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Arbitrary Power Splitting Couplers Based on 5x5 Multimode Interference Structures for VLSI Photonic Integrated Circuits

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Abstract. Chip level optical links based on VLSI photonic integrated circuits have been proposed to replace metal electrical data paths in cases where high frequencies make electrical traces impractical. This is especially relevant to high-speed clock signals as silicon CMOS circuit technology is scaled higher in speed to the GHz range and beyond. In this paper, new structures of optical couplers and power taps based on 5x5 multimode interference structures using CMOS technology are presented. The proposed devices can be useful for all-optical interconnects, clock distribution and many other all-optical processing applications. The transfer matrix method and the 3D Beam Propagation Method (3D BPM) are used to optimize the proposed devices.

Keywords: Integrated optics, multimode interference (MMI) couplers, CMOS technology, all-optical processing

1. Introduction

The recent emergence of chip multiprocessors that obtain a better performance increasing the number of computational cores has changed the trend in system interconnects and global communications infrastructure. Chip multiprocessor architectures reach high parallel computing and their performance is directly tied to how efficiently the parallelism of the system is exploited and its aggregate compute power used. The realization of a scalable on-chip and off-chip communication infrastructure faces critical challenges in meeting the enormous bandwidths, capacities, and stringent latency requirements demanded by chip multiprocessors maintaining a suitable performance-per-watt. The importance of improving a low-power communication infrastructure for those next generation multiprocessors lets photonic Networks on Chip using complementary metal–oxide–semiconductor (CMOS) technology offer a promising solution.

Current integrated photonic technology presents huge advancements in fabrication capabilities of nano-scale devices and precise control over their optical properties. Importantly, these breakthroughs

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have led to the development of silicon photonic device integration with electronics directly in commercial complementary metal–oxide–semiconductor technology. Silicon photonics [1-3] was chosen because the fabrication of such devices require only small and low cost modifications to existing fabrication processes. SOI technology is compatible with existing complementary metal–oxide–semiconductor technologies for making compact, highly integrated, and multifunction devices [4, 5]. The SOI platform uses silicon both as the substrate and the guiding core material. The large index contrast between Si (n_{Si}=3.45 at wavelength 1550nm) and SiO_2 (n_{SiO_2}=1.46) allows light to be confined within submicron dimensions and single mode waveguides can have core cross-sections with dimensions of only few hundred nanometres and bend radii of a few micrometers with minimal losses. Moreover, silicon nanophotonics offer potential for monolithic integration of electronic and photonic devices on a single substrate.

The multimode interference effect based devices have the advantages of low lost, compactness and cost-effective solutions. The realization of optical couplers and power taps based on 2x2 multimode interference (MMI) structures has been given in the literature [6, 7]. However, these proposed devices required to have long pattern length and large size.

In this paper, optical coupler and power taps with arbitrary power splitting ratios based on 5x5 multimode interference (MMI) structures using CMOS technology are proposed. The variable coupling feature of the optical tap makes it ideal for high speed clock distribution, whereby an optical clock signal is distributed via optical paths to multiple tap points on an electronic circuit board or chip. The transfer matrix method and the 3D-BPM are used to design and optimize the device.

2. Theory and simulation results

The structure of a 5x5 RI-MMI coupler is shown in Fig. 1. The width and the length of the MMI coupler are W_{MMI} and L_{MMI}, respectively. Here the length of the MMI coupler is chosen to be $L_{MMI} = \frac{L_\pi}{4}$, where L_π is the beat length of the MMI coupler [8], a_i (i=1,2,3,4,5) and b_j (j=1,2,3,4,5) are the complex amplitudes of the signals at input and output ports, respectively.

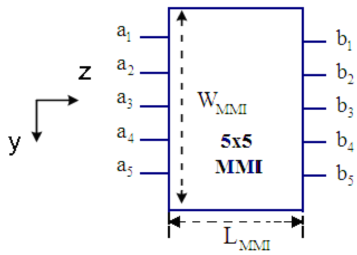


Fig. 1. A 5x5 MMI coupler based on the restricted interference used for the design of 2x2 MMI couplers having arbitrary power splitting ratios

By using the transfer matrix method [9], the MMI coupler can be described by a transfer matrix, which shows the relationship between the output complex amplitudes and input amplitudes at the input and output ports as follow

