separation is fixed at 7.75 μm)

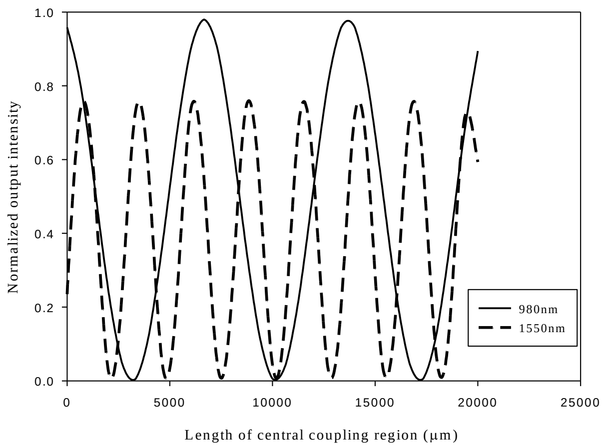


Figure 3.7: Graph showing output intensity as a function of the length of central coupling region calculated by the BPM. (Edge-to-edge separation is fixed at 2.48 μm)

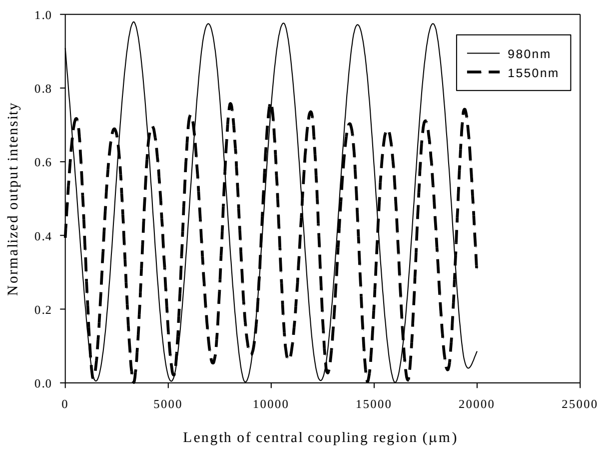
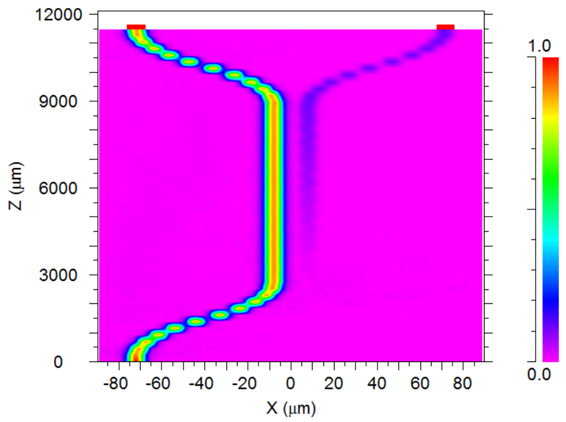


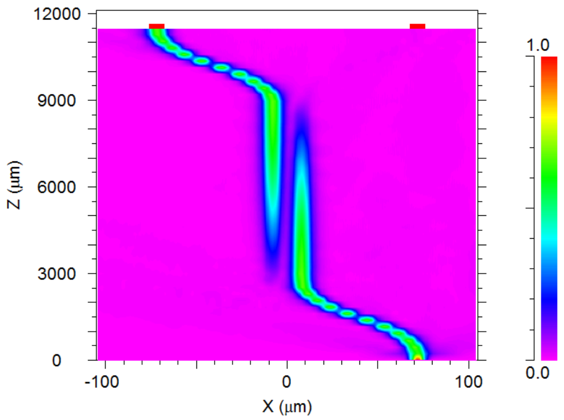
Figure 3.8: Graph showing output intensity as a function of the length of central coupling region calculated by the BPM. (Edge-to-edge separation is fixed at 1.39 μm)

The simulation was executed by fixing the length of the central coupling region, *L*=6000 μm. From Figure 3.5, it is seen that four and five maximum powers emerge from output 1 for 980 nm and 1550 nm respectively. To fine-tune the design, further iterations of the edge-to-edge spacing was carried out in order to obtain the highest normalized output intensity. The edge-to-edge spacings chosen were *d* = 1.39 μm, 2.48 μm, and 7.75 μm. Figure 3.6 to 3.8 show the normalized output intensity at output 1 by varying the length of central coupling region at edge to edge spacing *d* = 1.39μm, 2.48 μm, and 7.75 μm respectively.

