Design of Silicon TE_0/TE_1 Mode Router Using Mach-Zehnder and Multimode Interferometers

Tran X. Hop, Dang T. Nuong, Ho D. T. Linh*, Duong Q. Duy, Nguyen T. H. Yen,
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Abstract—This paper proposes a new design of two-input-mode three-output-port optical TE_0 mode router for mode division multiplexing systems. The device consists of a Mach-Zehnder interferometer (MZI) and a multimode interferometer (MMI), which utilizes silicon material for photonic integrated circuits (PIC). By setting appropriate values for the two butterfly-shaped phase shifters (PSs) at MZI and MMI, the input mode, either transverse electric TE_0 or TE_1 mode, TE_0 mode can be routed to the desired output among the three output ports. The device is designed and optimized via three-dimensional beam propagation method (3D BPM). The proposed device achieves very low insertion loss and small cross-talk, which are less than 0.4 dB and -24.5 dB, respectively, over the whole C band.

Index Terms—Y-Junction, mode division multiplexing, photonic integrated circuit, multimode interference, phase shifter.

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1. Introduction

THE current optical communications imposes more and more challenging constraints on electrical chips to meet the demand of ever-developing technologies, such as better bandwidth efficiency, higher bit-rate, more data capacity, and high flexibility [1]. Photonic on-chip interconnection is a solution, where silicon-on-insulator (SOI) material platform is of favour due to low cost, high refractive index contrast, and its improved compatibility with metal oxide semiconductor technologies [2]. The technique of wavelength division multiplexing (WDM), which uses multiple laser sources with different wavelengths for different transmission channels, and the technique of polarization multiplexing, which uses transverse electrical modes (TE) and the transverse magnetic (TM), have been researched extensively in the past decades [3, 4]. These technologies, however, cannot satisfy the ever-increasing need of bandwidth due to limited exploitable wavelengths. By combining high-order modes, mode division multiplexing (MDM) is a promising approach for the bandwidth issue. Especially, the combination of WDM and MDM allows a multi-fold increase in the total data capacity [5, 6]. In order to construct the MDM system, many optical devices have been proposed such as mode multiplexer/ demultiplexer [7]-[11], high-order mode filters [12], multimode bends [13], power splitters [14], and mode switches. The last one, mode switches, plays a significant role in the on-chip optical network using MDM technology, is the subject of this work.

Several recent research about mode division multiplexing switching on an optical chip has been proposed and tested experimentally [15-18]. Furthermore, mode multiplexers based on asymmetrical directional couplers (DCs) have also been proposed in [16]. However, those structures are limited by their sensitivity to fabrication errors. In [17], the authors experimentally demonstrated the high-speed and flexibility of their proposed mode switching device using a two-mode switching structure. The device proposal may process both modes simultaneously by combining the multimode interference (MMI) couplers structure and the Y-junction, but the processing of two optical modes interrupts with the same polarization. Alternatively, [18] experimentally shown that for basic TE modes, the mode selector switches (MSS) are based on cascade MMI couplers and photothermal phase shift. However, the vertical stacking structure suffers from the limited design-flexibility and may not be compatible with other on-chip components.

In this paper, we introduce a new structure of a 1x3 mode router for two optical modes using SOI material platform, which is assembled from a Mach-Zehnder interferometer, and a mode demultiplexer that consists of a 1x3 Y-junction and a 3x3 multimode interference (MMI). Two phase shifters are used to route the input modes, TE_0 and TE_1, to the desired output ports. The optimization process and operation description

