A controllable nanosize combiner in T-shaped metal-insulator-metal waveguides

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Abstract: We numerically analyzed the performance of a T-shaped combiner with metal-insulator-metal plasmonic waveguides. We showed that an extremely low combining loss can be realized over a wide infrared wavelength region. Moreover, the combining efficiency can be controlled between 0 and 1 by changing the phase difference between two input light sources, and it appears to be insensitive toward unequal powers of input light sources. Finally, we proposed a novel, optical 90° hybrid coupler with a modified T-shaped structure.

Keywords: T-shaped combiner, phase difference, 90° hybrid coupler

Classification: Fiber optics, Microwave photonics, Optical interconnection, Photonic signal processing, Photonic integration and systems

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1 Introduction

Metal-insulator-metal (MIM) plasmonic waveguides based on the oscillation and propagation of surface-plasmon polariton (SPP) optical waves at metal-insulator interfaces can tightly confine light within its nanosized slot region [1, 2, 3, 4]. Due to its characteristics of high confinement and low bending loss [5, 6, 7], many special structures and devices that are not able to be made with conventional dielectric waveguides have been realized with MIM waveguides. Among of them, T-shaped structures in MIM waveguides were proposed and wildly used as optical splitters [5, 8, 9, 10, 11, 12]. However, T-shaped combiner which seems to have a low combining efficiency, have not been proposed so far. As a matter as fact, according to our initial simulations, we determined that a T-shaped structure is not only a feasible approach but also a highly effective approach for producing a combiner using MIM waveguides due to the standing wave condition produced by two input light sources. Therefore, in this paper, we focus on a T-shaped combiner comprising MIM waveguides and analyze the wavelength and optical phase dependencies of the combining efficiency. In addition, we demonstrate an optical 90° hybrid coupler as a potential novel application.

2 Simulation

A T-shaped combiner using MIM waveguides was simulated using a two-dimensional finite-difference time-domain (FDTD) method. The uniform grid resolution was 5 nm (one-tenth of the MIM waveguides’ minimum width). Fig. 1 shows the waveguide structure used in our simulations. A T-shaped air gap with a width of d was embedded in silver with a dielectric constant of $\kappa = 10^{3} + j8.231$ [13]. The output waveguide was perpendicularly connected with the input waveguide at $x = 0$. Two identical coherent traveling waves were simultaneously launched from two input ports 1 and 2. The transmission coefficient of the combiner was defined.

![Fig. 1. A schematic of a T-shaped combiner comprising MIM waveguides. Air gaps of width d are embedded in silver.](image-url)
as the ratio of the output power to the total input power of both oppositely propagating light sources. Here, the input and output light powers were measured using three monitors (green marks in Fig. 1) set close to the connection to isolate the combining loss contribution from the other transmission losses.

3 Result

First, we analyzed the transmission coefficient under the simple condition of two identical monochromatic input light sources. In Fig. 2(a), we show the wavelength ($\lambda$) dependence of the transmission coefficient for $d = 50$ and 100 nm. We can see that the combining loss is extremely low and close to zero in the region of $\lambda > 1 \mu m$. This result shows similar trends to the results for a 90° sharp bend in the MIM waveguide in Ref. [5, 6, 7]. The Poynting vectors in the inset of Fig. 2(a) show that most of the light turns in a direction perpendicular to the input waveguide around $x = 0$, rather than directly propagating in the opposite direction. When either of the input light sources was turned off, 49.4% of the input power was delivered into a perpendicular output port and 49.8% went straight into the other input port. The residual 0.8% was mainly due to metal absorption and numerical errors. This waveguides also demonstrated superior performance as a simple power splitter. From the above results, we can infer that the standing wave formed by two colliding input waves results in an impact on the coupling phenomenon. Therefore, the combining ratio can be controlled by changing the phase difference of the two input light sources.

