

Silicon-Based Mode Converter and Demultiplexer for Wavelength Division Multiplexing Transmission by Using Multimode Interference Couplers

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Abstract

We present a mode converter and demultiplexer structure for wavelength division multiplexing (WDM) transmission by employing multimode interference (MMI) on Silicon-on-Insulator (SOI) platform. The mode converter and demultiplexer have a compact size of less than $2.7 \mu\text{m} \times 43.7 \mu\text{m}$. Moreover, the crosstalk between neighboring wavelength channel within C band (1530 nm to 1570 nm) can be reduced by utilizing the tapered phase shifter cascaded with MMI. The simulated results indicate that this structure has a low insertion loss of less than 1 dB, a low crosstalk of better than -15 dB and a relatively high fabrication tolerance of ~ 10 nm. Such structure may find many potential applications in silicon photonic integrated devices.

Keywords

Multimode Interference, Wavelength Division Multiplexing, Mode Converter, Silicon-on-Insulator

1. Introduction

Silicon-based on-chip optical interconnect has become an emerging technology for its unique advantages of high level of integration. Recently, research work to further increase the transmission capacity of wavelength division multiplexing (WDM) system has become a hot spot in the chip-scale optical communication systems. However, the capacity of WDM is limited by the small bandwidth of fiber amplifier and the low launched power due to fiber nonlinearity. To further

increase the optical transmission capacity, various kinds of methods have been proposed, such as polarization multiplexing (PDM) and mode multiplexing (MDM) technologies [1]. In addition, WDM interconnections which are compatible with MDM are achieved by using different types of mode de/multiplexer (DE/MUX), which are based on asymmetrical directional couplers (ADC) [2], adiabatic couplers [3] and asymmetrical Y-junctions [4] [5]. However, the ADC structure requires additional phase section to realize mode conversion, leading to a limited fabrication tolerance. The adiabatic couplers can reach a low crosstalk, but at the expense of large footprints. The asymmetrical Y-junction has a small footprint, however, the relatively high insertion loss restricts its applications. In contrast, the multimode interference (MMI) combines the advantages of compact size, low crosstalk, large optical bandwidth, and large fabrication tolerance [6] [7]; thus, it may become a good scheme to achieve high-capacity WDM interconnections.

In this paper, we report a new silicon-based mode converter and demultiplexer structure by employing MMI and tapered phase shifter. As the wavelength is increased, the phase shift induced by tapered phase shifter becomes smaller while the phase shift introduced by MMI becomes larger. Therefore, combining the MMI with the tapered phase shifter, the crosstalk between adjacent wavelengths channels will be reduced substantially. The insertion loss and crosstalk of the presented device are simulated by using 3D finite-difference time domain (FDTD) method. The simulated results show the total device has a low insertion loss of less than 1 dB, a crosstalk of better than -15 dB, and the footprint of $\sim 2.7 \mu\text{m} \times 43.7 \mu\text{m}$ (except the length of input/output).

2. Principle and Device Design

The structure of MMI based on the self-image principle has been proposed by Lucas B. Soldano [8], and the input image reproduced as mirror or direct images at the period intervals along the propagation direction. L_π is defined as the beat length of the two lower-order modes:

$$L_\pi = \frac{\pi}{\beta_0 - \beta_1} \cong \frac{4n_r W_e^2}{3\lambda_0} \quad (1)$$

where β represents the propagation constant of optical mode, n_r and W_e is the effective refractive index and the width of MMI for wavelength in vacuum of λ_0 , respectively.

