Optical Mode Cross-Connect Using Multimode Interference Mmi Based On Silicon Material

Ho Duc Tam Linh*, Vo Duy Phuc, Nguyen Quang Viet, Nguyen Duc Hien, Nguyen Tan Hung

Abstract—An optical mode cross-connect (OMXC) between fundamental modes using a multimode interference coupler (MMI) with high performance has been proposed in this paper. These basic modes can be transmitted in turn or at the same time to any input and be able to select arbitrary outputs. The following inputs can only select the remaining outputs, so this process will not cause bottlenecks in the circuit. In order for the signals to be flexibly switched to the outputs without conflict, the phase shifters will be used to control their lightpaths. Through the BPM-3D beam propagation method, we have shown the flexible switching process between the input and output ports of the device with an insertion loss always smaller than 1.8 dB in the range of wide wavelength from 1.53 μm to 1.57 μm. Specifically, attenuation only reaches -0.5 dB at the central wavelength of 1.55 μm. In addition, the crosstalk is always in a very small range from -30 dB to -20 dB for the entire band considered above. With these advantages, it is a promising device for optical mode processing circuits in the MDM system.

Index Terms—Optical mode cross connect; BPM-3D; SOI; channel structure; MMI.

1. Introduction

IN recent years, with the rapid development of optical transmission, it has contributed to solve the electric transmission disadvantages, which are limited in bandwidth and slow transmission speed and difficult to develop further in the future. Currently, WDM wavelength division multiplexing technology dominates the optical transmission network, but this technology is also facing the exhaustion of the number of wavelengths. Therefore, MDM technology is being studied in combination with WDM technology to overcome the shortage of these wavelengths. A very important component of the WDM system is the optical cross connector (OXC), which is widely studied and applied [1]–[5]. However, optical mode cross-connecters (OMXC) for mode division multiplexing networks are rarely studied. Several 2-mode switches that act as optical mode cross-connectors are published. Specifically, based on an asymmetric directional coupler and optical thermal effect, a two-mode selective switch with a total size of 16.5 mm is proposed [6]. Each mode is selected for any output by controlling the heater. The paper [7] is also a two-mode flexible switch using a multimode interfererence coupler, a Y-junction and a PN-doped junction-based phase shifter. Another proposal uses MEMs microelectromechanical systems to switch LP01 and LP11 modes at the desired output [8].

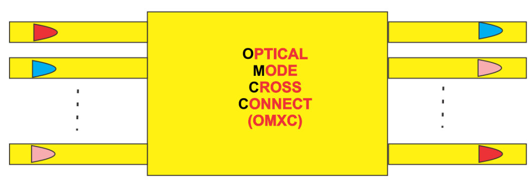

Fig. 1: General diagram of optical mode cross connector OMXC.

To build a switch that supports more channels in the MDM system illustrated in Fig. 1, we designed a single-mode OMXC 3x3 in this paper. The advantage of the MMI component is its compact size and ease of fabrication, so the design of the OMXC device using the MMI component will reduce the size of the device compared to the previous proposals. By changing the appropriate phase values to control the path of the signal, each signal at the input is selected to any output without overlap at the output.

2. Structure Design

The OMXC is designed and shown in Fig. 2. The device consists of four MMIs divided into two pairs (MMI1; MMI4) at the device's beginning and end, and a pair (MMI2; MMI3) in the middle. Each of these MMI pairs is the same completely. In addition, the

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Manuscript received April 13, 2022; revised May 10, 2022; accepted June 15, 2022.
Digital Object Identifier 10.31130/ud-jst.2022.160ICT

device structure has five phase shifters located at the appropriate input and output positions of MMI. In addition, we will use a quadrilateral taper to improve optical signal transmission performance between MMI and access waveguide, with L_{TP} = 4 μm and W_{TP} = 0.8 μm corresponding to its length and width.

