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

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Abstract
In this paper, we have proposed, analyzed, and verified the performance of an optimized plasmonic 10-dB directional coupler and a 3-dB directional coupler in 2-D plasmonic waveguides using the 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 the 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 feature 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.

Keywords Plasmonic directional coupler · Metal–insulator-metal (MIM) waveguide · Finite-difference-time-domain (FDTD) · Coupling length

Introduction
The increasing demand for high-speed systems urges us to design a system with low complexity and power consumption. In the current scenario, to achieve the technology demand of higher capacity at a lower cost, 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, which have some limitations like high power dissipation, high input power, and low switching time [1, 3–5, 35]. 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 [5–9]. Due to these reasons, researchers have shifted focus on the optical signal to transmit the information [1, 4, 5, 7, 10–13]. Different types of optical techniques are employed such as metal–insulator-metal (MIM) [3, 6, 14–18], insulator–metal-insulator (IMI) [14, 16], dielectric-loaded surface plasmon polaritons (DLSPP) [10, 11, 15, 16, 19–22], metal slot waveguide [3, 6]. The directional coupler already has been implemented by using a semiconductor optical amplifier (SOA) [17, 23–27] photonic crystal [13, 15, 17, 27–35] and lithium niobate (LiNbO3) [5,8,15,]. SOA has some limitations like gain saturation and high driving current input, and in LiNbO3, 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, 15, 16, 19–22, 36] 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 a potential solution for size and operating speed mismatch problems in electronics and photonics [3, 5, 6]. The motivation behind plasmonic is the ability to realize very compact photonic devices [13, 15]. To obtain a satisfactory performance between loss and confinement, MIM [3, 5, 6, 14–18] has been preferred due to the ability to confine surface plasmon diffraction limit [37]. The important structure in optical communication is the directional coupler [3, 6, 9, 14, 16, 21, 35, 38–43], and it can be implemented in various applications like power splitters [44, 45], optical switches, and wavelength selective couplers, etc. [5]. The term optimization method is to get the solutions, which maximize or minimize the parameters such that the design compactness increases as well as its functionality.

In this paper, the structure of the optimized 10-dB and 3-dB directional couplers is proposed. The compact design of the directional coupler is proposed in the footprint of 8 μm × 4 μm. The proposed design is verified using the FDTD [1, 6, 7, 15, 19, 27, 29, 30, 32, 41, 43] method. There is much professional software to carry out the FDTD method. The software used to carry out the FDTD method is optiFDTD. In this paper, the optimized design of 10-dB and 3-dB directional couplers is discussed in the “Design of Optimized Directional Coupler” section and the functionality of both the couplers is presented in the “Simulation Results and Discussions” section. Finally, the conclusion of the paper has been deliberated.

**Design of Optimized Directional Coupler**

The theoretical modeling of a directional coupler is represented that agrees with the simulation value, which is simulated and optimized with the professional software optiFDTD. The properties of a directional coupler are bandwidth, directivity, and impedance matching. The coupling length for the upper input port can be defined as

\[ C(dB) = 10 \log \left( \frac{P_{TP}}{P_{CP}} \right) \text{dB} \]

An isolation of a directional coupler is defined as

\[ I(dB) = 10 \log \left( \frac{P_{TP}}{P_{IP}} \right) \text{dB} \]

The directivity of a directional coupler is defined as

\[ \text{directivity (dB)} = I(dB) - C(dB) \]

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 × 4 μm. The structure of an optimized directional coupler is designed using plasmonic MIM configuration. For the desired operation of the directional coupler, the structure is constructed 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 (high intensity) and 0.017 W/m (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 applied at the input port through the reference input port is very essential to get at the output port. The output power is detected by using the observation point at the coupled port (output 1) and through port (output 2).

**Design of 10-dB Directional Coupler**

In a 10-dB directional coupler, the input is given at the input port (upper input), and the output is detected at the through port (output 2). Hence, the lower input port is treated as an isolated port, and no power is at the coupled port (output 1). When the input is given at the lower input port, the output is detected at the coupled port (output 1). Hence, the upper input port is treated as an isolated port, and no power is at the through port (output 2) shown in Fig. 1. The separation distance between the two linear waveguides is less
than 0.4 µm. To find the beneficial impact on the output, the coupling length is varied from 3.2 to 0.8 µm. The formula for coupling length is

\[ LC = \frac{\pi}{2k}, \text{ where } k = \text{wavelength dependent constant} \]

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

**Design of 3-dB Directional Coupler**

A 3-dB directional coupler is used to split an input signal into two signals of equal amplitude and a constant 90° or 180° 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 (output 1) and through port (output 2), 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 a constant where the coupling length varies from 3.2 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.