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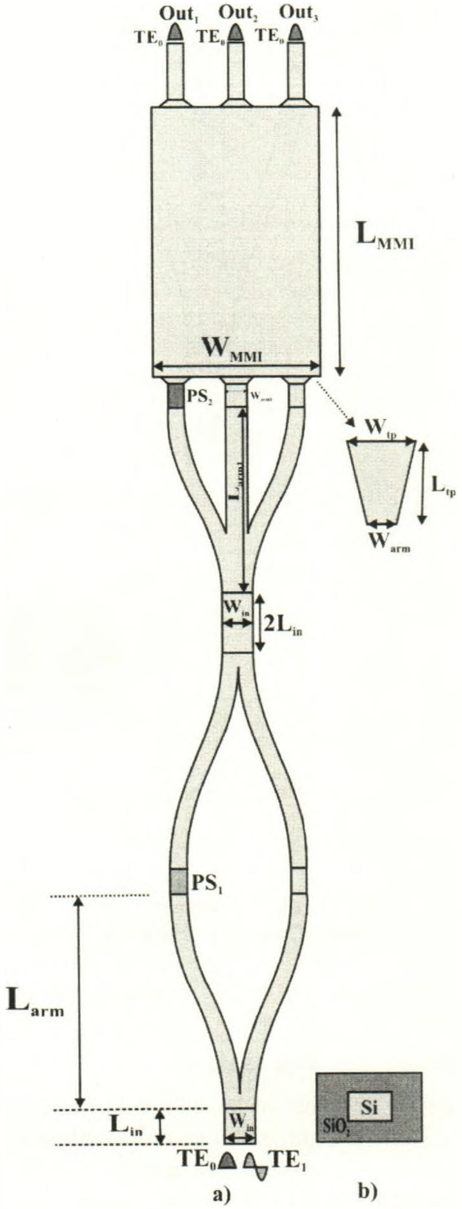
Manuscript received November 29, 2020; revised January 19, 2021; accepted March 25, 2021.
Digital Object Identifier 10.31130/ict-ud.2021.128

are performed by three-dimension beam propagation method (3D BPM). The simulation results show that the proposed router gives good performance with high efficiency of over 83% (insertion loss is lower than 0.8 dB) and small crosstalk being less than -20 dB over the bandwidth from 1.52 μm to 1.58 μm. Over the C band, the efficiency is more than 91% (insertion loss is lower than 0.4 dB), reaching up to 99% (insertion loss is 0.05 dB) at the wavelength of 1550 nm, meanwhile, the crosstalk is less than -24.5 dB.

2. Structure Design

2.1. General Description



a) b)

Fig. 1: General diagram of two-input-mode Three-output-port optical TE_0 mode router.

Figure 1a) shows the general diagram of the suggested mode router. The device encompasses a Mach-Zehnder interferometer (MZI), and a mode demultiplexer, which is made from a 1x3 Y-junction and a 3x3 MMI. Two phase shifters, denoted as PS_1 and PS_2, are respectively located at one arm of the MZI and one outer input port of the MMI to route the input modes, TE_0 and TE_1, to the desired output ports. The input width W_{in} is carefully set so that it can support both TE_0 and TE_1 modes. The MZI, which is constructed from two 1x2 Y-junctions, possesses two branches, left and right, with the width W_{arm} being small enough to support only TE_0 mode. Its function is either converting TE_0 to TE_1 and vice versa, or just letting the input modes go through without any change by setting PS_1 at 180^0 or 0^0, respectively.

The output of the MZI is connected to the input of the mode demultiplexer, which is built from a 1x3 Y-junction and a 3x3 MMI. The width of the two side branches and the middle one of the 1x3 Y-junction, denoted as W_{arm} and W_{arm1}, respectively, are chosen so that they can only support mode TE_0. Its three output ports are then connected with the three input ports of the 3x3 MMI. If TE_0 is the output mode of the MZI, then this mode will pass through the middle arm of 1x3 Y-junction, and reach to the Out_2 of the device. If TE_1 is the output mode of the MZI, setting the value of PS_2 at 90^0 or -90^0, the signal is routed to Out_1 or Out_3, respectively. The output mode is always converted to TE_0. Table I summarizes input/output routing scenarios of the proposed devices with respect to phase settings for PS_1 and PS_2.

In this design, the device utilizes ridge waveguide structure over SOI platform. As shown in Figure 1b), it has a silicon core and a silicon dioxide cladding, of which the refractive index is 3.47, and 1.44, respectively. To optimize the device, simulations based on three-dimensional beam propagation method (3D BPM) are carried out.

TABLE 1: Input/output routing scenarios of the proposed devices with respect to phase settings for PS_1 and PS_2.