We propose a mode converter and demultiplexer structure for WDM transmission by employing the principle of MMI, and the wavelength signals are multiplexed into a mode converter and multiplexer structure, then transmitted through the symmetric structure and demultiplexed into the data channel respectively. The mode converter and demultiplexer structure consists of three parts, a symmetric interference MMI coupler (MMI1) as a mode converter, a tapered $\pi/2$ phase shifter and a 3 dB general interference MMI coupler (MMI2) as illustrated in **Figure 1**. The length of MMI1 and MMI2 are $3L_\pi/4$ and $3L_\pi/2$, re-

spectively. The fundamental mode (TE_0) is injected from *Port1* and imaged in *Port3* and *Port6*, then extracted from *Port9*. In addition, the first-order mode (TE_1) will be split into two fundamental modes in the *Port2* and *Port4* with the same power and π phase difference. After transmitting through the tapered $\pi/2$ phase shifter and MMI2, the two modes will be converted into the TE_0 mode through constructive interference in MMI2, and then output from *Port8*. Therefore, the TE_0 mode will be directed out from *Port9* while the TE_1 mode will be converted into TE_0 mode and coupled out from *Port8*, thus realizing the mode converter and demultiplexer.

In the design above, an SOI wafer with a 220 nm top silicon layer and 2 μm buried oxide (BOX) layer is considered as the fabrication platform, and the input width of *Port1* is set to be 1 μm so that fundamental mode and first order mode can exist at the same time. The width of MMI1 is chosen to be 2.4 μm in consideration of the compact device size and fabrication requirement. Firstly, the effective refractive index of the fundamental mode in MMI1 at the wavelength of 1550 nm is numerically calculated to be ~ 2.83 , and the length of the MMI1 is 10.5 μm according to Equation (1). As shown in **Figure 2(a)** that the optimal length of MMI1 is 9.2 μm when TE_0 and TE_1 mode injected into *Port1* and analyze the power in *Port2*, *Port3* and *Port4* respectively, and produce a high transmission

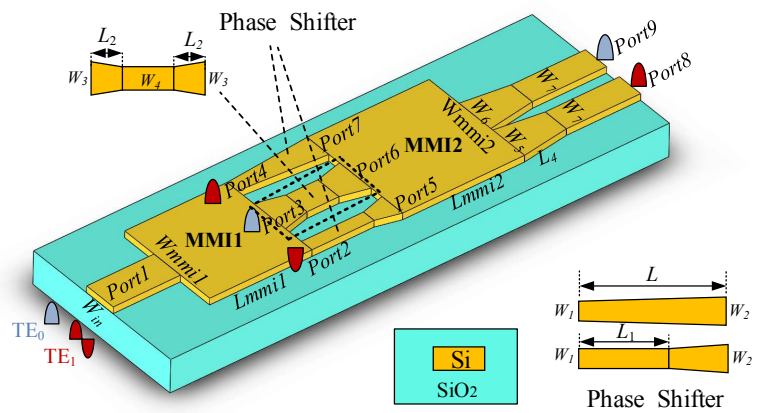


Figure 1. Schematic diagram of the mode converter and demultiplexer structure.

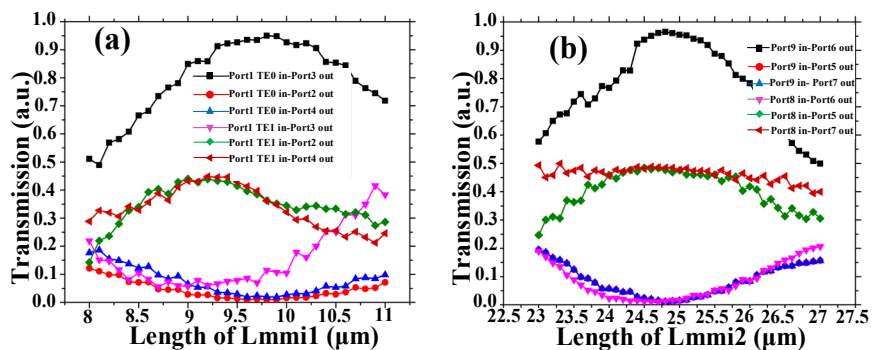


Figure 2. The transmit efficiency varies with (a) the MMI1 length, (b) the MMI2 length.

efficiency for both TE₀ and TE₁ modes. For the 3 dB coupler, MMI2 has a width of 2.7 μm. Similarly, as TE₀ mode injected in *Port8* and *Port9* and analyzing the power in *Port5*, *Port6* and *Port7*, respectively, the optimal length of MMI2 is 25 μm through FDTD simulations, as exhibited in **Figure 2(b)**.

