RETRACTED CHAPTER: Design of Silicon-on-Insulator Based Mode Splitters with Asymmetrical Variation of Slots

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Abstract Due to rapid increase in the demand of internet data rates, it is difficult to satisfy the requirement using the single-mode fiber. Therefore, the multimode fiber can replace the single-mode fiber, by treating each mode as an individual channel, to increase the capacity. Due to intermodal dispersion, the multimode fiber has not been considered in the past for data transmission. Nonetheless, by using each mode of multimode fiber separately, we can increase the overall data rate. However, it is a challenging task to separate the individual mode from a multimode fiber, without mixing, and utilizing them as different signal channels. In this paper, we are demonstrating a mode splitter using the coupled waveguide with slots. By introducing a slot in the waveguide, a desired coupling length ratio of 2:1 between the fundamental and higher modes can be obtained. Also, the asymmetrical variations of slot, and its impact on the coupling length ratio have been demonstrated.

Keywords Mode splitter · Coupling length ratio · Asymmetrical directional coupler

1 Introduction

In order to fulfill the exponentially increasing demand of data rate, the optical fiber/waveguide technology based approaches, such as multicore/multimode

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The original version of this chapter was retracted: The retraction note to this chapter is available at https://doi.org/10.1007/978-981-16-2818-4_63

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M. Tiwari et al. (eds.), *Optical and Wireless Technologies*, Lecture Notes in Electrical Engineering 771, https://doi.org/10.1007/978-981-16-2818-4_15

fiber/waveguide have significant potential to achieve the requirement [1–3]. In multicore fiber technology, due to the presence of closely packed cores, the crosstalk can deteriorate the performance of fiber technology, which usually worsen with the increase in the number of cores in the same cladding region [2]. On the other hand, the few/multimode based multiple-input-multiple-output (MIMO) approach can be the alternative solution to address the rapidly growing demand of information carrying capacity of the optical systems and networks. [3]. For the multimode based optical technology, various devices, such as filters, splitters, couplers, interconnects, etc. [4, 5] are essentially required to investigate the different data signal channels as different modes of few/multimode waveguide/fiber [6]. Signals can be coupled from the multimode fiber to the splitter by using the grating coupler [7], and taper [8] techniques. However, utilizing each of the modes as an independent channel is a challenging task [9]. To undertake this issue, the design of symmetrical mode splitter has been proposed in [10]. The authors have used the symmetrical directional coupler as a mode splitter and evaluated the performance of the proposed structure in terms of coupling length ratio (L_{R}), which should be equal to 2, to avoid the dispersion phenomena for the efficient reception of the different signal channels at the output. The work presented in [10] has been extended in the current work by designing the asymmetrical mode splitter, in anticipation of improvement in the device performance in terms of different waveguide parameters, while maintaining the coupling length ratio as $L_{\mathrm{R}} = 2$. The asymmetrical structure of the mode splitter has been realized by creating the unsymmetrical directional coupler.

Here, in this paper, one of the slots of the symmetrical directional coupler has been shifted by a slot offset, represented by 'a' or 'Δa', to achieve the design of the asymmetrical directional coupler. The main aim of this work is to achieve the coupling length ratio of 2, by which dispersion can be minimized.

2 Design of Symmetrical and Asymmetrical Directional Coupler

Directional coupler is the most common device to split or combine the light in the photonic systems. It consists of the parallel waveguides that can be used to separate the different modes in such a way that each mode can act as an independent transmission channels [11, 12]. The design of mode splitter depends on the coupling length ratio, which is the ratio of coupling length for the fundamental mode and the same for the higher mode. Moreover, the coupling length (L_{C}) is usually dependent on the dimension of the waveguide, including the separation between the waveguides [10], and it can be expressed as in Eq. (1),

$$L_{\mathrm{C}} = \frac{\pi}{\beta_e - \beta_o} \tag{1}$$

where, β_e and β_o are the propagation constants of the even and odd modes, respectively, and it can be calculated by using the Eq. (2) below,

$$\beta = \frac{2\pi n}{\lambda} \tag{2}$$

where, n is the effective index and λ is the operating wavelength. Further, the length of the device (L) can be calculated as [10],