The Silicon core material layer with a refractive index of n = 3.47 is covered by upper and lower layers made of silicate material. These two shells have a refractive index of 1.44. The height of this channel waveguide is chosen at H = 0.22 μm.

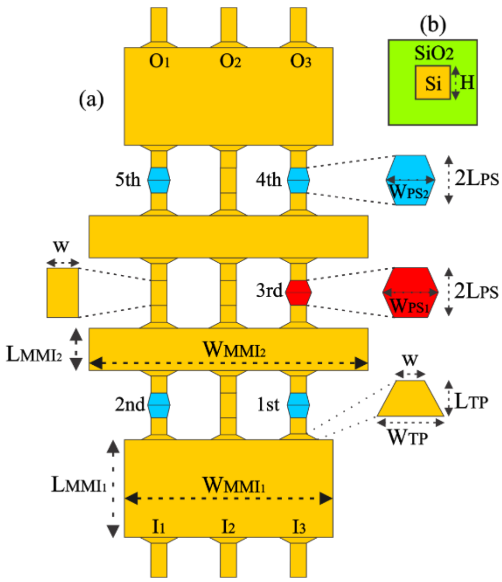

Fig. 2: Structure of OMXC 3x3.

2.1. Multimode Interference (MMI) Coupler

The MMI device consists of two parts: a rectangular multimode waveguide in the center, and access waveguides that only support a single mode placed in the rectangular waveguide's input and output positions. We designed them using the self-imaging principle, as shown in [9], [10], and the relationship between signal amplitude and phase, as shown in [11]. Based on that theory, we choose a width of W_{MMI1} = 3.9 μm and a length of L_{MMI1} = 64.2 μm for the MMI coupler, with the positions of the three access waveguides corresponding to $\pm W_{MMI1}/3$ and the central location of the MMI1 region. For two MMI2 and MMI3 couplers, they also have an access waveguide placed in the central position, and the two remaining waveguides are arranged at two positions W = $\pm$ 2 μm. The rectangular MMI2 and MMI3 have lengths and widths chosen W_{MMI2} = W_{MMI3}= 5.0 μm and L_{MMI2} = L_{MMI3} = 25.8 μm, respectively.

For MMI1, we have two properties as follows: when sending a signal to the input port 2 of MMI1, the signal will go straight to the output port 2. Another characteristic of MMI1 is that when we only transmit one signal to port 1 or port 3, we will simultaneously get two signals of equal amplitude at ports 1 and 3, but the phase of the two signals at these two ports is different by an amount of 90 degrees.

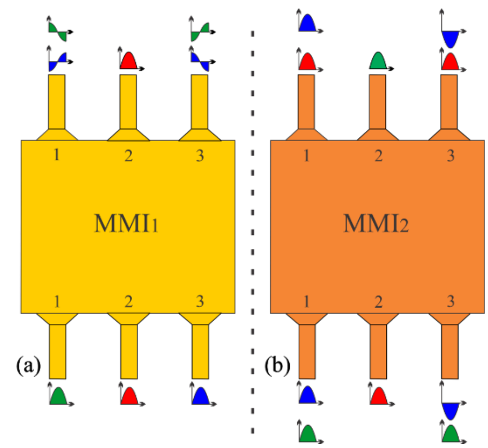

Fig. 3: The operating principle of two couplers MMI1 and MM2.

In contrast to the nature of MMI1, when a signal is transmitted to the input port 2 of MMI2, two signals with the same phase and amplitude at two output ports, 1 and 3, will be obtained at the same time. In addition, if we send two signals exactly the same on ports 1 and 3, we will get a composite signal at output port 2. On the other hand, at the two inputs 1 and 3, two signals are transmitted simultaneously with equal amplitudes but out of phase by 180 degrees. Then the two output ports 1 and 3 of MMI2 also receive the correct amplitude and phase of the two input ports.