In order to obtain high transmission efficiency as much as possible, we design and optimize the width of W_1 , W_3 , W_5 and W_6 . As shown in **Figure 3(a)**, we fix the width and length of MMI1, then injected TE₁ mode from *Port1* and calculated the power in *Port2* (the same power in *Port2* and *Port4*) with the change of the width of W_1 . From the figure we can find that the transmission loss can be reduced to minimum in the case of $W_1 = 0.5$ μm. Similarly, we injected TE₀ mode in *Port1* and analyzed the transmission efficiency varied with the width of W_3 , as shown in **Figure 3(b)**, the width is optimized as $W_3 = 0.9$ μm. In order to avoid the coupling between *Port2*, *Port3* and *Port4*, we set the width of W_4 and W_7 as 0.5 μm, which can only support the fundamental mode, and the length of L_2 and L_4 is set as 2 μm and 5 μm. In order to optimize the widths of W_5 and W_6 , we fix the size of MMI1 and MMI2, then inject TE₀ and TE₁ mode from *Port1* and change the widths of W_5 and W_6 from 0.3 μm 1.3 μm, respectively. As shown in **Figure 3(c)** and **Figure 3(d)**, we find the maximum transmission power in *Port9* and *Port8* in the case of $W_5 = 0.9$ μm and $W_6 = 0.9$ μm respectively.

When designing the tapered phase shifter, the length of L is chosen as 9.5 μm and the width of W_2 is 0.8 μm. Then we scan the phase shift of tapered phase shifter of different length L_1 , as shown in **Figure 4**. The result shown a $\pi/2$ phase shifter at 1550 nm with the length of $L_1 = 7.6$ μm. Moreover, we get the phase difference with different wavelength of 1530 nm, 1550 nm and 1570 nm in **Figure 4**,

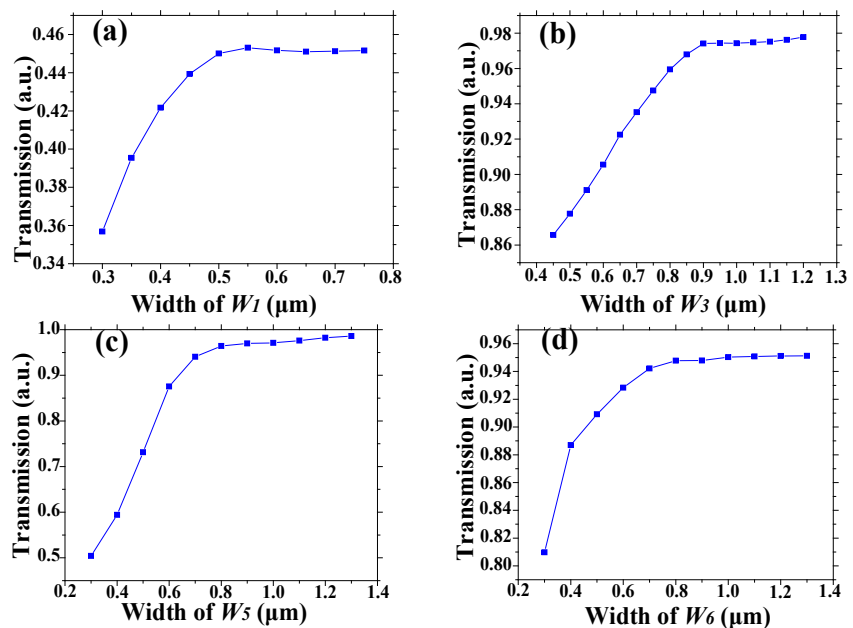


Figure 3. The transmit efficiency varies with the width of (a) W_1 , (b) W_2 , (c) W_5 , (d) W_6 at 1550 nm.

which indicates a variation range of lower than two degrees difference range over the whole C band wavelength (1530 nm to 1570 nm).

