Design of All-Optical Directional Coupler Using Plasmonic MIM Waveguide for Switching Applications

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Research Article

Keywords: Plasmonic directional coupler, metal-insulator-metal (MIM) waveguide, finite-difference-time-domain (FDTD), coupling length

Posted Date: April 19th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-377069/v1

Abstract

In this paper, we have proposed, analyzed, and verified theperformance of an optimized plasmonic 10-dB directional coupler and a 3-dB directional coupler in 2-D plasmonic waveguides using finite-difference-time-domain (FDTD) method. A plasmonic 10-dB directional coupler and a 3-dB directional coupler are based on the metal-insulator-metal (MIM) slab waveguide and analyzed at the telecommunication wavelength (λ) of 1550 nm. Here, coupling and transmission characteristics are analyzed with the optimized separation distance between the two parallel waveguides. The developed approach ensures the minimization of the crosstalk and overall directional coupler length via simultaneous adjustment of the separation distance between the parallel waveguide and length of the linear waveguide. Then an optimized structure is acquired by trading off between coupling length and separation distance. The proposed 10-dB directional coupler and 3-dB directional coupler features good energy confinement, ultra-compact and low propagation loss, which has potential applications in photonic integrated devices, optical signal processors, and other all-optical switching devices.

1. Introduction

The increasing demand for high-speed systems urges to design the system with low complexity and power consumption. In the current scenario, to achieve the technology demand of higher capacity at a lower cost the optical communication has been introduced. In optical communication, the transmission capacity is large along with the longer transmission distance [1-2,7]. But in earlier decades, devices were implemented using semiconductor technology, where it has some limitations like high power dissipation, high input power, and low switching time [1,4-6,19]. To overcome the limitations of semiconductor technology, optical communication came into consideration. Optical communication is quite instrumental in the field of telecommunication due to its large bandwidth, high speed, and low interference [3,6-9]. Due to these reasons, researchers have shifted focus on the optical signal to transmit the information [1,5-7,10-13]. Different types of optical techniques are employed such as metal-insulator-metal (MIM) [3-4,28,31,33,37,43], insulator-metal-insulator (IMI) [28,33], dielectric-loaded surface plasmon polaritons (DLSPP) [10-11,21-22,29,31,33,35], metal slot waveguide [3-4]. The directional coupler already has been implemented by using a semiconductor optical amplifier (SOA) [15-16,23,27,36-37] photonic crystal [13,19,31,36-42,44-45] and lithium niobate ($LiNbO_3$) [5,8,15,]. SOA have some limitations like gain saturation and high driving current input and in $LiNbO_3$ the electrical signal is used to switch the optical signal. The current work purposes the optimization of the area in the directional coupler structure. Surface plasmon polaritons (SPPs) [10-11,18,21-22,29,31,33,35] are the electromagnetic waves that travel along a metal-dielectric or metal-air interface and SPPs are excited by both electrons and photons. Plasmonic is considered as a potential solution for size and operating speed mismatch problems in electronics and photonics [3-4,6]. The motivation behind plasmonic is the ability the realization of very compact photonic devices [13,31]. To obtain a satisfactory performance between loss and confinement, MIM [3-4,6,28,31,33,37,43] has been preferred due to the ability to confine surface plasmon diffraction limit [20]. The important structure in optical communication is directional coupler [3-4,9,14,19,28-30,32-

34] and it can be implemented in various applications like power splitter [17], optical switches, and wavelength selective coupler, etc. [6]. In this paper, the structure of the optimized 10-dB and 3-dB directional coupler is proposed. The compact design of the directional coupler is proposed in the footprint of 8 μm x 4 μm. The proposed design is verified using FDTD [1,3,7,14,21,31-32,36,39-40,42] method. In this paper, the optimized design of 10-dB and 3-dB directional coupler is discussed in Section 2, and in Section 3 simulation resultsand discussions are presented. Finally, the conclusion of the paper has been deliberated.