Figure 3.9 illustrates the simulated transmission results for signal at wavelengths of 980 and 1550 nm respectively. It is seen that the 980 nm pump and 1550 nm signal emerge from one output port. However, Figure 3.9 (a) shows that there is <10% residual power at output 2. In Figure 3.9 (b), it is seen that complete power transfer takes place from input 2 to output 1. From the work done, it is determined that the optimum length of central coupling region is 6200 μm. Similarly, the optimum edge-to-edge spacing is 7.75 μm.



(a) Wavelength=980nm



(b) Wavelength=1550nm

Figure 3.9: BPM simulation showing the transmission of uniform symmetric silica-on-silicon pump/signal multiplexer (*L*= 6200 μm, *d* = 7.75 μm) for (a) 980 nm and (b) 1550 nm.

The next section will discuss the analysis of the simulation of the 980/1550 nm uniform symmetric silica-on-silicon pump/signal multiplexer.

3.4.4 Simulation Analysis of 980/1550 nm Uniform Symmetric Silica-on-Silicon Pump/Signal Multiplexer

In this section the analysis of the simulation of the 980/1550nm uniform symmetric silica-on-silicon pump/signal multiplexer is presented.

3.4.4.1 Transmission Analysis

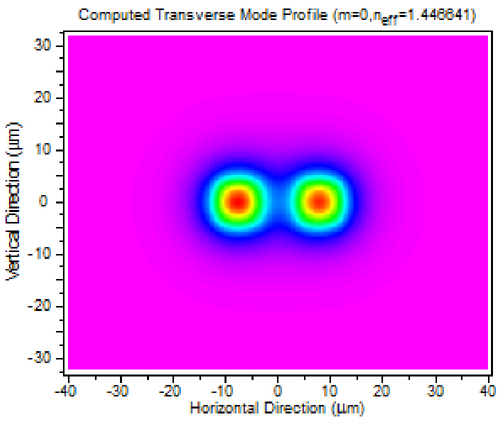
In Figure 3.5, it is seen that the maximum intensity of the 1550 nm signal wavelength is relatively smaller than the maximum intensity of the 980 nm pump wavelength with values of 77% and 98% respectively. This is a result of the longer signal wavelength (1550 nm) having a larger Mode Field Diameter (MFD) than the shorter 980 nm pump wavelength. The 1550 nm signal has a relatively larger distribution of evanescent field propagating in the cladding. Approximately 25 % of the signal power is lost after the 1550 nm signal is launched into input 2 (however this must take into account the fact that the power monitor is restricted to the launch field that was selected in the simulation). Figure 3.9 (a) and (b) clearly shows the transmission intensity of the 980 nm and 1550 nm wavelengths respectively.

3.4.4.2 Coupling Analysis

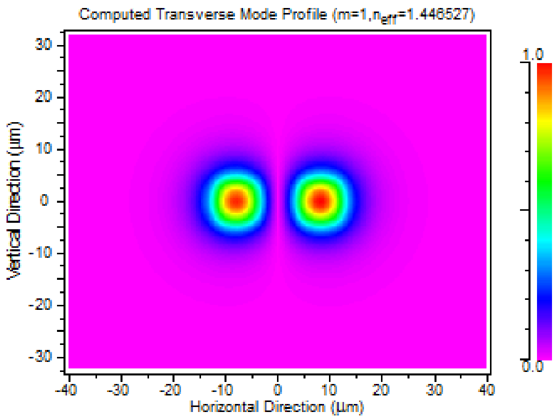
As discussed earlier in the Section 3.3.1, from the BPM mode solver it is evident that 980 nm pump and 1550 nm signal wavelength propagation is in a single-mode form, thus inferring that the pump/signal multiplexer can be directly coupled with single mode fiber. This is the advantage of silica-on-silicon pump/signal multiplexer over other materials. From Figure 3.9, it can be seen that the coupling strength gradually increases at the input signal approaches the straight coupling region and decreases at the output signal travels away from it [12]. There are also additional couplings between two waveguide cores along the converging and diverging s-bend near to the straight coupling region, and hence these converging and diverging s-bend had to be included in the simulation. From Figure 3.9(a), the 980 nm pump wavelength propagates through the waveguide from input 1 with a small amount of residual power coupled into the adjacent waveguide, and this is attributed to the 980 nm pump wavelength not propagating though the complete coupling length as the length of central coupling region design is optimized for the 1550 nm signal wavelength instead. This is shown in Figure 3.9(b), where the 1550 nm signal wavelength propagates from input 2 and its energy completely transferred to the neighbouring waveguide. There is no residual power at output 2 due to the 1550 nm signal transmitting exactly at the complete coupling length. The coupling length is an important parameter for a design to determine the power ratio of two outputs. To design an efficient directional coupler, the coupling length must be controlled. Figures 3.6 to 3.8 showed the normalized output intensity of 1550 nm signal and 980 nm pump wavelength as a function of length of central coupling region. It is observed that within the length of central coupling region of 20 mm, there is no synchronized maximum intensity for both wavelengths, and this is the primary reason that a lossless directional coupler cannot be obtained.