$$L = m.L_{\mathrm{C}}^{11} = n.L_{\mathrm{C}}^{ij} \tag{3}$$

where, m and n are the odd and even integer numbers, respectively, or vice-versa, and hence, the coupling length ratio (L_{R}) can be given by,

$$L_{\mathrm{R}} = \frac{L_{\mathrm{C}}^{11}}{L_{\mathrm{C}}^{ij}} \tag{4}$$

where, L_{C}^{11} is the coupling length of the fundamental mode and L_{C}^{ij} is the coupling length of the higher order modes. Figure 1 shows the schematic diagram of a mode splitter utilizing the directional coupler, where H_{11}^{y} and H_{21}^{y} are, respectively, the fundamental and higher order mode, launched at the *port* 1 of the directional coupler. Considering m as odd, let $m = 1$, for the H_{11}^{y} mode, and n as even, let $n = 2$, for the H_{21}^{y} mode, then, the H_{11}^{y} should appear in the cross-port, and H_{21}^{y} in the bar-port, as illustrated in Fig. 1.

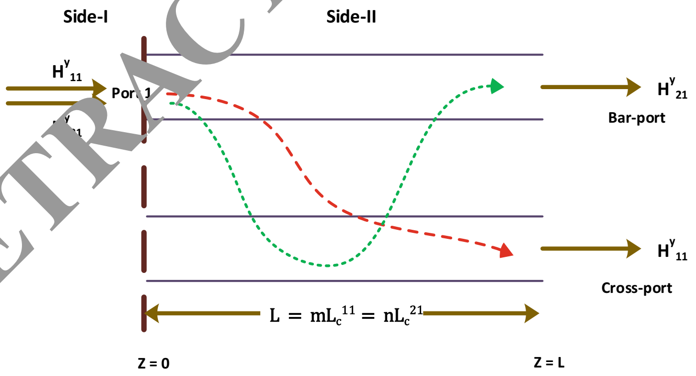


Fig. 1 Schematic diagram of a mode splitter [10]

2.1 Symmetrical and Asymmetrical Directional Couplers

The design of symmetrical mode splitter using the symmetrical directional coupler, whose properties mainly depend on the coupling length ratio has been presented in [10] and its cross-sectional view has been provided in Fig. 2. From figure, it is clear that each of the two parallel arms of the symmetrical directional coupler, having equal dimension with total height of '*H*', is consisting of one slot of height '*t*', at the middle. The separation between the two arms is '*S*', the width of slot is '*g*', and the total width of each arm is '*W*'. Usually, the symmetrical coupler without slots provides a high value of the coupling length ratio, however, the main objective of the current work is to obtain a lower value of coupling length ratio to minimize the dispersion phenomena. In order achieve it, one slot has been introduced in the middle of the waveguide. By introducing the slot, the modal properties of fundamental (H_{11}^{y}) mode are strongly affected, however, it has a very less effect on the modal properties of the second mode, H_{21}^{y} [10]. As, H^{y} is the dominant field, hence, the effect of slot can be observed by the variations of H^{y} along the *x*-direction. The input light is provided at a port in silicon core and light get coupled to another waveguide in the coupler, after a certain length known as, coupling length, as shown in Fig. 1. The refractive indices of silicon core, silica buffer, and air cladding are considered, respectively, as 3.47638, 1.44427, and 1.0, at the operating wavelength of 1550 nm. Further, the authors [10] have observed that the L_{R} value decreases by increasing both the slot height as well as the slot width and the desired coupling length ratio of 2:1 has been realized with $g = 150$ nm, $t = 150$ nm, $W = 850$ nm, $S = 100$ nm, and slot offset, $a = 11$ nm. The slot offset is basically represents the shift (left/right) in slot position to realize the variations in the coupling length ratio (L_{R}) and to achieve the desired ratio, $L_{\mathrm{R}} = 2$.