Then we calculate the phase difference when TE_0 mode injects from *Port8* then transmits through MMI2 and phase shifter with wavelength varying from 1530 nm to 1570 nm, as shown in **Figure 5(a)**. The results clearly show that the phase shift induced by phase shifter is inversely proportional to the wavelength shift, which means a reduction of phase shift when wavelength increases. Nevertheless, the phase difference caused by MMI2 becomes larger with the increase of wavelength. Furthermore, we also analyze the total phase difference of these two components, as exhibited in **Figure 5(b)**. It is obvious that the total phase difference is between -0.025 and 0.025 rad when wavelength varying within C band. Such small phase difference may enhance the transmission performance of the device.

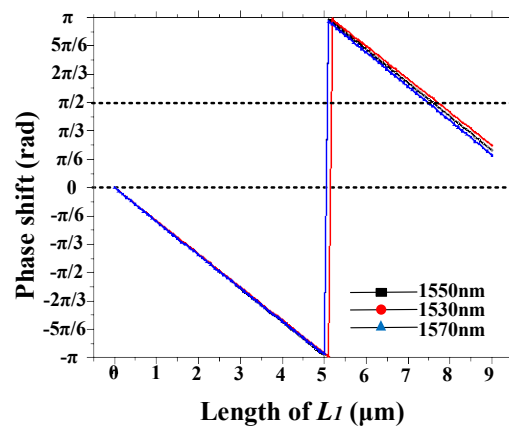


Figure 4. The phase difference of 1530 nm, 1550 nm and 1570 nm as function of length L_1 .

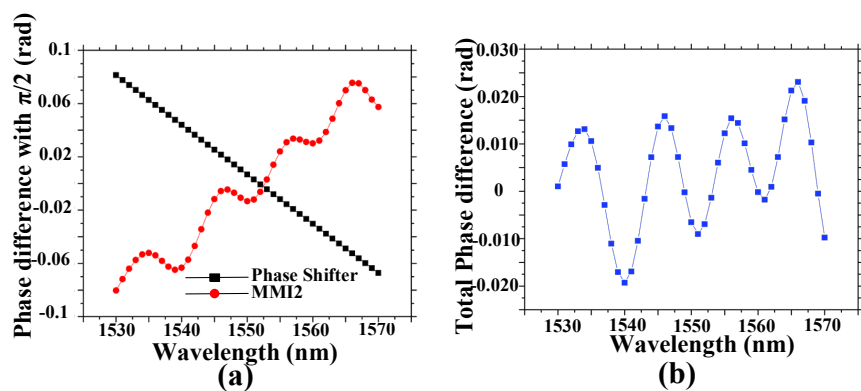


Figure 5. (a) The phase difference of phase shifter and MMI2 as function of wavelength, (b) the total phase difference of MMI2 and phase shifter as function of wavelength.

3. Results and Discussion

The total device is simulated by way of 3D FDTD method. To demonstrate the

mode converter and multiplexer of TE_0 - TE_0 , TE_0 - TE_1 , we simulate the optical field distributions, and the results are shown in **Figure 6(a)** and **Figure 6(d)**. The TE_0 mode injected in center-port (*Port9* in **Figure 1**) will keep TE_0 mode transmission to the output port. However, the TE_0 mode injected in under-port (*Port8* in **Figure 1**) will be converted into TE_1 mode with high conversion efficiency. Additionally, for the mode demultiplexer, the light output from *Port9* for the TE_0 mode input, and the light output from *Port8* for TE_1 mode input. One should note that both output modes are TE_0 modes, as displayed in **Figure 6(b)** and **Figure 6(e)**. Then we simulate the transmission field distributions of the mode multiplex and de/multiplex structure, as shown in **Figure 6(c)** and **Figure 6(f)**, there is an obvious and direct correspondence between the input port and the output port.