Input	Output	PS1	PS2
TE_0	Out_1	180^0	90^0
	Out_2	0^0	any
	Out_3	180^0	-90^0
TE_1	Out_1	0^0	90^0
	Out_2	180^0	any
	Out_3	0^0	-90^0

2.2. Mach-Zehnder Interferometer (MZI)

Figure 2 shows the design of MZI. It consists of two 1x2 Y-junctions and a butterfly-shaped phase shifter, denoted as PS_1. The structure is featured by the fact that it consists of two sine waveguides coupled together. To support two modes TE_0 and TE_1, the input and output width of this set , W_{in}, are chosen to be 1.1 μm. The input and output length of this set, L_{in}, are chosen to be 20 μm. The width of the two branches W_{arm} are set to be 0.3 μm so that only mode TE_0 can travel through. The length of each Y-shaped structure, L_{arm}, is of 150 μm. The phase shifter size (L_{PS} x W_{PS}) is adjusted to obtain the phase difference of 0^0 or 180^0. The former case can be attained by setting (L_{PS} x W_{PS}) of ($20.2\mu m$ x $0.3\mu m$). The latter case can be achieved by choosing (L_{PS} x W_{PS}) of ($20.2\mu m$ x $0.45\mu m$). When the phase shift is 0^0, the two modes can go through the Mach-Zehnder with no change. When the phase shift is 180^0, the input TE_0 mode is transformed into TE_1 at the output, and vice versa.

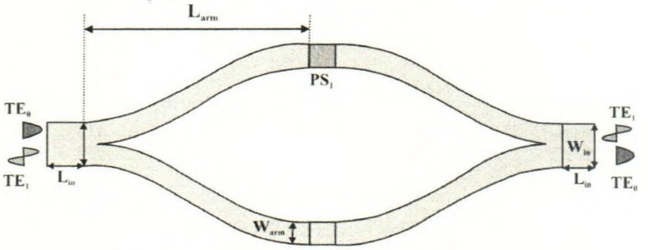


Fig. 2: The structure of Mach-Zehnder.

2.3. 1x3 mode division (de)multiplexer

In this 1x3 (de)multiplexer, the three output ports of the 1x3 Y-structure are connected with the three input ports of the 3x3 MMI. The butterfly-shaped phase shifter PS_2 is attached to the left side arm of the Y-junction in order to route signal to desired output. The structure is illustrated in Fig. 3.

The 1x3 Y-shaped structures has input width W_{in} of 1.1 μm so that the TE_0 mode and TE_1 mode can coexist. Its two side arms' width are the same, denoted as W_{arm}, and being of 0.3 μm so that only TE_0 mode exists. The middle branch, which also supports only TE_0 mode, has the width W_{arm1} of 0.4 μm, and the length L_{arm1} of 130 μm. The PS_2 's size is adjusted to get the phase deviation of 90^0 or -90^0. The width of the phase shifter in the two cases are $0.68\mu m$ and $0.57\mu m$, respectively, while its length is $20.2\mu m$ in both situations. A 3x3 MMI has the length L_{MMI} of 54.4 μm and the width W_{MMI} of 3.6 μm. To optimize signal transmission between the 3x3 MMI and the 1x3 Y-junction, a taper is used, having the length L_{tp} of 5 μm and the width W_{tp} of 0.7 μm.

In photonic chip fabrication technology, the voltage control method or the thermal control method is often used to control the optical signal phase in the waveguide. The principle of these two methods is changing the refractive index of the waveguide material to acquire the wanted phase shift. However, to demonstrate the routing functionality of the proposed device, just a simple simulation is implemented, which specifically designs a butterfly-shaped waveguide as a phase shifter as shown in Fig. 4.

Observing the red part in Fig. 4, the phase shifter can be seen to have same width of W_{arm} = 0.3 μm at the two ends, and have length of L_{ps} = 20.2 μm. To obtain the phase shift of -90^0, 90^0, or 180^0, the width of the central waveguide, W_{PS} is 0.57 μm, 0.68 μm, and 0.45 μm, respectively.