Moreover, in this paper, the work presented in [10] has been extended by considering the asymmetrical directional coupler/mode splitter, to achieve the ratio, $L_{\mathrm{R}} =$ 2:1, with the anticipation of reduced slot offset, slot width, etc. The asymmetrical structure, as depicted in Fig. 3, has been realized by shifting the position of one of the slot, left or right, for some range of slot offset (0.1–17 nm). Further, the asymmetrical structure has been simulated using the COMSOL Multiphysics platform,

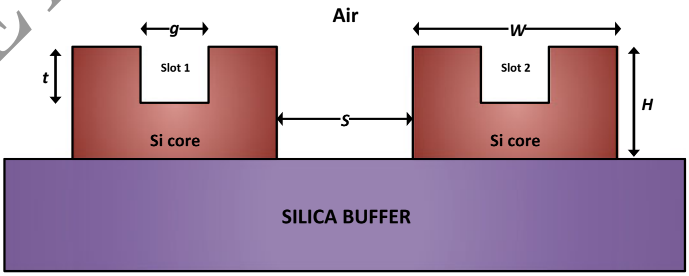


Fig. 2 Cross-sectional view of a symmetrical directional coupler

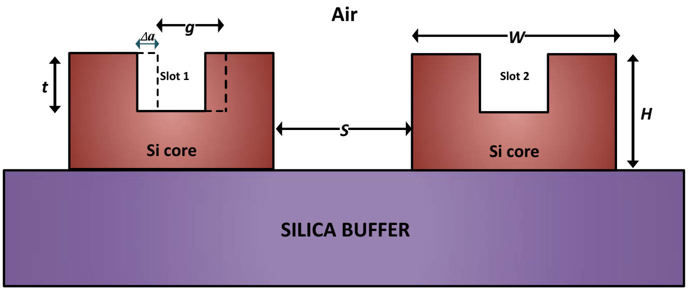


Fig. 3 Cross-sectional view of the directional coupler with the asymmetrical shift of slot

by considering similar waveguide parameters, such as $H = 300$ nm, $S = 1$[illegible]0 nm, $W = 850$ nm, $g = 135$ nm and 150 nm, and $t = 150$ nm. As the presence of slot mainly affects the magnetic field distribution of fundamental mode, the coupling length ratio also depends on the geometry of the slot. The authors in [10] have illustrated that the ideal L_R value of 2 can be realized at the slot offset, $\Delta a = 11$ nm, when the slots of symmetrical coupler have been shifted along right side. While for the other offset values, it is difficult to realize $L_R = 2$. Similar to its symmetrical counterpart, the presence of the slot in asymmetrical waveguide mainly affects the fundamental mode and again, it has very marginal effect on the higher order modes, as observed in terms of the variations of magnetic field along the arc length/width (W) of the waveguide.

The variations in magnetic field along the width of the arms of directional coupler have been shown in Figs. 4a, b, respectively, in the absence (i.e., $g = 0$), and in the presence of the slot, in the mid of arm of the directional coupler. These variations have been obtained through the COMSOL Multiphysics simulations for the fundamental mode propagation. Therefore, the presence of a slot causes the discontinuity of the magnetic field in the middle of the waveguide. Similarly, for the higher order mode

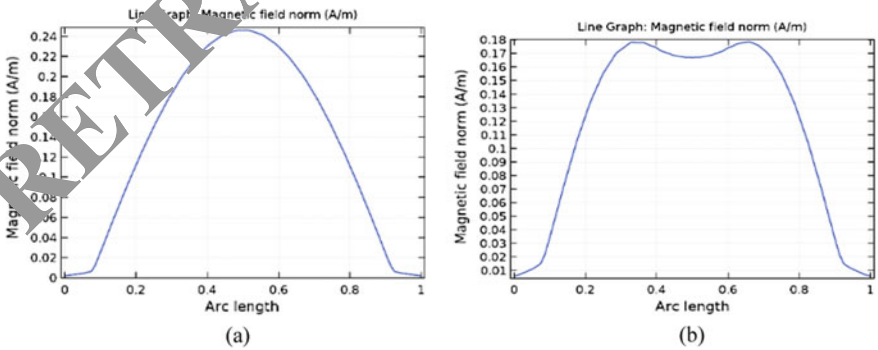
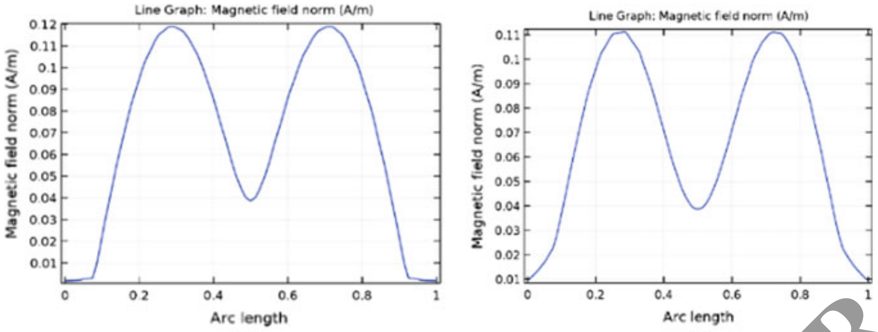