2.2. Phase shifter

For simulations, instead of using thermo-optic [12]–[15] or electric-optic [16]–[25] phase shifters, a passive phase shifter in which the length L_{PS1} = 8.4 μm and the width W_{PS1} = 0.35 μm of tapered waveguide is used to shift amount of phase of 180 degrees. Another phase shifter with the length L_{PS1} = 8.4 μm and the width W_{PS2} = 0.38 μm will shift a phase of 90 degrees (Figure 4). We will use these two phase shifters to control the signals in the proposed device.

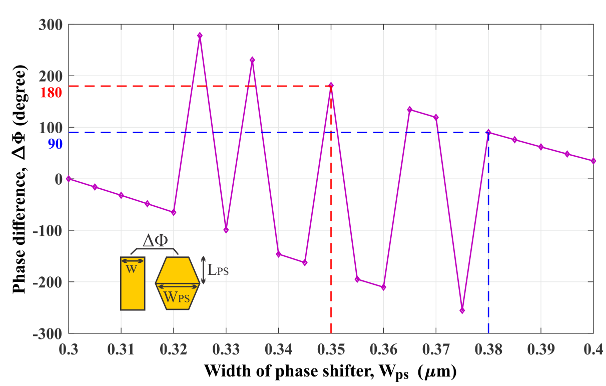

Fig. 4: Phase shifting value as functions of the central width W_{PS}.

In order for the signals at the inputs to switch to the desired outputs, the phase shifters must be placed at the appropriate positions. With three inputs and outputs, six general cases will describe all switching cases, as shown in the Table 1.

TABLE 1: Setting of phase shifters for all situations of the OMXC.

Switching cases	Phase shifter				
	1st	2nd	3rd	4th	5th
I_1 - O_1 I_2 - O_2 I_3 - O_3	0^0	90^0	0^0	0^0	90^0
I_1 - O_1 I_2 - O_3 I_3 - O_2	0^0	90^0	180^0	0^0	90^0
I_1 - O_2 I_2 - O_3 I_3 - O_1	90^0	0^0	180^0	0^0	90^0
I_1 - O_2 I_2 - O_1 I_3 - O_3	90^0	0^0	180^0	90^0	0^0
I_1 - O_3 I_2 - O_2 I_3 - O_1	0^0	90^0	0^0	90^0	0^0

3. Performance Evaluation And Discussion

With the theory mentioned in Section II, the wavelength λ = 1.55 μm is chosen to survey the proposed device. Because there are so many switching cases, we only choose one general case to explain the working principle of optical cross-connectors, and the remaining general cases are explained in a similar way.

From the Fig. 2a, assuming the signal at input port I_1 is the first priority to select the output port, it has three output choices (O_1, O_2, O_3). If the input signal I_1 switches to output O_1, two inputs (I_2, I_3) have only two choices to output (O_2, O_3). If the signal is switched from input I_2 to O_2, the remaining input I_3 is required to select O_3 output. With the above selection ($I_1 \rightarrow O_1$, $I_2 \rightarrow O_2$, $I_3 \rightarrow O_3$), based on the table in Section II, Part B, two phase shifters of 90 degrees are placed at the positions (2nd and 5th). Conversely, if the input signal I_1 still selects O_1 output but the signal at input I_2 to switch to output O_3, then the O_2 output will surely receive the signal when the input signal is input I_3. Based on Table 1, we can see that, for switching ($I_1 \rightarrow O_1$, $I_2 \rightarrow O_3$, $I_3 \rightarrow O_2$), all three phase shifters will be used, with two 90-degree phase shifters located at the positions (2nd and 5th) and the remaining 180-degree phase shifter will be placed in the 3rd position. In particular, the signaling order at the inputs is not important for output selection.

To illustrate the case of clear and detailed switching, the images of the field distribution at the input switches to the desired outputs with the beam propagation method (3D-BPM) [26] are shown in Figs. (5, 6 and 7).