For a multiplexer and de/multiplexer structure, the two most important parameters are insertion loss (IL) and crosstalk (CT). Here we analyze the relationship between transmission efficiency and wavelength by calculated the IL and CT of the device. **Figure 7** shows the result of two modes multiplex, demultiplex and mode multiplex and de/multiplex. Numerical calculation results show

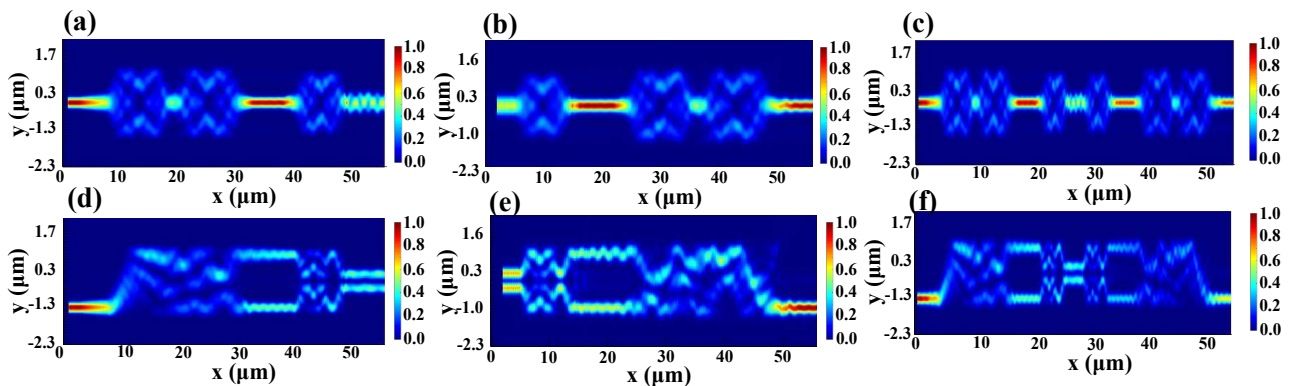


Figure 6. Transmission field distributions of (a), (d) the mode multiplexer with TE_0 injected in *Port9* and *Port8*, respectively. (b), (e) the mode demultiplexer structure with TE_0 and TE_1 injected in *Port1*, and (c), (f) the mode multiplexer and de/multiplexer with TE_0 injected in *Port9* and *Port8*, respectively.

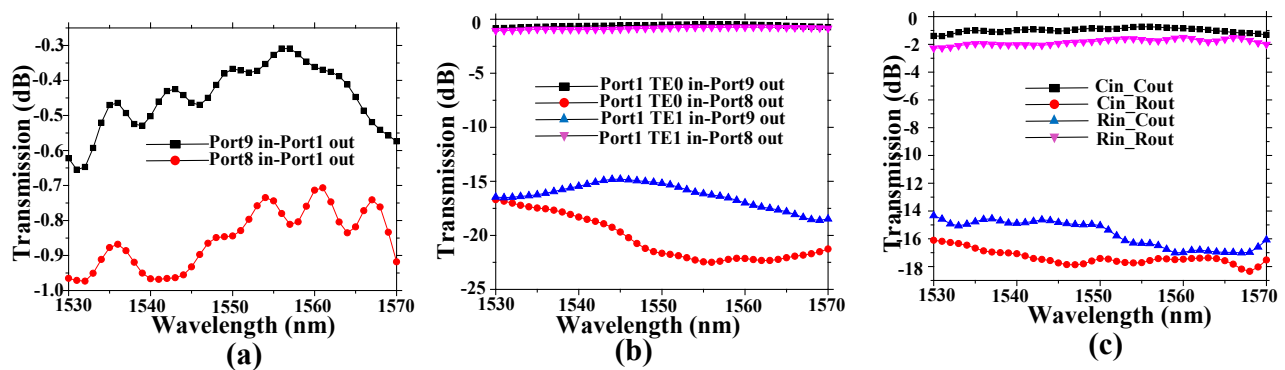


Figure 7. Wavelength dependence of (a) the mode multiplexer when the input is the TE_0 in *Port9* and *Port8*, (b) the mode demultiplexer structure with TE_0 and TE_1 injected in *Port1*, and (c) the mode multiplexer and de/multiplexer when the input is the TE_0 in *Port9* and *Port8*, respectively.

