Structurally-tolerant vertical directional coupling between metal-insulator-metal plasmonic waveguide and silicon dielectric waveguide

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Abstract: Vertical directional coupling between a metal-insulator-metal (MIM) plasmonic waveguide and a conventional dielectric waveguide is investigated. The coupling length, extinction ratio, insertion loss and coupling efficiency of the hybrid coupler are analyzed. As an example, when the separation between the two waveguides is 250 nm, a maximum coupling efficiency of 73%, an insertion loss of -1.4 dB and an extinction ratio of 16 dB can be achieved at a coupling length of 4.5 μm at 1.55 μm wavelength. A particular feature of this hybrid coupler is that it is highly tolerant to the structural parameters of the plasmonic waveguide and the misalignment between the two waveguides. The performance of this hybrid coupler as a TM polarizer is also analyzed and a maximum extinction ratio of 44 dB and an insertion loss of -0.18 dB can be obtained. The application of this hybrid coupler includes the signal routing between plasmonic waveguides and dielectric waveguides in photonic integrated circuits and the polarization control between TE and TM modes. In addition, it provides an approach for efficiently exciting MIM plasmonic modes with conventional dielectric modes.

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References and links

1. Introduction

In recent years, there is a tremendous amount of research conducted on surface plasmon polaritons (SPPs). The SPPs exploit extraordinary optical properties of metallic nanostructures to manipulate light beyond the diffraction limit, thus harboring immense potential for the implementation of optical interconnections at nanoscale. However, the SPPs usually suffer severe losses owing to the inherent absorption inside the metal. Conventional dielectric photonic devices exhibit low losses; however, they are limited in size by the diffraction limit to about half of light wavelength. Therefore, it is preferable to integrate plasmonic and conventional photonic devices on the same chip to take advantage of the strengths of each technology [1-4].

So far, several types of plasmonic waveguides which are capable of achieving subwavelength field confinement have been reported, including wedge waveguides, groove waveguides, dielectric-loaded waveguides, metal-insulator-metal (MIM) slot waveguides and hybrid waveguides [5]. The use of one type of waveguide over another depends on application-specific constraints. In this paper, we focus on the MIM slot waveguide, where the modal size is mainly decided by slot dimensions and can thus be squeezed significantly smaller than the diffraction limit [6, 7, 8]. The directional coupling between two MIM slot waveguides has been investigated theoretically [9, 10]. The butt-coupling between MIM plasmonic waveguides and dielectric waveguides has been investigated theoretically and experimentally [11-16]. However, there is no report concerning the directional coupling between MIM plasmonic waveguides and dielectric waveguides thus far. The hybrid directional couplers are fundamental building blocks for splitting or redirecting signal in optical integrated circuits (PICs) and have a range of applications in optical communication systems including spatial switches, power splitters, modulators, etc.

This paper is organized as follows. Section 2 is the description of the hybrid directional coupler composed of a MIM plasmonic waveguide and a silicon dielectric waveguide. Here we opt for silicon as the material of the dielectric waveguide because silicon photonics holds tremendous promise for providing a platform for the integration of plasmonic and conventional
photonic and even electronic devices. Section 3 is the analysis of field evolution behaviors in the hybrid coupler based on the coupled mode theory. Section 4 is the analysis of the performance of the hybrid coupler. We will show that strong coupling can be achieved even though the two arms of the hybrid coupler are completely different. The coupling length, extinction ratio and insertion loss of the hybrid coupler are analyzed. A distinguished feature of this hybrid coupler is that it exhibits high tolerance to structural parameters of the MIM plasmonic waveguide and the misalignment between the two waveguides. The application of this hybrid coupler as a TM polarizer is presented in Section 5. Section 6 is the conclusion.

2. Device description

The proposed vertical hybrid coupler is shown in Fig. 1. It consists of two arms: the lower arm is the silicon dielectric waveguide with a dimension of $W_1 \times H_1$; the upper arm is the MIM plasmonic waveguide with a dimension of $W_2 \times H_2$ for the slot. The plasmonic slot and the dielectric arm are vertically aligned with an edge-to-edge separation of $s$. The two arms are embedded in SiO$_2$. To guarantee a strong coupling between the two arms, the effective refractive indices of the guided modes in the two arms should be close. The TE mode ($E_x$ is the main electric field component) supported by the MIM plasmonic waveguide couples with the TE mode guided by the silicon waveguide and two eigenmodes (quasi-even and quasi-odd) are consequently formed in the hybrid coupler.

