Hybrid three-arm coupler with long range surface plasmon polariton and dielectric waveguides

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The characteristics of hybrid three-arm coupler, which consists of the middle long range surface plasmon polariton waveguide and two outside conventional dielectric waveguides, are analyzed numerically with finite element method. Since the middle arm can only transfer the TM mode from one dielectric arm to the other one, this structure is promising for realizing integrated polarization splitter. Compared with the two-arm hybrid coupler, the loss of three-arm hybrid coupler based device can be reduced. Furthermore, different from conventional three-arm dielectric coupler, the authors find that the three-arm hybrid coupler with asymmetric structure can reach a much higher extinction ratio. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2747666]

Surface plasmon polariton (SPP) is a transverse-magnetic surface electromagnetic excitation that propagates in a wavelike fashion along the metal and dielectric interface.[1] The metal strip guided long range surface plasmon polariton (LRSPP) mode attracts much attention for its low loss[2–4] and capability of carrying optical signals and electrical signals simultaneously.[5] Meanwhile, the combination of the SPP with the conventional optical devices[6–8] is worthy of expectation in the communication and sensor field.

Both integrated plasmon and dielectric waveguides[6] and SPP-single mode dielectric waveguide polarizer[7] have shown the conversion between SPP and dielectric waveguide mode and the intention to realize integrated dielectric-plasmon circuits. However, high transmission loss of the SPP makes them impractical. We have demonstrated theoretically that the two-arm hybrid coupler has a high efficient coupling between LRSPP and dielectric waveguide mode with significantly reduced loss.[8] In this letter, three-arm hybrid coupler, which consists of two outside dielectric arms and a middle metal strip arm, is proposed. Besides the advantages of the pure LRSPP coupler[4,5,9] and two-arm hybrid coupler,[8] the proposed three-arm hybrid coupler has two dielectric arms for coupling to avoid the extra transmission loss on the metal strip. Furthermore, we demonstrated theoretically that asymmetric structure can improve the extinction ratio remarkably by introducing an offset of the middle arm. This characteristic is quite different from the conventional three-arm dielectric coupler.[10]

Figure 1(a) shows the simulation model for the proposed three-arm hybrid coupler. The propagation direction is along z axis. Different from the conventional three-arm dielectric coupler,[10] the middle arm is replaced by a metal strip (LRSPP waveguide) with thickness T_m. The two T_d thick outside arms are the same dielectric waveguides with distance D. The three arms have the same width W. We first consider the symmetric structure without the metal strip offset. Coupled eigenmodes supported by the hybrid coupler were calculated directly by software FEMLAB[11] to analyze the coupling characteristics among the three arms instead of solving the coupled-mode equations,[12] just as that reported in Ref. 8.

Here, we assume that the two outside dielectric waveguides (n_d=1.54) and the Au (ε_m=−132+$i\times$12.65) strip are surrounded by SiO_2 (n_s=1.444) at λ_0=1.55 μm,[13] with width W=2 μm. With fixed thickness of the dielectric arms T_d=393 nm, we should adjust Au film thickness T_m around 81 nm to meet a certain relation of the effective indices of three eigenmodes to achieve a high extinction ratio. This will be discussed later in this letter.

Similar to the conventional three dielectric waveguides coupler,[10] the proposed hybrid coupler also has three TM polarized eigenmodes, two symmetric modes A and B, and an antisymmetric mode C. Their magnetic fields are shown in Fig. 1(b), where D=7 μm. For mode A, the magnetic field has the same direction in all the positions. For mode B, the field direction around the middle arm is opposite from that around outside arms. While mode C has opposite field direction around the two outside arms.

Any TM mode supported by the hybrid coupler can be expressed in terms of a linear superposition of eigenmodes A, B, and C,

$$\mathbf{H}(x,y,z) = \sum_j a_j \mathbf{H}_j(x,y) e^{i\beta_j z} \quad (j = \mathrm{A,B,C}), \tag{1}$$

where $\mathbf{H}_j$ are the magnetic fields of eigenmode A, B, and C when z=0, $\beta_j=\beta_{jr}+i\beta_{ji}$ are the corresponding complex

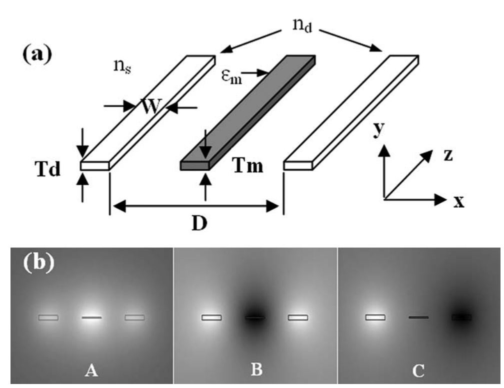

FIG. 1. (a) Parallel three-arm hybrid coupler, dark arm (middle) stands for the metal strip and white arms (left and right) stand for the dielectric waveguide. (b) Magnetic field of three eigenmodes in the x-y plane.