3.4.4.3 Supermode Analysis

When light energy is launched into the input port of the directional coupler, it excites equally the even and odd supermodes. The supermode is defined as the modes of a composite structure involving more than one waveguide (directional coupler structures being one of these) where waveguides are placed within close proximity to one another. They propagate with different velocities given by propagation constant β_e and β_o . The complete transfer of light energy is achieved when the two supermodes are π out of phase [1]. Therefore the coupling process between two waveguide is due to the interference between the two supermodes [4]. The interference pattern can be interpreted as a coupling process. Figures 3.10 and 3.11 show the BPM simulation showing the fundamentals supermode of directional coupler-typed pump / signal multiplexer excited by a 1550 nm signal and 980 nm pump signal respectively.

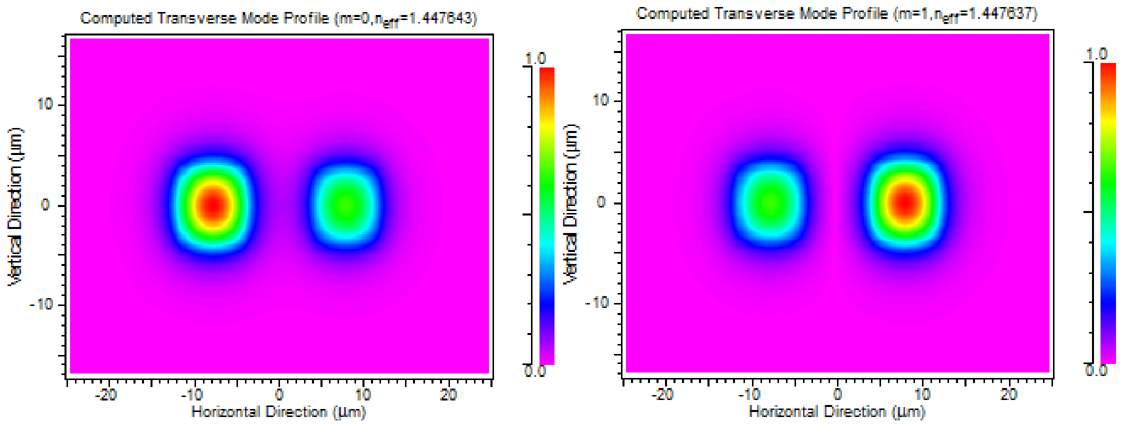


(a) Even mode



(b) Odd mode

Figure 3.10: BPM simulation showing the fundamentals supermode of DC-typed pump/signal multiplexer excited by wavelength 1550 nm.



(a) Even mode (b) Odd mode

Figure 3.11: BPM simulation showing the fundamentals supermode of DC-typed pump/signal multiplexer excited by wavelength 980 nm.

In Figure 3.10, the patterns of the 1550 nm signal wavelength supermode are exactly similar and this can be interpreted to be the complete energy transfer from one waveguide to another waveguide In Figure 3.11 the supermodes for 980 nm pump wavelength shows weak coupling due to the greater distance between two waveguides. Only a small amount of energy is being coupled to the adjacent waveguide, which is observed as <10% of residual power at output 2.

3.4.4.4 Fabrication Tolerance Analysis

In order to realize the fabrication of directional coupler-typed silica-on-silicon pump/signal multiplexer, the fabrication tolerance is considered. In the practical fabrication, it is hard to control accurately the waveguide dimension. Small changes of parameters like wavelength, edge to edge spacing, and length of central coupling region would influence the device performance. In Figure 3.5, several output peaks are observed for 1550 nm and 980 nm signals respectively. Edge to edge spacing 7.75 µm is chosen due to its less sensitivity to the small change. Meanwhile, in Figure 3.6, the length of central coupling region of 6200 μm was chosen for its maximum intensity and less sensitivity to the small parameter change which allow larger fabrication tolerance. Figure 3.12 shows the output intensity of output 1 as a function of wavelength when the signal is incident through input 1 and input 2.