**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. The FDTD method is used here to analyze the directional coupler due to its simplicity in both concept and implementation. The PML is used as a boundary condition because of its ability to restrict almost all reflections during the propagation of the wave. The proposed design is analyzed with the mesh size of \( \Delta x = 0.0738 \) µm and \( \Delta y = 0.0738 \) µm, which is very small enough to capture the change in the magnetic field. According to the above parameters, the analysis has been done.

**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 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. In Fig. 2a, the input is applied at the upper input port and the output at the through port; similarly, in Fig. 2b, the input is applied at the lower input port and the output at the coupled port as per Fig. 1.

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 Eq. (1):

\[
\text{Extinction Ratio (ER)} = 10 \log_{10} \left( \frac{P_{\text{ON}}}{P_{\text{OFF}}} \right)
\]

where \( P_{\text{ON}} \) is the output power at the on state, and \( P_{\text{OFF}} \) 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.

**Simulation Results of 3-dB Directional Coupler**

For the designing of a 3-dB directional coupler, the coupling length is varied from 3.2 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 powers of amplitude at the coupled port (output 1) and through port (output 2). 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.

Propagation of light through a 3-dB directional coupler is split into two equal power amplitudes, which are shown in Fig. 4. In Fig. 4a, the input is given at the upper input

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

| 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            |
of high intensity and the output power detected at both the output, i.e., coupled port (output 1) and through port (output 2); and in Fig. 4b, the input is given at the lower input of high intensity and in a similar fashion; the output is detected at the coupled port (output 1) and through port (output 2).

In Fig. 5, the graph between output port power versus coupling length is shown wherein both the ports have 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.

The comparison table with respect to the previous and the proposed work is shown in Table 3.

| 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               |
Fig. 4 Propagation of light through a 3-dB directional coupler. (a) Input is given at the upper input port; (b) input is given at the lower input port.

Fig. 5 Result analysis of 3-dB directional coupler: coupling length versus normalized output power.

Table 3 Performance and design parameter comparison of proposed plasmonic MIM waveguide

| Sl. no | Parameters          | [12]          | [46]          | [47]          | [48]          | Proposed method |
|--------|---------------------|---------------|---------------|---------------|---------------|-----------------|
| 1      | Dimensions          | $93 \times 3.7 \, \mu m^2$ | n.r.a | $16 \times 3.7 \, \mu m^2$ | $19.8 \times 10 \, \mu m^2$ | $8 \times 4 \, \mu m$ |
| 2      | Wavelength          | n.r.a         | n.r.a         | 1.55 \, \mu m | n.r.a         | 1.55 \, \mu m   |
| 3      | Polarization        | TM            | n.r.a         | TE            | n.r.a         | TM              |
| 4      | Extinction ratio (dB)| 26            | 9.73          | 10.25         | 16.53         | 10.36           |
| 5      | Insertion loss (dB) | n.r.a         | n.r.a         | 0.756         | n.r.a         | n.r.a           |

n.r.a, not reported
Conclusion

A novel and compact design of 10-dB and 3-dB directional couplers using a plasmonic waveguide has been proposed and successfully verified using FDTD. The design of both the directional couplers is constructed on the footprint of 8µm × 4µm 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.

Author Contribution Rupalin Rath: investigation, formal analysis, and writing—original draft. Ramakrushna Rath: formal analysis and methodology. Sandip Swarnakar: conceptualization, investigation, formal analysis, writing—original draft, methodology, and supervision. Santosh Kumar: validation, writing—review, and editing.

Availability of Data and Material We can provide the data as per request.

Code Availability No source code is available for this manuscript.

Declarations

Consent to Participate For this type of study, formal consent is not required.

Consent for Publication Not applicable.

Competing Interests The authors declare no competing interests.

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