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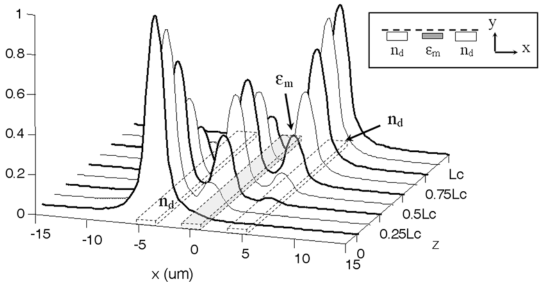

FIG. 2. Intensity of magnetic field (TM polarized) sampled along the dashed line in the inset, where $D=7$ μm. Energy couples from left dielectric waveguide (left), the right dielectric waveguide (right), to the LRSPP waveguide (middle) along the propagation direction z. The inset shows the x-y plane cross section of the hybrid coupler.

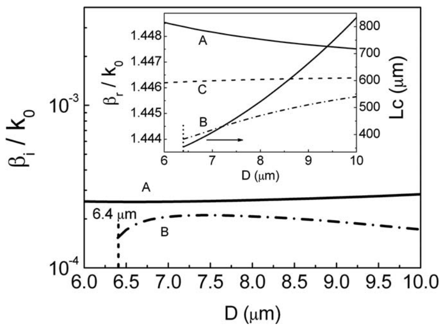

FIG. 3. Normalized attenuation constants (β_i/k_0) and effective index (β_r/k_0) (inset) of modes A (solid line), B (dash-dotted line), and C (dashed line) vs D. For mode B, the cutoff distance D is 6.4 μm. Coupling length of hybrid coupler L_c (solid line) is also shown in the inset.

propagation constants, and a_j ($j=$A,B,C) are the corresponding mode amplitudes. The eigenmode fields and propagation constants can be derived by FEMLAB. Then the individual TM mode $\boldsymbol{H}_d$ ($\boldsymbol{E}_d$) of the left dielectric arm is considered as the input from that arm.[8] Therefore, the amplitudes of three eigenmodes can be derived from[12]

$$a_j = \frac{1}{2}\int (\boldsymbol{E}_d \times \boldsymbol{H}_j^*) \cdot \hat{z} dxdy \quad (j = \text{A,B,C}). \qquad (2)$$

With normalized fields for all modes, the intensity of the magnetic field supported by the three-arm hybrid coupler can be expressed as

$$|\mathbf{H}(x,y,z)|^2 = \sum_j [b_j \mathbf{H}_j(x,y)]^2 + \sum_{mn} 2b_m b_n \mathbf{H}_m(x,y)\mathbf{H}_n(x,y)\cos(\beta_{mr} - \beta_{nr})z,$$

$$(b_j = a_j e^{-\beta_{ji} z},\ j,m,n = \text{A,B,C}). \qquad (3)$$

Therefore, according to Eq. (3), we depict how energy couples among three arms. Figure 2 shows the intensity of the magnetic field along the dotted line in the inset, rather near the top surface of the strips, since LRSPP mode has its maximum field value on the surface.[2] It is shown that energy transfer gradually from the left dielectric arm to the middle LRSPP arm, then right dielectric arm.