Fig. 4 Magnetic field variations along arc length/width of coupler for fundamental mode, H_{11} **a** without slot, **b** with slot



(a) (b)

Fig. 5 Magnetic field variations along arc length/width of coupler for higher order mode H_{21} **a** without slot, **b** with slot

(i.e., H_{21}), Fig. 5 illustrates the variations of magnetic field with respect to the arc length/slot width for both the cases of $g = 0$ nm, and $g \neq 0$ nm. From this figure, it has been observed that the higher order mode is affected very marginally by the presence of slot, and the field was close to zero, near in the middle of the slot. Further, by shifting the slot on both, right and left sides, by 'Δa', the variations of L_R values have been observed.

3 Simulation Results

The simulations of slot waveguide have been performed mainly with two values of slot gaps, i.e., $g = 125$ nm, and $g = 150$ nm, to analyze the performance of asymmetrical directional coupler, and hence, the asymmetrical mode splitter. The impacts on the variations in L_R values have been observed for the above two values of slot gaps, in the asymmetrical mode splitter, which have been discussed below.

Case-I: Considering the Slots 1 and 2, with the parameters as, $W = 850$ nm, $S = 100$ nm, $H = 300$ nm, $t = 150$ nm, and $g = 150$ nm. By shifting the Slot 1 only, towards the right or left side, the variations in L_R with respect to the slot offset 'Δa' have been observed, and plotted in Fig. 6. The solid (blue) line graph is obtained, when Slot 1 was shifted right side, and the dash (red) line graph was obtained, when the Slot 1 was shifted toward left. From the figure, it is clear that when the Slot 1 was shifted towards the right side, the L_R values are approximately close to the optimized value of L_R (= 2), and the ratio of 2:1 has been realized at $\Delta a = 14.1$ nm. Further, when the Slot 1 was shifted towards the left side, the coupling length ratio decreases and always remains less than 2, as shown in Fig. 6. In the anticipation of reduction in the value of slot offset with the optimized value of L_R, i.e., 2:1, the similar kind of analysis has been done with another value of slot width, and presented below as Case-II.

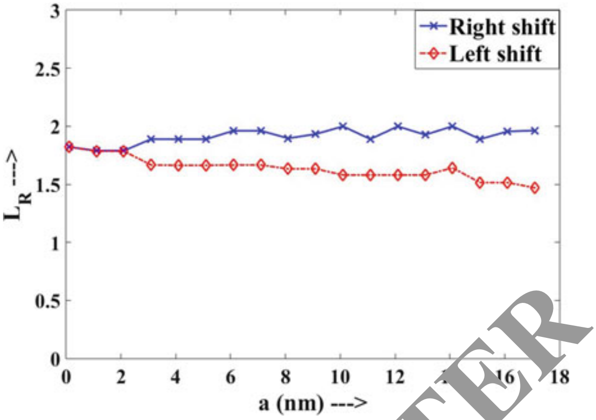


Fig. 6 Variations in coupling length ratio, of L_R, with respect to slot offset, 'a', for $g = 150$ nm

Case-II: Considering the Slot 1 again, to shifting it left/right, with the slot width of $g = 135$ nm, while, other parameters are the same as that in the *Case I*. The variations of coupling length ratio with respect to the slot offset, 'Δa' has been observed and illustrated in Fig. 7. In this particular case, when the slot was shifted towards the right side by 'Δa', the L_R values are observed as ≥ 2 (but close to 2) with the increasing values of 'Δa'. Here, the L_R ratio of 2:1 have been realized at $a = 3.1$ nm and $a = 4.1$ nm. Moreover, when the slot was shifted towards the left side, the L_R value decreases as the value of 'Δa' increases and remains less than 2, as shown in Fig. 7. Further, the shifts in Slot 2 only, towards the left side can provide the desired coupling length ratio of 2:1.