2. Design Of Optimized Directional Coupler

In this paper, the optimized 10-dB and 3-dB Directional couplers are designed using a plasmonic-based MIM waveguide within the footprint of 8 μm x 4 μm. Fig.1 shows the structure of an optimized directional coupler using plasmonic MIM configuration. For the desired operation of the directional coupler, the structure is designed by using two S-Bend and one linear waveguide. The width of the directional coupler and refractive index used in the channel is 0.5 μm and 2.01 respectively. The continuous wavelength of 1.55 μm exceeds the transverse magnetic (TM) mode with the input power of 0.0317 W/m (treated as 'high intensity') and 0.017 W/m (treated as 'low intensity'). The design of an optimized directional coupler is represented in the XZ plane as shown in Fig. 1.

In the proposed design, the vertical input plane is used for the input port (Upper Input). This input port is used to send the input signal. The signal is applied at the input port through the reference input portis very essential to get at the output port. The output power is detected by using the observation point at the coupled port (Output1) and through port (Output2).

2.1 Design of 10-dB directional coupler

In 10-dB directional coupler, When the input is given at the input port (Upper Input), and the output is detected at the through port (Output2). Hence, the lower input port is treated as an isolated port and no power is at the coupled port (Output1). When the input is given at the lower input port, the output is detected at the coupled port (Output1). Hence, the upper input port is treated as an isolated port and no power is at the through port (Output2) shown in Fig.1. The separation distance between the two linear waveguides is less than 0.4 μm. To find the beneficial impact on output the coupling length is varied from 3.2 μm to 0.8 μm. The formulafor coupling length is,

$L_C = \frac{\pi}{2k}$, where k = wavelength dependent constant

The high-intensity level input is applied at the input port (Upper Input) in a perfectly matched layer (PML) boundary condition where air has been taken as a cladding material.

2.2 Design of 3-dB directional coupler

A 3-dB directional coupler is used tosplit an input signal into two signals of equal amplitude and a constant or phase difference. For designing a 3-dB directional coupler,the separation distance between two linear waveguides is more than 4 μm but less than or equal to 6 μm. An input signal is applied in the input port (Upper Input) and the output power is measured at the coupled port (Output1) and through port (Output2), where the lower input port is treated as an isolated port and vice versa. In the proposed design, the separation distance between two linear waveguides is taken as constant where the coupling length varies from 3.2 μm to 2 μm to get a good result. The high-intensity level (logic ‘1’) is applied at the upper input i.e 0.0317 W/m.

3. Simulation Results And Discussions

The continuous wave (CW) source is fed to the directional coupler to control the signal with the transverse magnetic polarization and the half-width of 0.5 μm with a wavelength of 1550 nm. FDTD method is used here to analyze the directional coupler due to its simplicity in both conceptually and implementation. The PML is used as a boundary condition because of its ability to restrict almost all reflection during the propagation of the wave. The proposed design is analyzed within the mesh size of Δx = 0.0738 μm and Δy = 0.0738 μm, which is very small enough to capture the change in the magnetic field. According to the above parameters, the analysis has been done.

3.1 Simulation results of 10-dB directional coupler

The design of a 10-dB directional coupler is verified by the FDTD method. In this case, the separation distance between two linear waveguides is kept constant but the coupling length is varied from 2.6 μm to 0.9 μm to get the best result which is shown in Table.1. The propagation of light through the 10-dB directional coupler is shown in Fig.2. Where in Fig.2.a the input is applied at the upper input port and the output at the through port similarly in Fig.2.b the input is applied at the lower input port and the output at the coupled port as per Fig.1.

Table 1: Extinction ratio with different normalized output power and coupling length

Normalized Output Power			
Coupling Length	**Coupled port Power**	**Through port Power**	**Extinction Ratio**
2.6	0.50	0.75	3.42
2.5	0.48	0.75	3.80
2.4	0.41	0.76	5.34
2.3	0.38	0.77	6.16
2.0	0.31	0.79	7.92
1.9	0.25	0.80	9.99
1.8	0.23	0.78	10.26
1.7	0.24	0.80	10.36
1.6	0.24	0.79	10.28
1.5	0.26	0.78	9.47
1.4	0.25	0.79	9.85
0.9	0.36	0.79	6.63

From the above Table.1, the extinction ratio is shown with the variation of coupling length. The extinction ratio between the optical intensity at the ON state and the OFF state is determined by equation [1],

Extinction Ratio (ER) = $10\log_{10}\left(\frac{P_{ON}}{P_{OFF}}\right)$ $10\log_{10}$ (1)

Where P_{ON} is the output power at the ON state and P_{OFF} is the power at the OFF state. Based on the above equation, the ER is calculated as shown in Table.1. When the coupling length is 1.8 μm and 1.9 μm the proposed design ER got more desired results.