$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \\ b_5 \end{bmatrix} = \frac{1}{\sqrt{12}} \begin{bmatrix} \eta^7 & \sqrt{3}\eta^4 & 2\eta^{-1} & \sqrt{3}\eta^{-8} & \eta^7 \\ \sqrt{3}\eta^4 & \sqrt{3}\eta & 0 & \sqrt{3}\eta & \sqrt{3}\eta^{-8} \\ 2\eta^{-1} & 0 & 2\eta^3 & 0 & 2\eta^{-1} \\ \sqrt{3}\eta^{-8} & \sqrt{3}\eta & 0 & \sqrt{3}\eta & \sqrt{3}\eta^4 \\ \eta^7 & \sqrt{3}\eta^{-8} & 2\eta^{-1} & \sqrt{3}\eta^4 & \eta^7 \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ a_5 \end{bmatrix} \qquad (1)$$

where $\eta = \exp(j\frac{\pi}{12})$. When only input ports 2 and 4 are used for the input light beams, a 2x4 MMI coupler will be formed, in which the output signals are expressed

$$\begin{aligned} b_1 &= \frac{1}{2}(\eta^4 a_2 + \eta^{-8} a_4) \\ b_2 &= b_4 = \frac{1}{2}(\eta a_2 + \eta a_4) \\ b_3 &= 0 \\ b_5 &= \frac{1}{2}(\eta^{-8} a_2 + \eta^4 a_4) \end{aligned} \qquad (2)$$

Therefore, if these two 2x4 MMI couplers are connected to each other and phase shifters $\Delta\varphi$ are introduced to the linking arms between them, a new device is formed as shown Fig. 2.

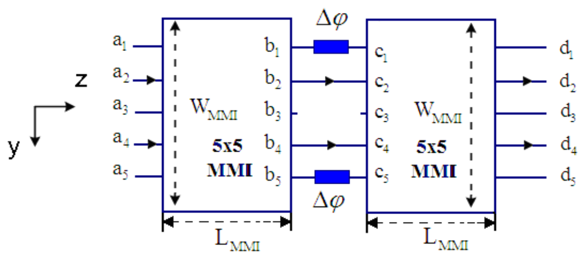


Fig. 2 A coupler with variable coupling ratios based on 5x5 RI-MMI couplers

From equations (1) and (2), if only output ports 2 and 4 are used for guiding the output signals, then the complex amplitudes at these output ports are

$$\begin{aligned} d_2 &= \frac{1}{2}\left[\eta^2 + \exp(j(\Delta\varphi + \frac{2\pi}{3}))\right] \\ d_4 &= \frac{1}{2}\left[\eta^2 + \eta^{-4}\exp(j\Delta\varphi)\right] \end{aligned} \qquad (3)$$

When an input signal is presented at input port 2, the normalized output powers at output port 2 (bar port) $P_b = P_2$ and at port 4 (cross port) $P_c = P_4$ can be controlled by adjusting the phase shifts as shown in Fig. 3. This means that by varying the phase shift $\Delta\varphi$, the power coupling ratios $|\kappa|^2$ can be adjusted, i.e., a 2x2 MMI coupler with arbitrary coupling ratios is realized.

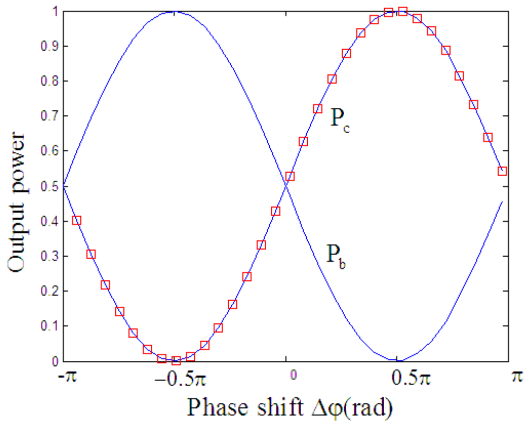


Fig. 3. The dependence of the normalized output powers at output port 2 and output port 4 on the phase shift $\Delta\varphi$

The waveguide structure used in the designs is shown in Fig. 4. Here, SiO_2 ($n_{SiO_2}=1.46$) is used as the upper cladding material. An upper cladding region is used to avoid the influence of moisture and environmental temperature. The parameters used in the designs are as follows: the waveguide has a standard silicon thickness of $h_{co}=220\text{nm}$ and access waveguide widths are $W_a=0.48\ \mu\text{m}$ for single mode operation. It is assumed that the designs are for the TE polarization at a central optical wavelength $\lambda=1550\text{nm}$.