the IL are below 1 dB in multiplex and de/multiplex structure over the whole C band (1530 nm to 1570 nm), while the IL of the whole structure of multiplex and de/multiplex is below 2 dB as shown in **Figure 7(c)**. It can be seen that the CT of mode multiplexer and de/multiplexer structure is lower than -14 dB and the designed two-mode multiplexer is below -15 dB within the bandwidth from 1530 nm to 1570 nm. Such simulated results show that the proposed structure is potential to be applied in practical silicon photonic integrated circuits.

At last, we calculate the fabrication tolerance of the proposed structure. It is clear that there is a quadratic curve relation between the beat length of MMI and the effective width of MMI, in other words, the performance of the device is much sensitive to the width of MMI. Therefore, we set the two mode demultiplexer structure with TE_0 and TE_1 mode injected into *Port1*, respectively. Then we analyze the normalized power with the MMI width varying from -50 nm to 50 nm at the wavelength of 1530 nm, 1550 nm and 1570 nm, respectively. As illustrated in **Figure 8(a)**, when MMI width varies from -10 nm to 10 nm, the insertion loss is lower than 1.5 dB.

For the phase shifter, its performance highly sensitive to dimensional variations, we simulate the transmission characteristics when the total length varies at the wavelength of 1530 nm, 1550 nm and 1570 nm. It can be easily observed from **Figure 8(b)** that the maximum transmission occurs when ΔL is 0 nm at 1550 nm, and the transmission efficiency decreases whether the ΔL increases or decreases. In the practical fabrication craft, the length variation can be selected from -30 nm to 30 nm, which can provide much convenience.

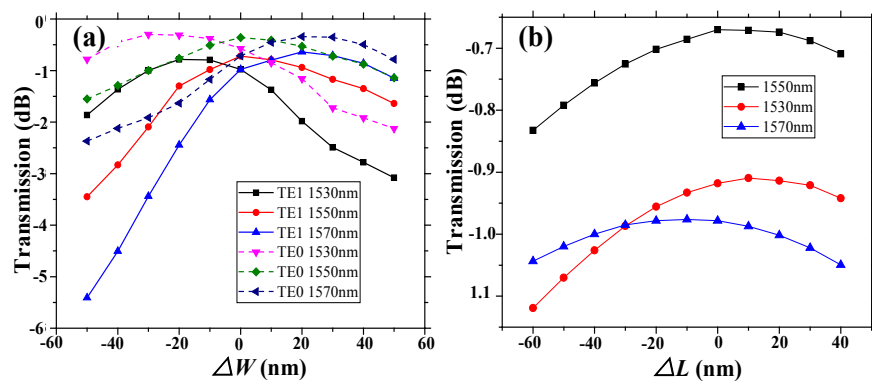


Figure 8. Fabrication tolerance of the (a) transmission efficiency varies with MMI width, (b) transmission efficiency varies with phase shifter length at the wavelength of 1530 nm, 1550 nm and 1570 nm.

4. Conclusion

We propose and simulate a SOI-based mode converter and demultiplexer structure for WDM optical interconnection and transmission by employing MMI and tapered phase shifter structure. The simulation results indicate that such a structure has a broad bandwidth of over the whole C band, a low transmission loss of less than 1 dB and a low crosstalk of less than -15 dB. A compact mode

converter and demultiplexer of less than $2.7 \mu\text{m} \times 43.7 \mu\text{m}$ is achieved and the fabrication tolerance is $\sim 10 \text{ nm}$ which can meet the demand of the practical fabrication. Such structure may provide a valuable selection in silicon photonic integrated circuits (PICs).

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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