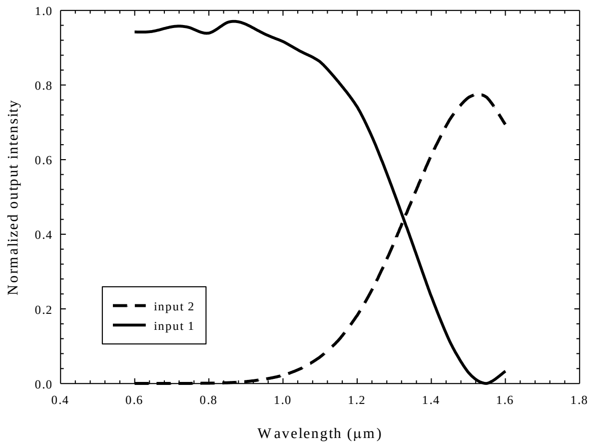


Figure 3.12: The graph showing output intensity as a function of wavelength from input 1 and input 2.

From Figure 3.12, it can be seen that the 3dB spectral at peak 980 nm and 1550 nm widens. Thus, the broad pump and signal pass band allows this design to be used for WDM application.

3.5 800/1310 nm Uniform Symmetric Silica-on-Silicon Pump/Signal Multiplexer

Over the past few years, the vast increase of data stream in the communication network has promoted the revolution of optical communication. Current amplification technology relies on erbium doped fiber amplifier (EDFA) where the amplification region falls in the 1550 nm window which is the lowest attenuation wavelength range for silica fibre. However, the typical amplification bandwidth of EDFA is only about 70 nm, which is unable to meet the increasing demand for bandwidth [13]. In order to achieve higher bandwidth and capacity of wavelength division mutiplexing (WDM) system, the existing telecommunication window has to be expanded. The other promising transmission window of silica fiber is the second telecommunication window (1260 nm-1360 nm) where signals experienced minimum dispersion. Research on amplifiers operating in this window has been focussed on praseodymium doped fiber amlifiers (PDFA). However their amplification bandwidth is as narrow as 25 nm [14] and PDFA cannot be fusion spliced to standard silica fibre. One of the ways to overcome these problems is by utilising bismuth doped silica based amplifiers.

Recently, bismuth doped glass have been extensively investigated for broadband optical amplification due to its large amplification bandwidth of around 300 nm in the 1310 nm region. Fujimoto reported 1310 nm amplification via 810 nm excitation using a silica bulk glass doped with 1.0 mol % Bi_2O_3 [15]. There are also reports of broadband 1310 nm emission in Bi-doped silica fiber [16]. However, to our best knowledge, there are no reports on Bi-doped planar waveguide on silica-on-silicon substrates. To this end, the area investigated in this section is in the design of an 800/1310 nm uniform symmetric directional coupler that will be used to multiplex both the pump and signal wavelengths into the amplifying medium. A similar device will also be used to de-multiplex the two wavelengths at the output of the chip. The design of the 800/1310 nm directional coupler is carried out using the BeamPROP software in the design procedure and structure similar to that of the 980/1550 nm directional coupler as discussed in the earlier section. Hence, only the simulation results and analysis will be written in this section.

3.5.1 Choice of Single or Multi-Mode Waveguides

From Figure 3.1, it is determined that the 800 nm pump and 1310 nm signal wavelengths are multimodal and single modal respectively for a rectangular step index core with an index difference (delta) of Δn = 0.004 and a 8 μm x 8 μm core size. The multimode mode propagation for the 800 nm pump wavelength and single mode propagation for the 1310 nm signal wavelength can also be confirmed via Rsoft BPM mode solving. To obtain single mode operation at 800 nm pump wavelength, core size and delta need to be reduced. However, losses increments are taken place in coupling between fiber and waveguide and mode transition in the bending segment. Henceforth, it was determined that in this research to work with waveguides that are multimode at 800 nm to extend the design flexibility at 1310 nm.

3.5.2 Structures for 800/1310 nm Uniform Symmetric Silica-on-Silicon Pump/Signal Multiplexer

The structure of the 800/1310 nm uniform symmetric silica-on-silicon pump/signal multiplexer is similar to 980/1550 nm uniform symmetric silica-on-silicon pump/signal multiplexer as depicted in Figure 3.2. The major difference from the previous directional coupler design however is the different core and cladding refractive index with Δn =0.004. These refractive indexes were calculated according to the Sellmeier equation, which is an empirical relationship between refractive index and wavelength for a particular transparent medium. In this case, fused silica and 1310 nm signal wavelengths were chosen to compute the suitable refractive index. Consequently the refractive index of core and cladding was selected to be 1.4508 and 1.4468 respectively. The separation between two inputs (channel separation) and output arms has to be fixed at 125 μm apart. Besides being easier to directly couple to fiber optic, the design is also compatible with commercial fiber V-groove pig-tailing technology [17]. Table 3.2 shows the parameters of the directional coupler which was utilized for the design:

Table 3.2: Parameters for the 800/1310nm uniform symmetric silica-on-silicon pump/signal multiplexer