At the coupling distance $z=L_c$ [$L_c=2\pi/(\beta_{\text{Ar}}-\beta_{\text{Br}})$ (Ref. 10)], with $\beta_{\text{Ar}}-\beta_{\text{Cr}} \approx \beta_{\text{Cr}}-\beta_{\text{Br}}$ when $D=7$ μm, as shown in the inset of Fig. 3, Eq. (3) can be simplified as

$$|\mathbf{H}(x,y,L_c)|^2 \approx [b_\text{A}\mathbf{H}_\text{A}(x,y) + b_\text{B}\mathbf{H}_\text{B}(x,y) - b_\text{C}\mathbf{H}_\text{C}(x,y)]^2. \qquad (4)$$

Considering the field pattern in Fig. 1(b), it is clear that the combination of modes A and B, $b_\text{A}\mathbf{H}_\text{A}(x,y)+b_\text{B}\mathbf{H}_\text{B}(x,y)$, forms the even mode of the two-arm coupler.[9] Mode C corresponds to the odd mode and has a phase difference π compared with the even mode. Thus Eq. (4) indicates that most of the energy has been coupled to the right dielectric arm when $z=L_c$.

The real parts of effective indices of three eigenmodes and coupling length $L_c=2\pi/(\beta_{\text{Ar}}-\beta_{\text{Br}})$ are both shown in the inset of Fig. 3 as a function of D. It is noticeable that near the cutoff distance ($D=6.4$ μm) of mode B, the coupling length is about 350 μm. This is of great potential for realizing compact optical components. As shown in Fig. 3, the attenuation constants (β_i/k_0) of modes A and B have no obvious change with D in the interested region. For mode C, loss can be neglected compared with modes A and B because mode C has little field around the middle LRSPP arm, as shown in Fig. 1(b).

Here we defined the coupling loss (C.L.) as

$$\text{C.L.} = 10\log\left[\sum_j a_j^2 \Big/ \sum_j (a_j e^{-\beta_{ji}L_c})^2\right] \quad (j = \text{A,B,C}). \qquad (5)$$

Comparing the attenuation constants (β_i/k_0) and the coupling length L_c of the three-arm hybrid coupler (shown in Fig. 3) with those of the two-arm hybrid coupler [Fig. 3(a) in Ref. 8], it seems that three-arm hybrid coupler has larger coupling loss. However, the reality is opposite. Take $D=7$ μm for example, the coupling length $L_c=408$ μm and coupling loss is 1.62 dB for the three-arm hybrid coupler. For the two-arm hybrid coupler, with corresponding arm distance of 2.5 μm, the coupling length L_c is 308 μm and coupling loss is 1.82 dB.[8] Although the three-arm hybrid coupler has thicker Au film (81 vs 70 nm in Ref. 8) and larger coupling length L_c, the coupling loss is still lower than that of the two-arm hybrid coupler. The reason is that near half of the energy is guided by mode C with very low loss. More importantly, for two-arm hybrid coupler, TM light is coupled to LRSPP guided by the Au strip with comparative high loss. Therefore, the total loss of the device includes the coupling loss of coupler and the extra transmission loss on the metal strip. However, in the case of three-arm hybrid coupler, the right lossless dielectric arm guides the TM light at last and all of the losses only result from the coupling loss.

Extinction ratio (E.R.), which is defined as the ratio of the output power from the right dielectric arm P_o and residual power guided by input arm P_r,[12]

$$\text{E.R.} = -10\log(P_o/P_r). \qquad (6)$$

If we assume that the eigenmodes are lossless ($\beta_{ji}=0$, $j=$A,B,C), the calculated extinction ratio is shown in Fig. 4(a) (dash-dotted line) and is consistent with $|(2\beta_{\text{Cr}}-\beta_{\text{Ar}}-\beta_{\text{Br}})/(\beta_{\text{Ar}}-\beta_{\text{Br}})|$ shown by the dashed line. It is clear that, when $\beta_{\text{Ar}}-\beta_{\text{Cr}} \approx \beta_{\text{Cr}}-\beta_{\text{Br}}$ (the thickness of metal arm T_m has been adjusted to meet this equation when $D \approx 7$ μm), high extinction ratio can be achieved, which is consistent with the conventional three-arm dielectric coupler[10] and can be understood by Eq. (3). However, in reality, the losses of the eigenmodes result in the bad extinction ratio, as that shown by the solid line in Fig. 4(a).