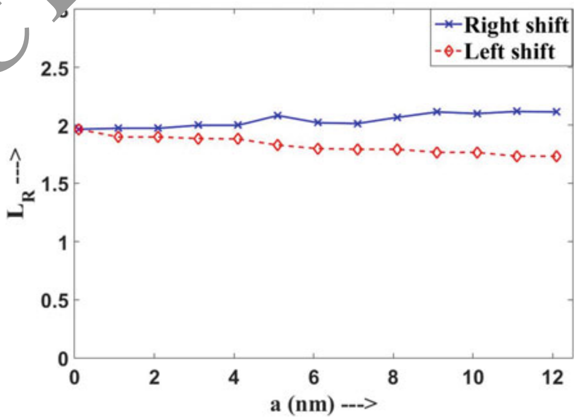


Fig. 7 Variations in coupling length ratio, L_R, with respect to slot offset 'a', for $g = 135$ nm

4 Discussion and Comparison

In the current work, we had designed the asymmetrical directional coupler to obtain the desired coupling length ratio of 2:1. Also, the variations in coupling length ratio with respect to the offset value 'Δa', have been investigated for the presented asymmetrical directional coupler. The directional couplers without the slots, usually have the high-coupling length ratio, therefore, a slot has been introduced in the middle of the waveguide that causes to reduce the coupling length ratio. Mainly, the fundamental mode propogations are affected by the introduction of slot, while, the higher modes are affected very marginally. In this work, basically the symmetrical directional coupler is modified into asymmetrical directional coupler by shifting the position of one slot at a time, towards the right/left side.

Here in our design, the ideal L_R value of 2 has been achieved at $\Delta a = 14.$[illegible] nm, for $g = 150$ nm, and to obtain the L_R value of 2 at the smaller slot offset, we had changed the slot width as $g = 135$ nm. With this reduced slot width, more optimized result in terms of the coupling length ratio of 2:1 has been obtained for the asymmetrical mode splitter, as described in just previous section (*Case-II*), where the slot offset values have been reduced to 3.1 nm and 4.1 nm. Whereas in case of symmetrical coupler, the authors in [10] have obtained the coupling length ratio of 2:1 for the slot offset value of 11 nm, with $g = 150$ nm, and after an offset value of 11 nm, the L_R becomes less than 2. Therefore, in comparison to symmetrical directional coupler, the designed asymmetrical directional coupler can achieve the desired value of coupling length ratio (2:1) with the significantly reduced slot offsets of 3.1 and 4.1 nm. Hence, the obtained coupling length ratio is decently optimized at $g = 135$ nm, in comparison to $g = 150$ nm.

5 Conclusion

In order to use each mode as an individual channel for data transmission, the mode splitter has been designed using the asymmetrical directional coupler, to get an optimized value of coupling length ratio, i.e., 2:1, which is also beneficial to avoid the dispersion phenomena. For the design of a mode splitter, an asymmetrical shifts in waveguide slots have been shown, which was used to get a desired value of L_R (= 2). From the results, it has been observed that as the Slot 1 was shifted towards the right side, the L_R value of 2 was achieved, whereas, when the Slot 1 was shifted towards the left side, the L_R value decreases and becomes less than 2. Similarly, when we shift the Slot 2 towards the left side, the L_R ratio of 2:1 was achieved and when the Slot 2 was shifted toward the right side, L_R value decreases, and remains always less than 2. Hence, it can be concluded that as the distance between slots decreases, the coupling length ratio of 2:1 can be realized, and conversely, when the distance between slots increases, the L_R value decreases, and achieved as, less than 2.

Acknowledgements The authors gratefully acknowledge National Institute of Technology Patna, and Science and Engineering Research Board, Department of Science and Technology, Government of India for providing COMSOL Multiphysics simulation software, used in the current simulation work.

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