Parameter	Values
Core dimension	8μm $\times$ 8μm
Refractive index of core, n_{core}	1.4508 at 1310 nm
Refractive index of cladding, $n_{cladding}$	1.4468 at 1310 nm
Refractive index difference, Δ	0.28%
curvature radius, *R*	25mm
channel separation	125μm

The next section contains the simulation results of the 800/1310nm uniform symmetric silica-on-silicon pump/signal multiplexer

3.5.3 Simulation Results of 800/1310 nm Uniform Symmetric Silica-on-Silicon Pump/Signal Multiplexer

The design procedures were based on the methods which were executed in the previous design. The validity of the directional coupler designs was proven via 3D BPM using BeamPROP (Version 6.0). The FD-BPM is implemented in the BeamPROP to simulate light propagation in the 800/1310 nm uniform symmetric directional coupler as a pump/signal multiplexer.

Once the initial directional coupler has been completed, investigation into the effect of length of central coupling region, *L* and edge-to edge-spacing, *d* are carried out. The output intensity of 800 nm and 1310 nm signals is determined by varying the two parameters stated above. With reference to Figure 3.2, the 800 nm pump and 1310 nm signals wavelength from input 1 and input 2 respectively are coupled into output 1. The Output 1 intensity for both the 800 nm pump and 1310 nm signal wavelength as a function of *L* and *d* are modeled and the results of these simulations are shown in Figure 3.13 below:

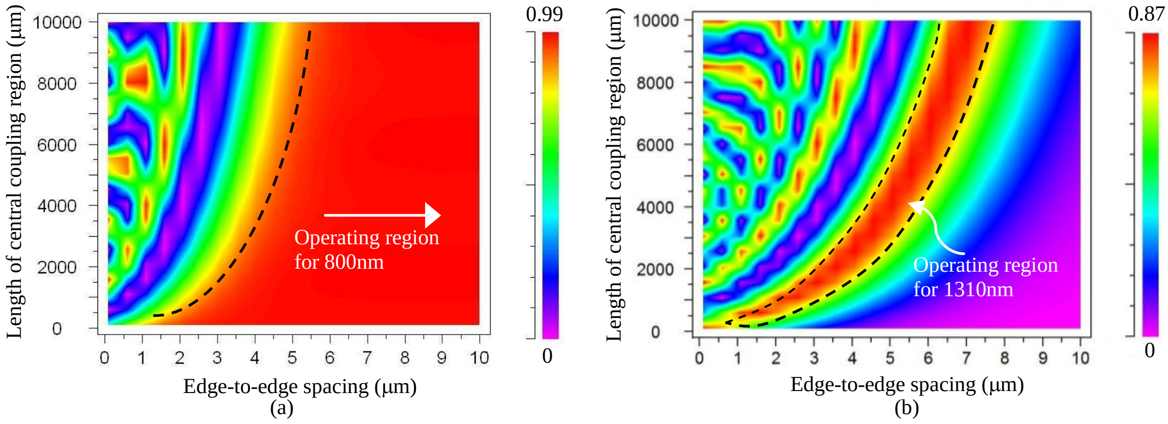


Figure 3.13: Topological charts showing the resulting power outputs for (a) 800 nm and (b) 1310 nm wavelength with variation in length of central coupling region, *L* and edge-to-edge spacing, *d*.

The red portion of the graphs indicates the highest output intensity at output 1. The highest normalized output intensity for 800 nm and 1310 nm wavelengths are 99% and 87% respectively. It is worth noting however that for the 1310 nm signals wavelength, this seemingly non-ideal output intensity level is caused by the fact that the waveguides were optimized for 1310 nm operation. This means that for 1310 nm signal wavelength, higher levels of intensity are in the evanescent. In Figure 3.13 (a), the optimum edge-to-edge separation and optimum length of central coupling region range for 800 nm coupling are > 4 μm and 0 to 10000 μm, respectively. In Figure 3.13 (b), the optimum parameters for >87% coupling of 1310 nm signal wavelength are limited in the region from 4.5 to 6.5 μm edge-to-edge separation *d* and 2000 to 8000 μm length of central coupling region *L*. Therefore, the optimization parameter will be limited within these regions. However, the two graphs only serve as a rough indication for the overlapping parameters that enable efficient coupling of the desired wavelengths and are not the finalized parameters for optimum pump-signal coupling.

Further optimization is focused on the edge-to-edge spacing. Figure 3.14 shows the optimum length of central coupling region, *L* and edge-to-edge spacing, *d* combination for our design, with Δ = 0.28%. Designing along this curve will produce the expected results. The graph in the inset in Figure 3.14 indicates the normalized output intensity of both 800 and 1310 nm signals as a function of length of central coupling region for a fixed edge-to-edge spacing of 4.5 μm.