For more accurate evaluation of optical power conversion efficiency, we use two insertion loss (IL) and crosstalk (CT) parameters to investigate and evaluate conversion efficiency (dB) between the signal inputs and the output signals at optical band C. The IL and CT are given by the formula:

$$IL(dB) = 10log_{10}(\frac{P_{out-desirable}}{P_{in}}) \quad (1)$$

$$CT(dB) = 10log_{10}(\frac{P_{out-desirable}}{\sum P_{out-unwanted}}) \quad (2)$$

where $P_{out-desirable}$ is the received power at the desired output, $P_{out-unwanted}$ is the unwanted power at other outputs and P_{in} is the transmit power of the input signals.

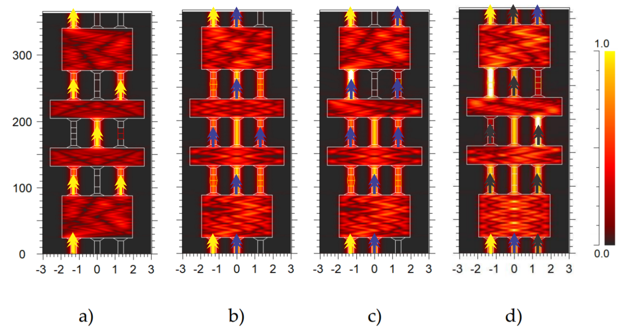

Fig. 5: The image of the optical field distribution of the signal at input port I_1 is the first priority to select the output port. (a) I_1 input – O_1 output; (b) Input I_1, I_2 - Output O_1, O_2; (c) Input I_1, I_2 - Output O_1, O_3; (d) Inputs I_1, I_2, I_3 - Outputs O_1, O_3, O_2.

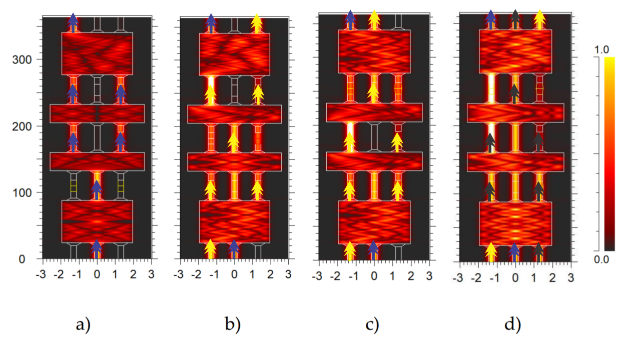

Fig. 6: The image of the optical field distribution of the signal at input port I_2 is the first priority to select the output port. (a) I_2 input – O_1 output; (b) Input I_2, I_1 - Output O_1, O_3; (c) Input I_2, I_1 - Output O_1, O_2; (d) Inputs I_2, I_1, I_3 - Outputs O_1, O_2, O_3.

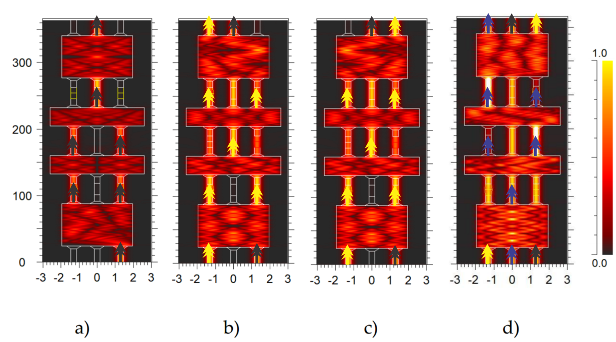

Fig. 7: The image of the optical field distribution of the signal at input port I_3 is the first priority to select the output port. (a) I_3 input – O_2 output; (b) Input I_3, I_1 - Output O_2, O_1; (c) Input I_3, I_1 - Output O_2, O_3; (d) Inputs I_3, I_1, I_2 - Outputs O_2, O_3, O_1.