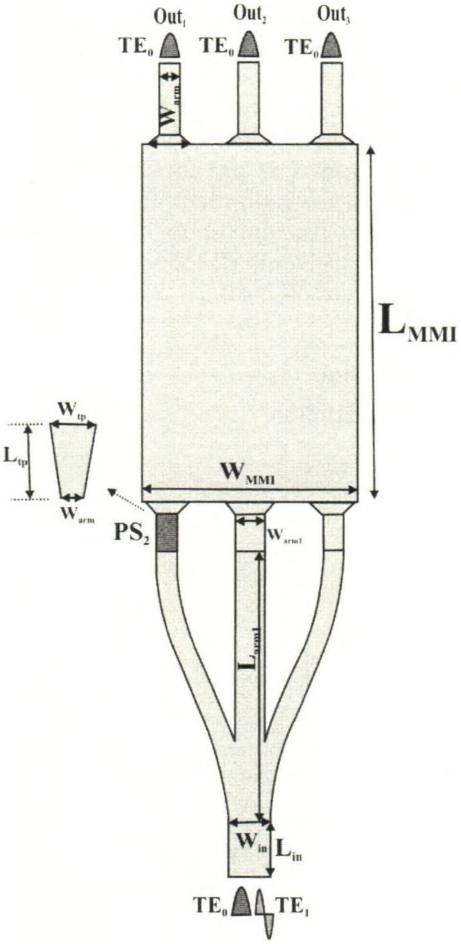


Fig. 3: The structure of mode division (de)multiplexer.

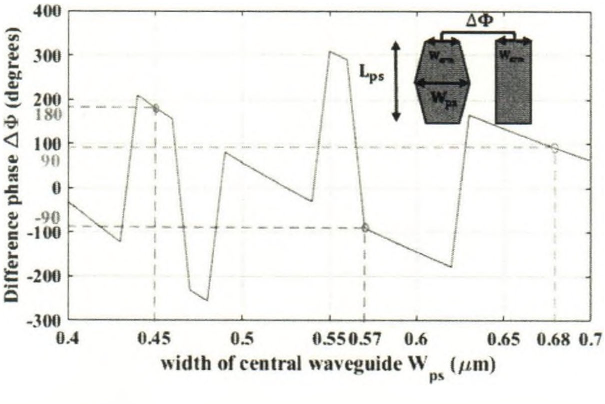


Fig. 4: The different of output phase as a function of phase shifter central width.

3. Simulation and Discussion

Numerical simulations based on 3D-BPM are carried out to evaluate the optical conversion efficiency of the mode router. We investigate the optical modes TE_0 and TE_1 when they are excited and passed through the device from the input port to the output port.

The simulation results in Figs. 5 and 6 show the router mode's electromagnetic field at a wavelength of 1550 nm when the two modes TE_0 and TE_1 are applied to the device. With the simulation results, it can be seen that the input TE_0 and TE_1 mode can routed to any output port among three output ports. Also, observing the aforementioned figures, it can be seen that light transmitted in the waveguides is almost not attenuated, which means that the efficiency is high.

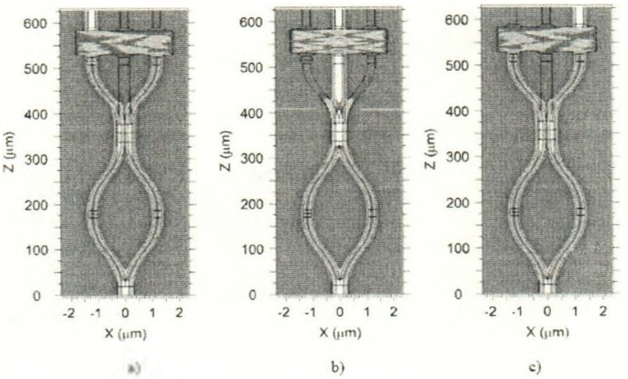


Fig. 5: Optical field distribution when TE_0 at the input and TE_0 at the corresponding output, a) Out_1, b) Out_2, c) Out_3.

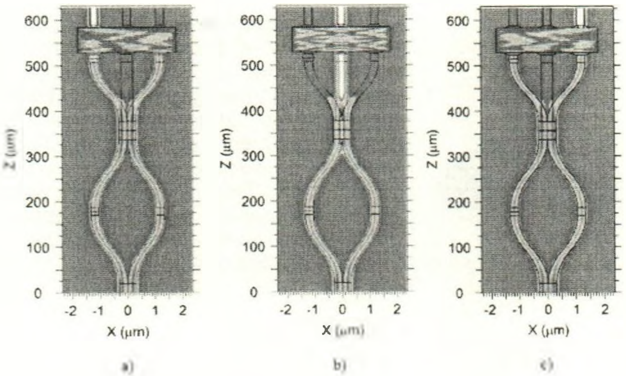


Fig. 6: Optical field distribution when TE_1 at the input and TE_0 at the corresponding output, a) Out_1, b) Out_2, c) Out_3.