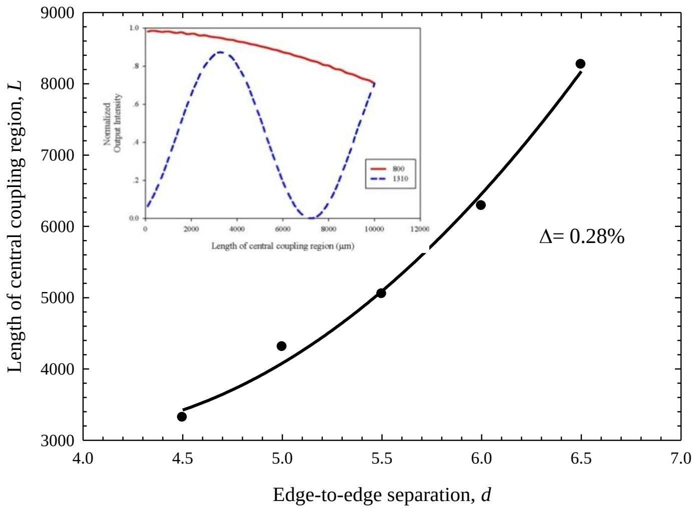
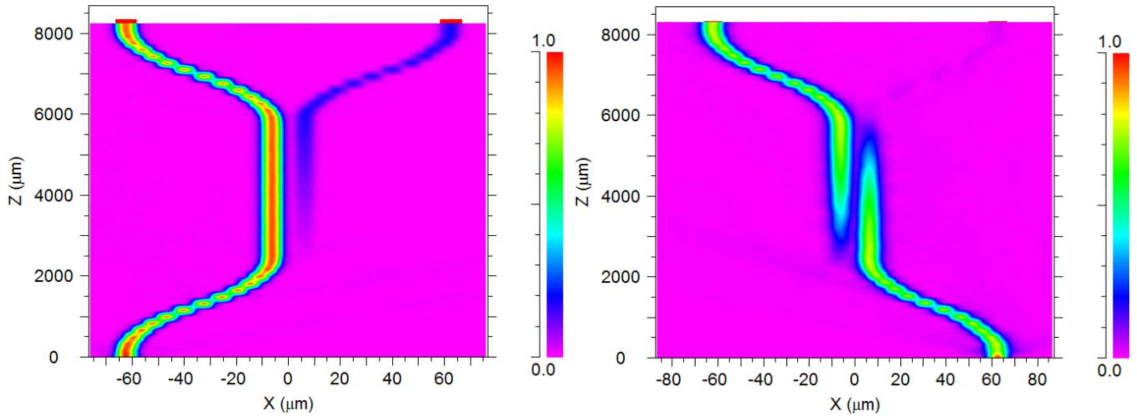


Figure 3.14: Graph showing the optimum length of central coupling region, *L* and edge-to-edge spacing, *d* combination for our design, with Δ = 0.28%. The inset shows the normalized output intensity of both 800 and 1310 nm signals as a function of length of central coupling region for a fixed edge-to-edge spacing of 4.5 μm.

In all cases, it is discovered that negligible coupling takes place for 800 nm whereas the 1310 nm signal displays the typical sinusoidal behavior associated with coupling between waveguides. A uniform symmetric directional coupler designed around the values along the quadratic graph shown in Figure 3.14 would therefore display good performance. However, in order to ensure subsequent fabrication of the device, we are also interested in determining the limitations of the design, specifically in terms of sensitivity to fabrication accuracy (fabrication tolerance).

To this end, using the coupling length values obtained for the previously described approach, we performed further iteration involving the coupling behaviors at fixed length of central coupling region, *L* and varying edge-to-edge spacing, *d*. The aim here is to identify the optimal length of central coupling region corresponding to the largest allowable edge-to-edge spacing. From the simulation results, it is observed that larger edge-to-edge spacing, *d* is preferable due to its larger coupling tolerance. However, in order to achieve compact devices, a smaller edge-to-edge spacing, *d* is preferable. As such, the optimal design parameters fulfilling both power throughput and ease of fabrication requirements would correspond to edge-to-edge spacing, *d* of 4.5 μm and length of central coupling region, *L* of 3317.5 μm.

Figures 3.15 (a) and (b) show the transmission evolution along the uniform symmetric directional coupler for the 800 nm and 1310 nm signals respectively.



(a) 800nm (b) 1310nm

Figure 3.15: BPM simulation showing the transmission of uniform symmetric silica-on-silicon pump/signal multiplexer (*L*= 3317.5 μm, *d* = 4.5 μm) for (a) 800 nm and (b) 1310 nm.