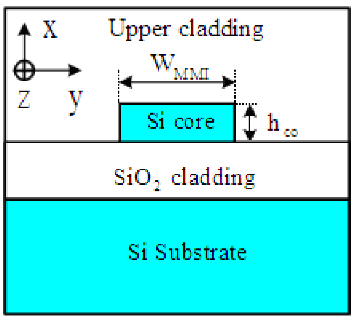


Fig. 4. Silicon waveguide cross-section used in the designs of the proposed device

By forming a surface pattern on the top of the MMI region at special positions or on the top of linking waveguides (SOI channel waveguides), any desired phase shift can be produced [7]. The refractive index is adjusted by changing the etch depth, etch width and/or the length of these patterns. The advantages of this approach are that the etching can be done after the device has been fabricated and patterns introduce only low additional loss. In addition, by using suitable masks, only one additional simple process step is required.

By using the 3D-BPM simulation, the effective refractive indices for the transverse electric (TE) fundamental mode for different waveguide thicknesses, but the same width of 480nm, are plotted in

Fig. 5. The simulations show that the effective refractive index is directly proportional to the waveguide thickness. This is the operating principle of introducing a phase shift using the surface pattern technique.

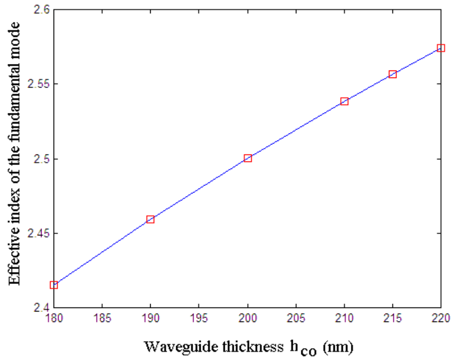


Fig. 5. The effective indices of the fundamental TE mode at different waveguide thicknesses for an SOI channel waveguide of width 480nm

In order to achieve a phase shift of Δφ= -π, the length L_p of the pattern region as a function of the pattern depths h_p ($h_p = h_{co} - h_{pt}$) calculated from $L_p = \frac{\lambda}{2\pi}\frac{\Delta\varphi}{\Delta n_e}$ is shown in Fig. 6. Here, Δn_e is the difference in effective indices between that for the waveguide having a thickness h_{co} and that for the standard waveguide having a thickness of $h_{co} = 220\text{nm}$.

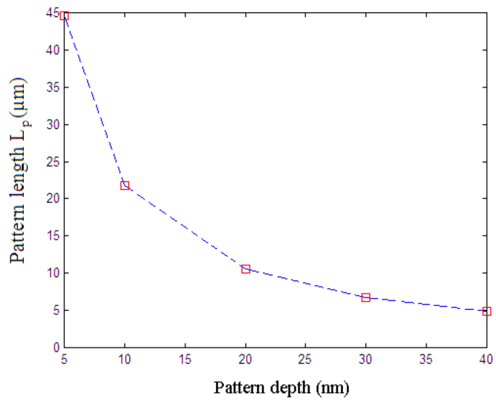
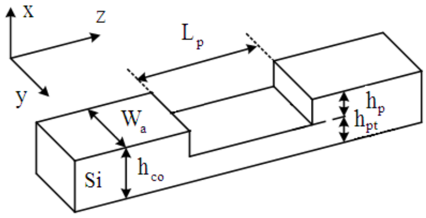
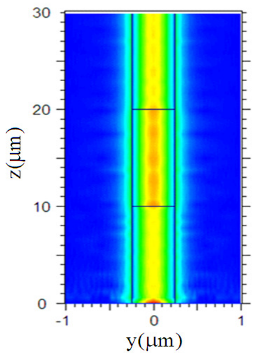


Fig. 6. Pattern length L_p required to achieve a phase shift of - π at different depths

The 3D-BPM simulation result (Fig. 7) shows that at a pattern length of $L_p = 10\mu\text{m}$, the loss of the signal propagating through the pattern section is only 0.043dB. A pattern depth of $h_p = 40\text{nm}$ is used throughout this chapter. These dimensions are suitable for practical fabrication.



(a) Structure of the pattern region



(b) Field distribution through the pattern

Fig. 7. Pattern used for introducing a phase shift (a) structure of the pattern region and (b) power distribution through a pattern having a length of $L_p = 10\mu m$

The device dimensions are determined by using both the mode propagation analysis (MPA) and 3D-BPM method. Here, an MMI width of $W_{MMI} = 5\mu m$ is chosen to limit crosstalk between adjacent waveguides. The first design step is to determine the length of the 5x5 MMI structure by using the MPA method. The MMI length calculated from this method is $L_{MPA} = 38.4\ \mu m$. Then, the MMI length is scanned around this length to find the optimised MMI length for the minimum excess loss. The optimised length of the 5x5 MMI coupler is found to be $L_{MMI} = 37\mu m$ by using the 3D-BPM.