Figures 2(a) and (c) depict the electric field ($E_x$) amplitude of the two eigenmodes supported by the coupler at $s=250$ nm, which is obtained from the finite-element-method based commercial software Comsol Multiphysics. The relative permittivities used in simulations are $-132+12.65i$ [17], 11.9 and 2.1 for Au, Si and SiO$_2$ at 1.55 $\mu$m wavelength, respectively. To ensure a good coupling between the two waveguides, the following structural parameters are used in simulation: $W_1=260$ nm, $H_1=220$ nm, $W_2=150$ nm and $H_2=200$ nm. The obtained effective indices for both the decoupled MIM plasmonic mode and the silicon dielectric mode are around 1.6 at 1.55 $\mu$m wavelength. The propagation loss is 0.36 dB/$\mu$m and the corresponding propagation length ($L_0$) is 12 $\mu$m for the decoupled MIM plasmonic mode. When the two
waveguides are placed close to each other, they will couple with each other, thus resulting in energy exchanges in between. Figures 2(b) and (d) provide the corresponding electric field ($E_x$) profiles along $x=0$. It can be seen that the electric fields in the plasmonic arm are much stronger than those in the dielectric arm. For the quasi-even eigenmode, the electric field oscillation orientations in the two arms are the same while they become opposite in the quasi-odd eigenmode. The quasi-odd eigenmode exhibits a dip in the coupled region.

The coupling strength between the plasmonic waveguide and the dielectric waveguide is separation-dependent. Figures 3(a) and (b) provide effective indices and propagation losses of the two eigenmodes versus the arm separation ($s$). The quasi-odd mode, which is cut-off at $s<150$ nm, has a lower refractive index than the quasi-even mode. As $s$ increases, the effective refractive indices for both modes approach 1.63, which is the refractive index of the decoupled plasmonic mode or the dielectric mode. The quasi-even mode locates more in the MIM slot compared with the quasi-odd mode. Consequently, it has a larger loss than the quasi-odd mode. The losses of both modes approach 0.18 dB/μm as $s$ increases, which is half of that of the decoupled MIM plasmonic mode. This is reasonable since half of fields locate in the silicon dielectric waveguide for both quasi-even and quasi-odd modes.
3. Theoretical analysis

In part 2, we have obtained the two eigenmodes supported by the hybrid coupler based on the finite-element-method. Note that this is different from the conventional coupled mode theory, where the eigenmodes supported by the coupler are obtained by solving coupled-mode equations involving the decoupled modes supported by the two individual waveguides [18]. Any TE mode supported by the coupler can be regarded as an admixture of the two orthogonal eigenmodes [19]. Considering the case that the fields in the coupler are excited by the dielectric mode \( \vec{E}_d \) at \( z=0 \), the electric field \( \vec{E} \) in the hybrid coupler can be expressed as a linear combination of the two eigenmodes (\( \vec{E}_e \) and \( \vec{E}_o \)) as [19]:

\[
\vec{E}(x, y, z) = C_{de}\vec{E}_e(x, y)e^{i\beta ez} + C_{do}\vec{E}_o(x, y)e^{i\beta oz} \tag{1}
\]

The subscripts \( d, p, e, o \) represent the decoupled dielectric mode, decoupled plasmonic mode, quasi-even eigenmode and quasi-odd eigenmode, respectively. The fields for each mode are assumed normalized. By using the orthogonality relation between the two eigenmodes, the coupling coefficient from the \( i \)-mode to the \( j \)-mode \( C_{ij} \) can be expressed as [20, 21]:

\[
C_{ij} = \frac{1}{2} \int \int \vec{E}_i \times \vec{H}_j \cdot \hat{z} dS = |C_{ij}| e^{i\theta_{ij}} \tag{2}
\]