It can be seen that both signals emerge from output 1. In Figure 3.15 (a), it is shown that there is <10% of residual power at output 2. For the 1310 nm signal, the power is completely transferred from input 2 to output 1 as shown in Fig. 3.15 (b). From the work done, it is determined that the optimum edge-to-edge spacing, *d* and optimum length of central coupling region, *L* are 4.5μm and 3317.5μm, respectively.

3.5.4 Simulation Analysis of 800/1310 nm Uniform Symmetric Silica-on-Silicon Pump/Signal Multiplexer

In this section the discussion of the analysis from the simulation of the 800/1310nm uniform symmetric silica-on-silicon pump/signal multiplexer is presented.

3.5.4.1 Transmission Analysis

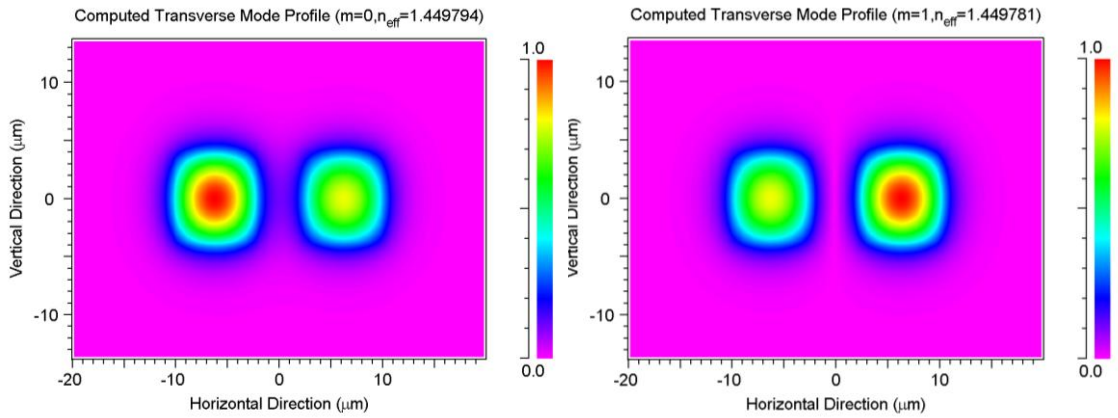
The problems of designing the 980/1550 nm uniform symmetric directional coupler was encountered again in designing the 800/1310 nm uniform symmetric directional coupler which is the maximum intensity of 1310 nm signal wavelength is relatively smaller than the maximum intensity of 800 nm pump wavelength with the value of 87% and 99% respectively.

3.5.4.2 Coupling Analysis

From the BPM mode computation, it is determined that the 800 nm pump and 1310 nm signal wavelength propagation modes are multimodal and single modal respectively. This problem can be solved by altering the waveguide confinement factor. In Figure 3.15 (a), the 800 nm pump transmitted through the waveguide from input 1 with a <10% residual power leaking into output 2. This is the consequence of the coupling length design which was optimized for 1310 nm as opposed to 800 nm. Figure 3.15 (b) shows the 1310 nm signals wavelength is completely transferred into output 1. The coupling length is defined as the minimum distance to achieve complete energy transfer from one waveguide to another waveguide. Therefore, coupling length is a significant parameter to determine the power ratio of the two outputs.

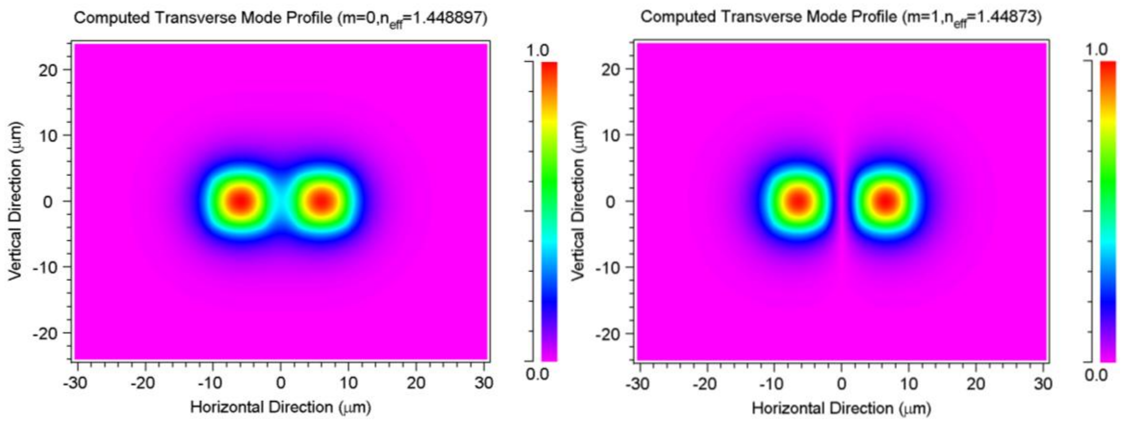
3.5.4.3 Supermode Analysis

Fig. 3.16 and 3.17 illustrates the two supermodes (even and odd modes) for 800 nm pump wavelength and 1310 nm signal wavelength, respectively. In Figure 3.16 (a), the even-like supermode of 800 nm pump wavelength shows most of the power is in the left-hand side guide and for the odd-like supermode indicate most of the power is accumulate in right-hand side guide.