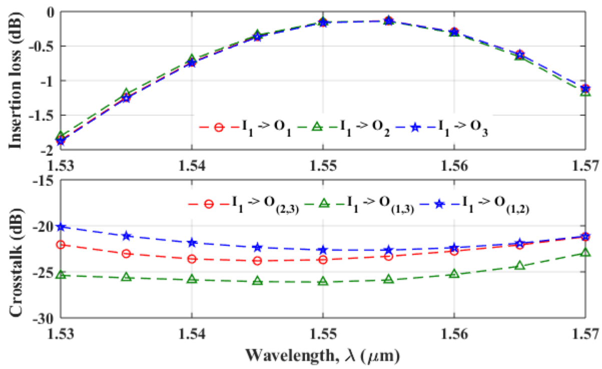

Fig. 8: Insertion Loss and Crosstalk as a function of wavelength for input signal I_1.

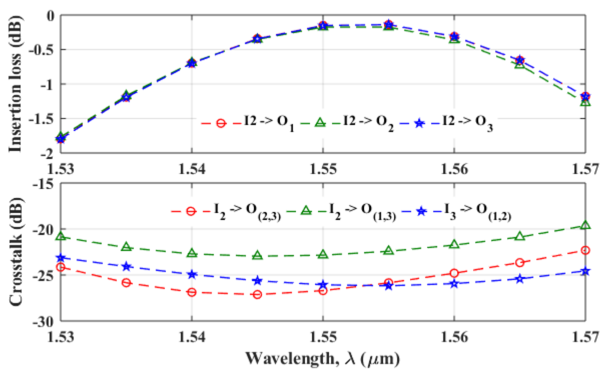

Fig. 9: Insertion Loss and Crosstalk as a function of wavelength for input signal I_2.

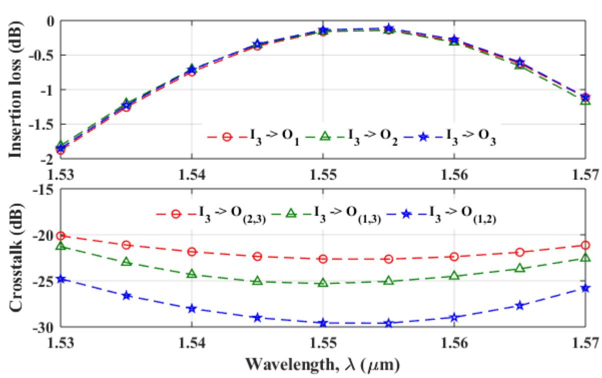

Fig. 10: Insertion Loss and Crosstalk as a function of wavelength for input signal I_3.

The simulation results are shown in Figs. (8, 9 and 10). In the entire C band, insertion loss is always less than 1.8 dB, especially at the center wavelength of 1.55 μm, this value is always less than 0.5 dB. We also consider that within this wavelength range, the value of crosstalk in all conversion cases is from -30 dB to -20 dB. When transferring signal from I_3 to O_3 at center wavelength, this desiable signal is leaked through two unwanted outputs O_2 and O_3 is -30 dB. The largest noise is the case of converting the signal from I_2 to O_2 at a wavelength of 1.57 μm, approximately -20 dB. However, at this wavelength, the optical conversion efficiency from the input to the desired output is also quite high, approximately 67%.

4. Conclusion

An OMXC optical mode cross connector with the ability to switch signals at any input to arbitrary output has been proposed in this article. The device's achieving insertion loss is always less than 0.5 dB corresponding to the received power of over 90% at 1.55 μm wavelength. In particular, in the entire C band, cross-channel noise always reaches values from -30 dB to -20 dB.

Acknowledgment

This research was supported by the University of Danang - Fund for Science and Technology Development under project number B2020-DN02-82.

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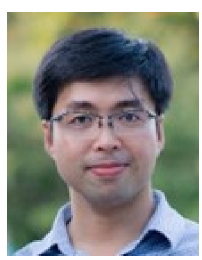

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