In Fig.3 the performance analysis between ER and coupling length is shown. The best ER found out at the coupling length of 1.9 μm is 9.99 dB.

3.2 Simulation results of 3-dB directional coupler

For the designing of a 3-dB directional coupler, the coupling length is varied from 3.2 μm to 2 μm and the normalized output power is calculated. In the case of a 3-dB directional coupler the input power is equally split into two equal power of amplitude at the coupled port (Output1) and through port (Output2). The normalized output power varies with the coupling length is shown in Table.2 where we got the maximum efficient value at the coupling length of 2.4 μm and the wavelength of 1.55 μm.

Table 2: Normalized output power with coupling length

Normalized output power		
Coupling Length	**Coupled port Power**	**Through port Power**
3.2	0.47	0.46
3.1	0.48	0.48
3.0	0.47	0.48
2.9	0.45	0.48
2.8	0.45	0.50
2.7	0.46	0.51
2.6	0.45	0.50
2.5	0.46	0.49
2.4	0.48	0.49
2.3	0.47	0.51
2.2	0.49	0.52
2.1	0.49	0.54
2.0	0.48	0.54

Propagation of light through a 3-dB directional coupler is split into two equal power amplitude which are shown in Fig.4. In Fig.4.a the input is given at the upper input of high intensity and the output power detected at both the output i.e coupled port (Output1) and through port (Output2) and in Fig.4.b the input is given at the lower input of high intensity and in a similar fashion, the output is detected at coupled port (Output1) and through port (Output2).

In Fig.5, it is shown the graph between output port power versus coupling length wherein output port both the port has been shown i.e through port power as well as the coupled port power. The best result is found at the coupling length of 2.4 μm where the through port power is 0.49 dB and the coupled power is 0.48 dB.

4. Conclusion

A novel and compact design of a 10-dB and 3-dB directional coupler using plasmonic waveguide has been proposed and successfully verified using FDTD. The design of both the directional coupler is constructed on the footprint of 8 μm x 4 μm and the continuous wavelength of 1.55 μm. In simulation results and discussion, some parameters like extinction ratio and normalized output power at the coupled port and through port obtained 9.99 dB, 0.48 dB, and 0.49 dB respectively. The directional coupler has numerous applications in signal routing and sample monitoring and can be useful for developing optical circuits in the future.

Declarations

Funding

This work was supported by the Science and Engineering Research Board, India [grant number: TAR/2018/000051].