where \( S \) is the infinite cross-section, \( \hat{z} \) is the unit vector in the propagation direction, \( |C_{ij}| \) and \( \theta_{ij} \) are the amplitude and the phase of coupling coefficient \( C_{ij} \), respectively. \( \beta \) is the propagation constant and can be expressed as: \( \beta = \beta_r + i\beta_i \). Therefore, the output electric fields from the dielectric waveguide and plasmonic waveguide become:

\[
\vec{E}_d(x, y, z) = |C_{de}C_{ed}| e^{-\beta_{de}z} e^{i(\beta_{de}z + \theta_{de})}\vec{E}_e(x, y) + |C_{do}C_{od}| e^{-\beta_{do}z} e^{i(\beta_{do}z + \theta_{do})}\vec{E}_o(x, y) \tag{3}
\]

\[
\vec{E}_p(x, y, z) = |C_{de}C_{ep}| e^{-\beta_{de}z} e^{i(\beta_{de}z + \theta_{de})}\vec{E}_e(x, y) + |C_{do}C_{op}| e^{-\beta_{do}z} e^{i(\beta_{do}z + \theta_{do})}\vec{E}_o(x, y) \tag{4}
\]

Similarly, the output magnetic fields from the hybrid coupler can be expressed with the input magnetic fields from the dielectric arm. Figures 4(a) and (b) show the electric field and magnetic field distributions along \( x=0 \) in the coupler as functions of the position \( z \) when the field is excited by the dielectric mode at \( z=0 \), respectively. As \( z \) increases, the field transfers from the dielectric arm to the plasmonic arm gradually due to the interference of quasi-even and quasi-odd eigenmodes. At coupling length \( L_c \), almost all the fields transfer to the plasmonic arm even if the two arms are completely different. The coupling length is a measure of the beating length

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Fig. 3. Effective refractive indices (\( n_{eff} \)) and losses of the two eigenmodes versus the arm separation (\( s \)).
of the two eigenmodes inside the coupler and can be related to propagation constants of the two eigenmodes and phases of coupling coefficients by: $L_c = \pi / (\beta_{er} - \beta_{or} + \theta_{de} + \theta_{ed} - \theta_{do} - \theta_{od})$. Actually, $\theta_{de}$, $\theta_{ed}$, $\theta_{do}$ and $\theta_{od}$ are close to zero and thus $L_c$ can be approximated as: $L_c = \pi / (\beta_{er} - \beta_{or})$. 

Fig. 4. (a) Electric field and (b) magnetic field intensities along $x=0$ in the coupler as functions of the position $z$ when the fields are excited by the dielectric modes at $z=0$ ($s=250$ nm), respectively. The green arrows indicate where the fields in the coupler are excited.

Fig. 5. Output power from the two output arms versus the interaction length $z$ at $s=250$ nm.
The output power from the two arms versus the interaction length $z$ is provided in Fig. 5. The power exchange between the two arms takes place every coupling length $L_c$ and thus the output power shows attenuated oscillations with an increasing interaction length. The power splitting ratio between the plasmonic arm and the dielectric arm can be controlled by tuning the interaction length. At $z = L_c$, 73% of the input power is converted from the dielectric mode to the plasmonic mode when the propagation loss is taken into consideration. Hence, this directional coupling provides a different approach for efficiently exciting the MIM plasmonic mode. The field evolution can also be obtained from other methods, such as 3-D finite-difference time-domain method [9].

4. Performance analysis

In this part, we evaluate the performance of the hybrid coupler. Three key parameters, including the coupling length, extinction ratio and insertion loss are analyzed. The tolerance of the coupler to structural parameters of the plasmonic waveguide and misalignment between the two waveguides is also analyzed.

4.1. Coupling length

Usually, the coupling coefficient $\kappa$ (note the coupling coefficient $\kappa$ here is different from the coupling coefficient $C$ in Section 3 and Subsection 4.2) is used to characterize the coupling strength between the two waveguides in the coupler. The coupling length is directly related to the coupling coefficient $\kappa$ by $L_c = \pi/(2\kappa)$ [18]. The coupling coefficient $\kappa$ is decided by the integral of overlapped fields over the coupling region, which decreases exponentially with the arm separation. Figure 6 shows the coupling length of the hybrid coupler versus the arm separation ($s$). It can be seen that $L_c$ increases exponentially with $s$. At $s=150$ nm, the coupling length is 2.5 $\mu$m, which is only 1/5 of the propagation length of the decoupled MIM plasmonic waveguide. At $s=250$ nm, the coupling length is 4.5 $\mu$m. The coupling length is almost the same as $L_0$ at $s=450$ nm.