Now consider the approach where phase shifters are implemented on the linking waveguides using the surface pattern technique. The normalized output powers are varied with the pattern length L_p as shown in Fig. 8. In this simulation, it is assumed that two patterns having the same width of 480nm and the same depth of 40nm are made in the two outer arms.

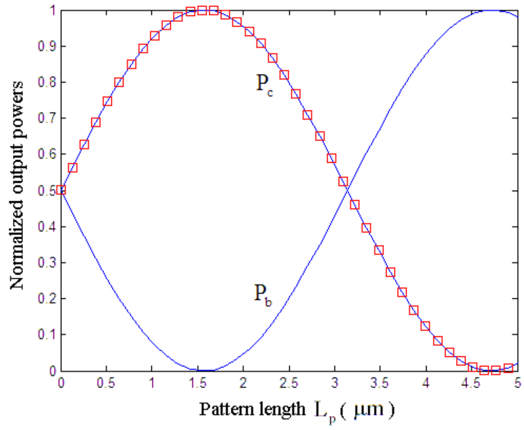
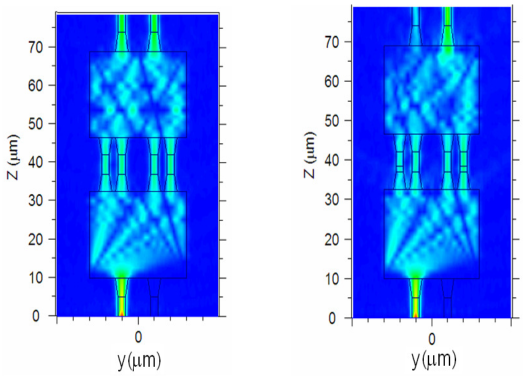


Fig. 8. Output powers of a 2x2 MMI coupler based on 5x5 RI-MMI couplers as functions of the pattern lengths. The pattern has a depth of 40nm and a width of 480nm

An MMI width of $W_{MMI} = 6\mu m$ is chosen to allow sufficient separation of the access and linking waveguides in order to limit crosstalk between the parallel waveguides. The 3D-BPM is used to investigate the device operation in two cases. The first case is for a device without the pattern. The 3D-BPM simulation is shown in Fig. 9(a). The computed output powers are 0.46 for the bar port and 0.45 for the cross port. The computed excess loss in this case is 0.4dB. The second case is for a pattern having a length of $0.5\mu m$, a width of 480nm and a depth of 40nm made in the outer linking arms. The 3D-BPM simulation for this case is shown in Fig. 9(b). The computed output powers are 0.22 for the bar port and 0.68 for the cross port, respectively. The computed excess loss is 0.45dB in this case.



(a) (b)

Fig. 9. 3D-BPM simulation for a 2x2 variable MMI coupler (a) without any pattern made in the arms, $L_p = 0\mu m$ and (b) with pattern length $L_p = 0.5\mu m$

Changing the length, depth and the width of the patterns enables any power coupling ratio to be obtained at the outputs. However, compared to the previous structures, the present structure requires only a maximum pattern length of $3\mu m$ to achieve the full range (from 0 to 1) of the power coupling ratios.

In an alternative approach, patterns can be made in the top of the MMI region at some special positions. In order to find these positions and pattern lengths, the 3D-BPM is used. Figure 10 shows the 3D-BPM simulations for calculating the pattern length produced inside the MMI region. Without any pattern made inside the device, the normalized output powers are 0.47 for the bar port and 0.46 for the cross port. The computed excess loss is 0.3dB. The maximum length of the patterns in this case is $1.2\mu m$. As a result, in general, it is possible to make the power-coupling ratio variable from 0 to 1 as indicated in Fig. 3.40 simply by changing the phase shift at the middle arms or at the two outer arms in the structure.

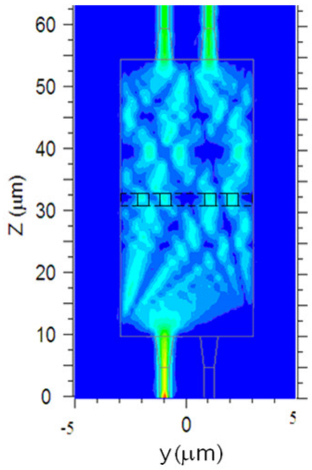


Fig. 10. 3D-BPM simulation for calculating the pattern positions inside a 5x5 RI- MMI coupler used for 2x2 variable MMI couplers

3. Conclusion

This paper has proposed a novel method for realizing optical power couplers and taps with arbitrary power splitting ratios based on 5x5 multimode interference using CMOS technology. The design of the proposed devices has been verified and optimised using numerical simulation methods. These devices can be useful for all-optical computing systems, clock distribution and VLSI photonic integrated circuits.

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