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Figures

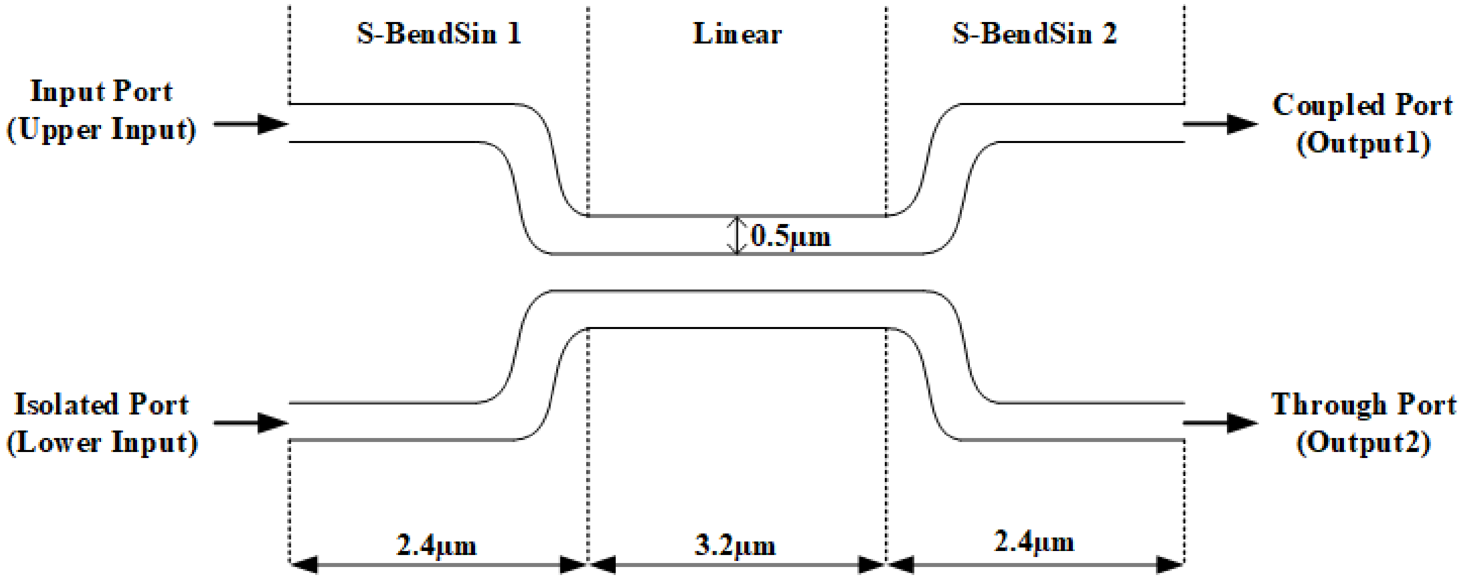

Figure 1

Schematic of optimized directional coupler

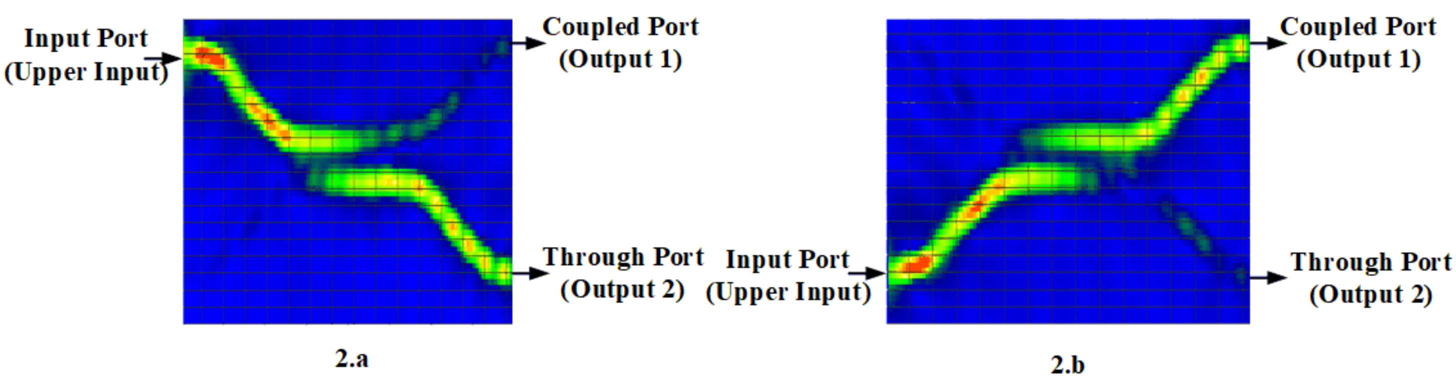

Figure 2

Propagation of light through 10-dB directional coupler a. input is given at the upper input port b. input is given at the lower input port