![Fig. 6. Coupling length ($L_c$) versus the arm separation ($s$) when the fields are excited by the dielectric mode. $L_c$ is normalized to the propagation length of the decoupled plasmonic waveguide $L_0$.](image)

4.2. Extinction ratio

In a directional coupler, it is desirable to have all the input power transferred to the other waveguide in a cross state and no coupling at all in a bar state. However, the quasi-even and quasi-odd
eigenmodes have different amplitudes due to the unequal excitation and experience different losses due to different field distributions. Consequently, the two eigenmodes will never be able to completely cancel each other, thus leading to a crosstalk [22]. The extinction ratio, which is defined as the ratio of maximum output power from the plasmonic arm to minimum output power from the dielectric arm when the input is fed from the dielectric arm, can be used to characterize the cross-talk of this directional coupler. From Eqs. (3) and (4), the extinction ratio (ER) can be approximated as:

$$ER = 20 \times \log \left| \frac{C_{de}C_{ep}}{C_{de}C_{ed}e^{-\beta erLc}e^{i(\beta erLc+\theta_{de}+\theta_{ep})} + C_{do}C_{op}} \right|$$

The extinction ratio of the hybrid coupler versus the arm separation is shown in Fig. 7(a). The extinction ratio exceeds 10 dB in the whole range of interest. At $s=250$ nm, the extinction ratio is around 16 dB. The maximum extinction ratio is 17 dB, which occurs at $s=300$ nm. The extinction ratio degrades with a decreasing $s$ at $s<300$ nm. This is mainly caused by the unequal excitation of the quasi-even and quasi-odd eigenmodes at $z=0$. Figure 7(b) shows coupling coefficients of the dielectric mode to the two eigenmodes ($|C_{de}|$ and $|C_{do}|$) and those of the two eigenmodes to the plasmonic mode ($|C_{ep}|$ and $|C_{op}|$). It can be seen that the difference between $|C_{de}|$ and $|C_{do}|$ increases with the decreasing $s$. Therefore, the excited quasi-even and quasi-odd eigenmodes are unequal, thus causing the extinction ratio degradation at small $s$. When $s>350$ nm, the extinction ratio degrades with an increasing $s$, which is mainly caused by the increase in the coupling length. The coupling length increases exponentially with $s$ and thus the propagation loss increases correspondingly, thereby degrading the extinction ratio at large $s$.

4.3. Insertion loss

The total insertion loss of the hybrid coupler consists of three parts: the coupling loss at the input end (in-coupling loss), the coupling loss at the output end (out-coupling loss) and the propagation loss for one coupling length in the coupler. These three types of losses and the total insertion loss of the coupler are shown in Fig. 8(a). The in-coupling loss and the out-coupling loss are below 1 dB in the whole range of interest and can be even neglected at large $s$. Figure 8(b) shows the decoupled dielectric field and the coupled field along $x=0$ at $z=0$. It can be seen that the coupled field at $z=0$ doesn’t totally agree with the decoupled dielectric field due to the introduction of the plasmonic arm, which causes the in-coupling loss. Similarly, the difference between the coupled field at $z=L_c$ and decoupled plasmonic field accounts for the out-coupling loss at $z=L_c$, which is shown in Fig. 8(c). Both the in-coupling and out-coupling
loss decrease when \( s \) increases. This is reasonable since the coupling becomes weak at large \( s \) and thus the in-coupling and out-coupling of the field are less affected by the other waveguide. The propagation loss in the coupler increases exponentially with \( s \), which is mainly caused by the increase in the coupling length. At \( s>300 \) nm, the propagation loss dominates the insertion loss. The minimum insertion loss is -1.4 dB, which occurs at \( s=250 \) nm.

Since the hybrid directional coupling can be utilized to efficiently excite the MIM plasmonic mode with the dielectric mode, it becomes necessary to analyze the coupling efficiency of the hybrid coupler. The coupling efficiency is defined as the percentage of maximum output power from the plasmonic waveguide with respect to the input power into the dielectric waveguide. The coupling efficiency (\( \eta \)) can be related to the insertion loss (in dB) by \( \eta = 10^{\alpha/10} \). The obtained maximum coupling efficiency is 73% at \( s=250 \) nm.