In the limited scope of the paper, to assess more accurately the performance optical switch device, we use the following parameters: the insertion loss IL, and attenuation due to crosstalk CT, which can be computed as follows

$$IL = 10\log_{10}\left(\frac{P_{out_{\text{desirable}}}}{P_{in}}\right), \tag{1}$$

$$CT = 10\log_{10}\left(\frac{P_{out_{\text{unwanted}}}}{P_{out_{\text{desirable}}}}\right), \tag{2}$$

Where $P_{in}, P_{out_{\text{desirable}}}, P_{out_{\text{unwanted}}}$ are subsequently the excited power at the device input, the desired power at the device output, and the unwanted power appearing along with the desired power at the output, respectively. It is obvious to observe from eqs. (1) and (2) that if $P_{in} = 1$W then one will achieve the output values as $P_{out_{\text{desirable}}} \in [0, 1]$W and $P_{out_{\text{unwanted}}} \in [0, 1]$W.

The values of these two parameters over wavelengths are plotted in Figs. 7 and 8, respectively. The former shows the efficiency being higher than 83% (insertion loss is less than 0.8 dB), over the bandwidth from 1.52 μm to 1.58 μm. This value can reach higher value in C-band, for instance, above 91% (insertion loss is smaller than 0.4 dB). The peak value of efficiency is obtained at the wavelength of 1550 nm, up to 99%. Figure 8 gives information of the crosstalk of the three channels, which is always below -24.5 dB over the entire C band and less than -20 dB over the whole surveyed frequency range.

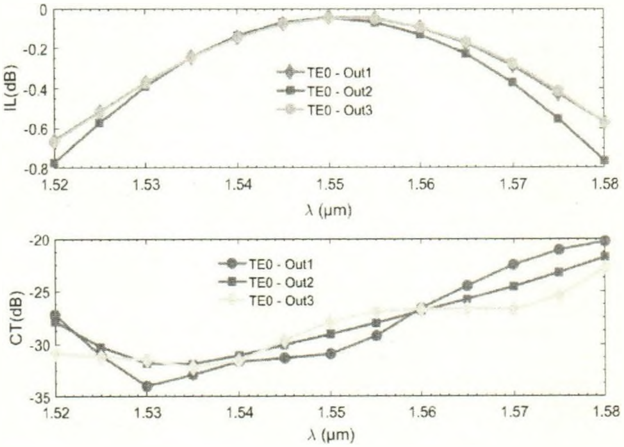


Fig. 7: Insertion loss and crosstalk as a function of wavelength when transmitting input TE_0 to output signals at three output ports Out_1, Out_2, Out_3.

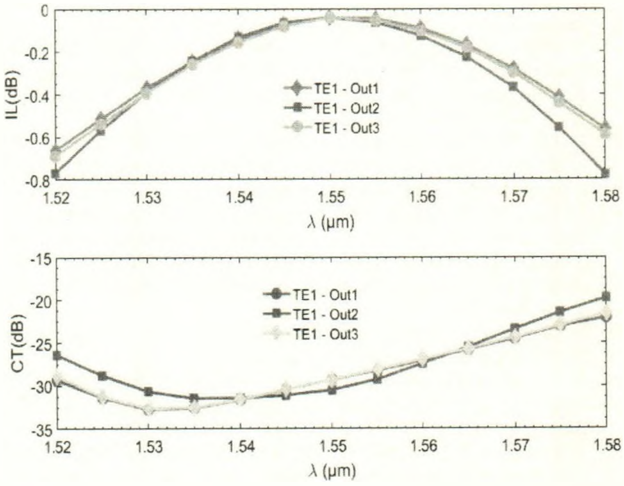


Fig. 8: Insertion loss and crosstalk as a function of wavelength when transmitting input TE_1 to output signals at three output ports Out_1, Out_2, Out_3.

4. Conclusion

The paper presents a new structure of a silicon-based two-mode three-port optical mode router. It can flexibly route the input modes of TE_0 or TE_1 to the desired output with high efficiency and low crosstalk over the whole C-band. At the wavelength of 1550 nm, it obtains up to 99 % efficiency and trivial crosstalk. With a compact size (3.6 μm × 634.8 μm × 0.3 μm), the device is a competitive candidate for applications of on-chip optical integrated circuits as well as of high-speed multimode optical networks in the future.

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