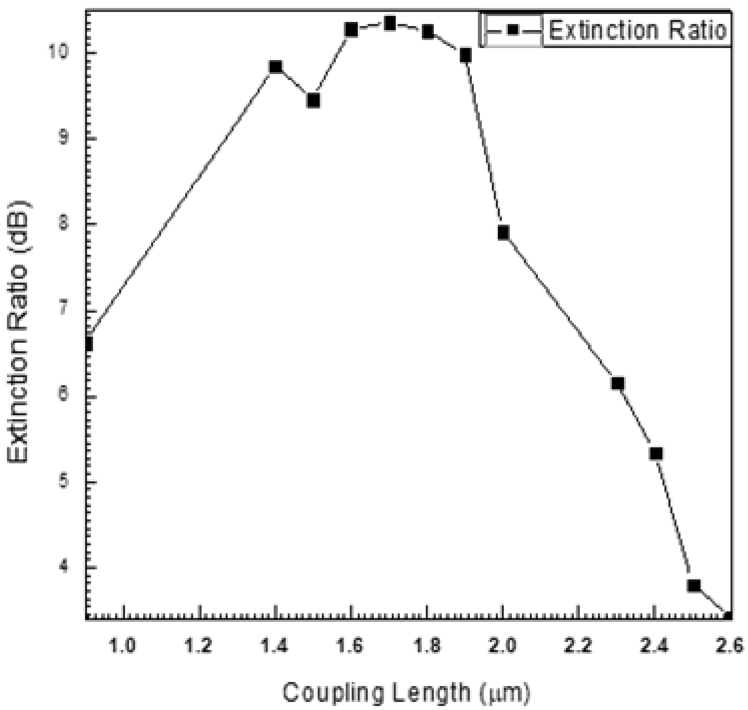

Figure 3

Result analysis of 10-dB directional coupler: coupling length versus extinction ratio

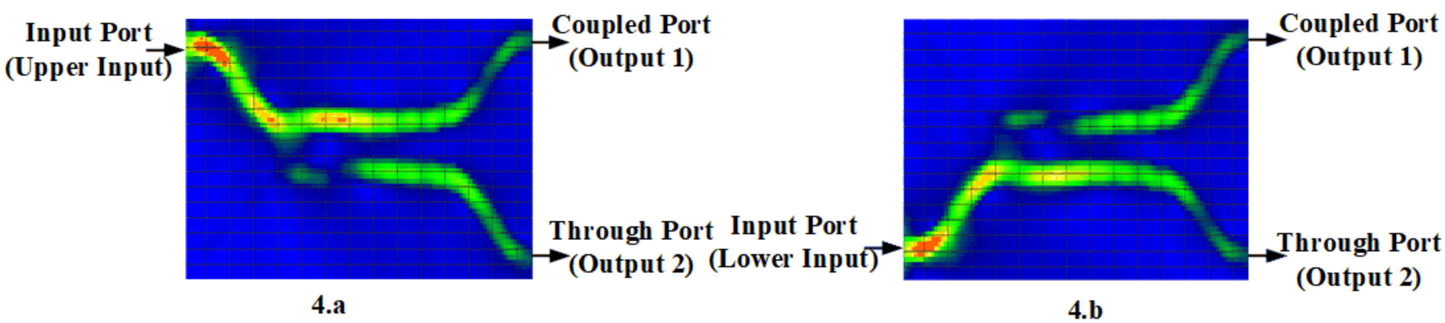

Figure 4

Propagation of light through 3-dB directional coupler a. input is given at the upper input port b input is given at the lower input port

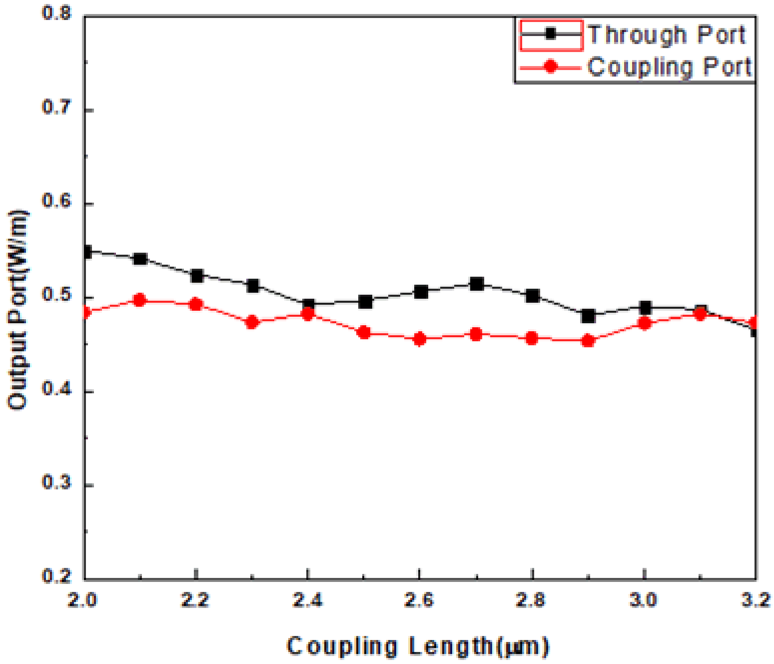

Figure 5

Result analysis of 3-dB directional coupler: coupling length versus normalized output power