### 4.4. Tolerance to the structural parameters of the plasmonic waveguide

For a directional coupler, structural parameters are quite critical in making the propagation constants of the two arms match each other. Therefore, the tolerance of the coupler to the structural parameters are usually very tight. However, for the hybrid coupler proposed here, it shows high tolerance to the structural parameters of the plasmonic waveguide, thus alleviating the stringent requirements in fabrications to some extent. Figures 9(a)-(c) show the tolerance of the coupling length, extinction ratio and insertion loss as functions of the plasmonic slot height for different slot widths. The dimension of the dielectric waveguide is still kept at 260 nm × 220 μm.

Fig. 8. (a) Losses versus the arm separation (\( s \)). (b) Comparison of the input dielectric electric field intensity and the coupled electric field intensity along \( x=0 \) at \( z=0 \). (c) Comparison of the output plasmonic electric field intensity and the coupled electric field intensity along \( x=0 \) at \( z=L_c \). The fields are excited by the dielectric modes at \( s=250 \) nm. The dashed lines in (b) and (c) indicate the boundaries of both arms.
nm and the arm separation at 250 nm. It can be seen that strong coupling exists even if the dimensions of the plasmonic waveguide change in a large range. The reason is that the effective refractive index of the plasmonic waveguide is not quite sensitive to the slot dimensions in a large range. Figure 10 shows the effective refractive index and the loss of the decoupled MIM plasmonic waveguide.

![Graphs showing coupling length, extinction ratio, and insertion loss](image)

Fig. 9. Tolerance of the hybrid coupler to slot structural parameters. (a)-(c) are the coupling length, extinction ratio (ER) and insertion loss (IL) versus the slot height for different slot widths at \( s=250 \) nm, respectively.

It can be seen from Fig. 9(a) that the coupling length of the hybrid coupler increases with the slot height. This is because the percentage of the overlapped field between the plasmonic mode and the dielectric mode decreases with the slot height, thereby leading to an increase in the coupling length. In contrast, the coupling lengths are less sensitive to the slot width. The coupling lengths are almost the same for \( W=125 \) nm, 150 nm and 200 nm because the percentage of the overlapped field doesn’t change too much with an increasing slot width. Even at \( W=100 \) nm, the coupling length decreases by less than 10%.

From Fig. 9(b), the extinction ratios for \( W=100 \) nm, 125 nm and 150 nm are above 10 dB in the range of interest. Especially, the extinction ratio is above 40 dB at \( W=125 \) nm and \( H=100 \) nm where there is almost no residual power in the dielectric arm.

For the insertion loss, it is below 2 dB for \( W=100 \) nm, 125 nm and 150 nm from Fig. 9(c). From Fig. 10(b), we can see that the propagation loss of the decoupled plasmonic mode increases with a decreasing slot width due to the increase of percentage of field in the metal regions. However, the propagation loss doesn’t change too much with the slot height because the percentage of fields inside the slot almost keeps constant. Since the propagation loss dominates the total insertion loss, the insertion loss of the hybrid coupler just follows the trend of the propagation loss for the decoupled plasmonic mode.
4.5. Tolerance to the misalignment between the plasmonic waveguide and the dielectric waveguide

For any directional coupler that adopting the vertical coupling configuration, the misalignment between the two waveguides is virtually unavoidable in fabrication. However, the hybrid coupler proposed here is quite tolerant to the misalignment between the plasmonic waveguide and the dielectric waveguide.

Fig. 10. (a) Effective refractive index and (b) loss of the decoupled MIM plasmonic waveguide versus the slot height for different slot widths.

Fig. 11. (a) and (b) are electric field ($E_x$) amplitudes of the quasi-even mode and quasi-odd mode in the hybrid coupler at $\Delta x=200$ nm ($s=250$ nm), respectively. All the parameters except $\Delta x$ are the same as those in Fig. 2. (c) Coupling length and extinction ratio (ER) versus the misalignment $\Delta x$ at $s=250$ nm. (d) Insertion loss (IL) versus the misalignment $\Delta x$ at $s=250$ nm.
Figures 11(a) and (b) provide the electric field ($E_x$) amplitudes of the quasi-even mode and quasi-odd mode in the hybrid coupler at $\Delta x=200$ nm, respectively. Here $\Delta x$ denotes the misalignment between the two waveguides in the $x$ direction. All the parameters except $\Delta x$ are the same as those in Fig. 2.