(a) Even mode (b) Odd mode

Figure 3.16: BPM simulation showing the fundamentals supermode of pump/signal multiplexer which excited by wavelength 800 nm.



(a) Even mode (b) Odd mode

Figure 3.17: BPM simulation showing the fundamentals supermode of pump/signal multiplexer which excited by wavelength 1310 nm.

This is a power imbalance in both guides and thus the light energy will couple the even and odd supermodes unequally in the coupling region [18]. This mean only part of the light energy can be coupled from one waveguide to the other. Due to the evanescent tail of 800 nm pump wavelength is short, distance between two waveguides utilized in the design can be considered larger. Thus the 800 nm pump shows a weak coupling. Only a small amount of energy is being coupled to the adjacent waveguide, which is observed as <10% of residual power at output 2. In Figuer 3.17, the patterns of the 1310 nm signal supermode are exactly similar. This can be interpreted 100% energy transfer from one waveguide to another waveguide.

3.5.4.4 Fabrication Tolerance Analysis

Fabrication tolerance is considered in order to realize the fabrication of planar wavelength selective directional coupler. The length of central coupling region, *L* of 3317.5 μm is chosen. This is because of its maximum normalized output intensity at output 1 and less sensitivity to the parameter change. However the edge to edge spacing of 4.5 μm is selected for its larger 3dB spectral which yield to larger fabrication tolerance. Figure 3.18 shows the output intensity of output 1 as a function of wavelength when signal is incident through input 1 and input 2.

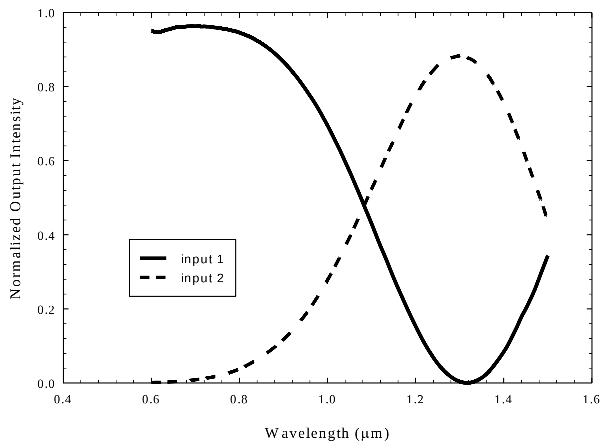


Figure 3.18: The graph showing output intensity as a function of wavelength from input 1 and input 2.

The 3dB spectral at 800nm and 1310 nm are 700 nm and 480 nm, respectively. The broad pump and signal pass band allows this design to be used for WDM application.

3.6 Summary

This chapter concerned pump/signal multiplexer for erbium doped waveguide amplifier (EDWA) and bismuth doped waveguide amplifier (BiDWA). The pump wavelength and signal wavelength for EDWA were 980 nm and 1550 nm whereas the pump wavelength and signal wavelength for BiDWA were 800 nm and 1310 nm. The architecture was utilized for both pump/signal multiplexers is uniform symmetric directional coupler. Due to the coupling coefficient and mode field diameter for signal wavelength is much larger than pump wavelength. Hence the coupler design to have near to 100% cross coupling at signal wavelength and bar coupling at pump wavelength. Small dimension of the device is highlighted in this work. However, the pump wavelength suffered losses for both multiplexer. This is thought to be caused by the coupler design is optimized for the signal wavelength. This can be confirmed by supermode analysis where the power imbalance in both guides. To overcome losses for pump wavelength, a longer length of coupling length is considered. Nevertheless, the insertion losses for pump wavelength are acceptable (<0.5 dB). The coupler design should be as process tolerant as possible. This can be achieved by selecting the design insensitive to the variation of waveguide parameters such as edge-to-edge spacing, wavelength, and coupling length. Simulation results show that the coupler has larger 3dB spectral. To meet the minimum loss requirement of the uniform symmetric directional coupler (0.3 dB), this coupler can be considered sensitive. However, uniform symmetric directional coupler is still appropriate to be used for WDM application.

3.7 Reference

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