![Fig. 2.](image_url)

(a) Transmission coefficient as a function of the wavelength ($\lambda$) for $d = 50$ nm and 100 nm. The inset shows the behavior of the time-averaged Poynting vectors near the interface region for $\lambda = 1550$ nm and $d = 50$ nm; (b) Transmission coefficient as a function of the phase difference between two oppositely traveling input light waves at $\lambda = 1550$ nm when Power 1 (light power from Input 1) and Power 2 (light power from Input 2) are equal (black line) and when Power 1 is two times larger than Power 2 (red line); (c) Time-averaged $|H_y|$ field distribution for zero phase difference; (d) Time-averaged $|H_y|$ field distribution for a phase difference of $\pi$.
The transmission coefficient is shown in Fig. 2(b) as a function of the phase difference between two colliding input light sources with $\lambda = 1550$ nm. We can see that as the phase difference between the two opposite waves increases from 0 to $\pi$, the transmission coefficient monotonously reduces from a maximum value of 98.8% to zero (black line) as a cosine curve. Since the phase difference also changes with the position $x$, this curve is equivalent to the power distribution of the standing wave along the $x$ axis. Figs. 2(c) and 2(d) show the time averaged $|H_y|$ field distributions when the two input waves are in-phase and out-of-phase by $\pi$ at $x = 0$, respectively. We can clearly see the standing waves along the input waveguides and their peak-position shift of $\pi$. Consequently, a traveling wave appears or disappears in the connected output waveguide in Figs. 2(c) and (d), respectively. These results reflect the calculated result at a phase difference of 0 and $\pi$ in Fig. 2(b). Note that the transmission coefficient varies with the power of the standing wave.

Next, we discuss the combining efficiency in the case of unequal input light powers. The black and red lines in Fig. 2(b) indicate the transmission coefficient when Power 1 and Power 2 (light powers launched at input ports 1 and 2) are equal and when Power 1 is twice as large as Power 2, respectively. Although the fringe contrast generally declines for a two-beam interference with uneven light power, the transmission coefficient is nearly unchanged for the two cases in this T-shaped combiner. At present, we cannot offer a complete explanation of this feature, but insist the optical phase of the two input light sources dominate the combining efficiency in this MIM waveguide. This insensitivity to input light powers may be preferable in actual combiner devices.

4 Application on optical 90° hybrid coupler

Because of the unique properties mentioned above, the T-shaped MIM waveguide can be applied to several nanosized devices such as an optical logic gate, a modulator, and a splitter/combiner. Here, we propose an optical 90° hybrid coupler comprising a modified T-shaped structure. An optical 90° hybrid coupler is often used for phase diversity optical coherent receivers, wherein a light signal is equally split into two and mixed with in-phase and $\pi$-phase-shifted local light. Because of the quadrature relationship between the two mixed light signals, a stable output is obtained independently with the differential phase between the signal and local light sources. Fig. 3(a) shows a simulation model that is realized using two perpendicular output waveguides with a specific distance of $D$, corresponding to the $\pi$-phase of the standing wave. In Fig. 3(a), we can imagine that a signal and local light are injected from input ports 1 and 2, respectively, and then, two coherently mixed signals are detected at output ports 1 and 2. The value of $D$ is normally determined from the operation wavelength and the propagation constant of the waveguide mode. It can also be estimated from previous simulation results for T-shaped waveguides as the interval between the maximum and minimum of the transmission coefficient. In our model, $D = 306.7$ nm. In Fig. 3(b), we show the transmission coefficients for each output port and the total output as a function of the phase difference between two input light sources with $\lambda = 1550$ nm.
We can see that the transmission coefficients of the two output waveguides changed periodically with an increase in the phase difference and that the sum of the transmission coefficients corresponding to the output of quadrature detection maintained a constant value of $\sim 0.9$ regardless of the phase difference. This stable output demonstrates the feasibility of applying our combiner model to an optical 90° hybrid coupler. A very compact structure is suitable for nanosized circuits because it enables low loss and high element density.

5 Conclusion

In conclusion, we demonstrated the feasibility of a T-shaped combiner comprising MIM plasmonic waveguides. It exhibits a very low combining loss, which is nearly zero in the long wavelength region. In particular, it enables the control of the transmission coefficient between 98.8% and zero by changing the phase difference of two oppositely traveling coherent waves. We also proposed a unique application for this T-shaped combiner structure on an optical 90° hybrid coupler and briefly verified its excellent performance.