The coupling length and the extinction ratio of the hybrid coupler versus the misalignment $\Delta x$ are shown in Fig. 11(c). The coupling length increases gradually with an increasing $\Delta x$. At $\Delta x=0$, the coupling length is $0.4L_0$. For the extinction ratio, it improves with the increasing $\Delta x$ first and then degrades with the increasing $\Delta x$. The change of extinction ratio with respect to the misalignment $\Delta x$ is quite similar to that with respect to the arm separation $s$. At small $\Delta x$, the unequal excitation of the two eigenmodes degrades the extinction ratio. At large $\Delta x$, the degradation of extinction ratio mainly results from the increase in the propagation loss.

The insertion loss of the hybrid coupler versus the misalignment $\Delta x$ is provided in Fig. 11(d). The insertion loss increases with the increasing $\Delta x$, which is mainly caused by the increase in the propagation loss. At $\Delta x=0$, the insertion loss is -1.4 dB. At $\Delta x=300$ nm, the insertion loss is -3.6 dB.

5. Application of the hybrid coupler as a TM polarizer

![Diagram](image)

Fig. 12. (a) and (b) are electric field ($E_x$) amplitudes of TM modes in the hybrid coupler at $s=250$ nm and the decoupled dielectric waveguide, respectively. (c) Insertion loss (IL) and extinction ratio (ER) of the TM polarizer at $s=250$ nm.
Since the MIM plasmonic waveguide only support the TE mode, the hybrid coupler can be implemented as a TM polarizer. Figures 12(a) and (b) provide electric field ($E_x$) amplitudes of the TM modes in the hybrid coupler and the decoupled dielectric waveguide, respectively. To obtain a high extinction ratio, we choose $H_2=100$ nm and $W_2=125$ nm for the MIM plasmonic arm while the parameters for the dielectric arm keep unchanged. It can be seen that the electric field distributions for the TM mode in the hybrid coupler are quite similar to those in the decoupled dielectric waveguide. A small difference is that the TM fields are truncated by the metal boundaries, which accounts for the loss of the TM mode in the hybrid coupler. The calculated loss of the TM mode in the hybrid coupler is 0.048 dB/$\mu$m. When the TE and TM modes are fed into the hybrid coupler from the dielectric arm simultaneously, the TE mode will transfer to the plasmonic arm gradually due to the directional coupling while the TM mode will propagate through the dielectric arm with a low loss. Therefore, by properly choosing the interaction length, the TE and TM modes can be separated at the output end. The loss of TM mode represents the insertion loss here. The extinction ratio of this TM polarizer is defined as the output TM power from the dielectric arm with respect to the residual TE power in the dielectric arm. Figure 12(c) shows the insertion loss and extinction ratio of the coupler versus the interaction length $z$. When $z$ is close to $L_c$, the maximum extinction ratio is 44 dB and the insertion loss is -0.18 dB. This hybrid coupler can also be used as a TE/TM polarization splitter or combiner.

6. Conclusion

The characteristics of asymmetrical directional coupling between metal-insulator-metal plasmonic waveguides and dielectric silicon waveguides have been investigated based on the finite element method and the coupled mode theory. The coupling length, extinction ratio and insertion loss of the hybrid coupler have been analyzed. A distinguished feature for this hybrid coupler is that it exhibits high tolerance to the structural parameters of the MIM plasmonic waveguide and the misalignment between the two waveguides, thereby alleviating the stringent requirements in fabrications to some extent. This directional coupler could be potentially exploited for developing photonic-plasmonic hybrid functional components for signal routing, power splitting, wavelength demultiplexing, etc in PICs. In addition, it provides an approach for efficiently exciting MIM plasmonic modes with conventional dielectric modes. Another application of this hybrid coupler is polarization control. TM polarizer, TE/TM polarization combiner, and splitter can be designed based on this hybrid coupler.

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