Due to the much higher loss of eigenmodes A and B than that of C, the symmetric three-arm hybrid coupler cannot reach a high extinction ratio no matter how the structure

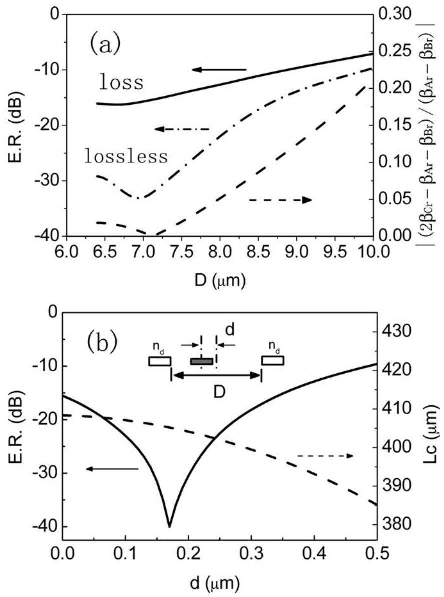

FIG. 4. (a) Extinction ratio vs distance D when considering eigenmode losses (solid line) or ignoring their losses (dashdotted line), and relation between the real part of eigenmodes effective indices $|(2\beta_{Cr}-\beta_{Ar}-\beta_{Br})/(\beta_{Ar}-\beta_{Br})|$. (b) Extinction ratio (solid line) and coupling length L_c (dashed line) for asymmetric structure when $D=7$ μm. The inset shows the asymmetric structure with the middle arm offset d.

parameters are adjusted. Fortunately, we find that by adjusting the position of the middle LRSPP arm, the extinction ratio can be improved remarkably. As shown in Fig. 4(b), in the case of $D=7$ μm, the extinction ratio increases to 40 dB with coupling loss of 1.87 dB when LRSPP arm offset $d=170$ nm. In the same figure, the dashed line shows that coupling length dose not change much with d.

The reason why asymmetric structure reaches a high extinction ratio can be analyzed as follows. Eigenmodes A and B can be considered together as an even mode, like that of the two-arm coupler[4,12] with high loss, while eigenmode C corresponds to a lossless odd mode. As shown in Fig. 5(a), for symmetric structure, even (dashed line) or odd (dotted line) mode is symmetric or antisymmetric. Therefore, the input mode (solid line) is decomposed to even and odd mode with equal energy at $z=0$. After propagation distance L_c, different transmission loss of even and odd modes results in unequal energy and thus low extinction ratio.[12] On the other hand, for asymmetric structure, even and odd modes have larger peak on different sides, as shown in Fig. 5(b). Therefore, to form the input, even mode should have more energy at $z=0$. When $z=L_c$, because of larger loss for even mode, the fields of even and odd on the left side can be almost equal with a phase difference π. Therefore, high extinction ratio can be achieved with the cost of increasing even mode loss. For example, when $D=7$ μm, with the cost of increased loss 0.25 dB (from 1.62 to 1.87 dB), 170 nm offset ($d=170$ nm) results in the increase of extinction ratio from −16 to−40 dB. Another cost of the asymmetric structure is that extinction ratio is worse than that in the symmetric case ($d=0$) when the input is applied to the right dielectric arm.

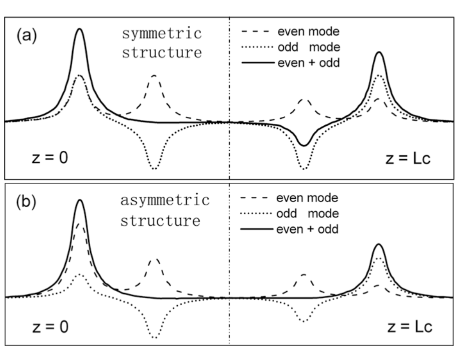

FIG. 5. Consider even and odd modes to illustrate why asymmetric three-arm hybrid coupler can reach higher extinction ratio than the symmetric. Even (dashed line) and odd (dotted line) modes and their combination (solid line) when $z=0$ and L_c for (a) symmetric and (b) asymmetric structure.

The coupling characteristics discussed above are just for TM mode. For TE mode, even and odd modes are supported by the two outside dielectric arms just as there is no middle LRSPP arm. Without the help of the middle arm, the distance between the two outside arms is very large, and the coupling length L_c of TE mode is two orders of magnitude larger than that of TM mode. Therefore, it can be considered that there is no coupling for TE mode within the TM coupling length. Thus, TE and TM modes can be separated with high extinction ratio at proper coupling length.

In conclusion, we demonstrate numerically that the high efficiency coupling of TM mode by the asymmetric three-arm hybrid coupler. Different from the conventional three-arm dielectric coupler, we find that asymmetric structure can reach a much higher extinction ratio than the symmetric one. Although the three-arm hybrid coupler has the similar coupling loss with the two-arm hybrid coupler,[8] extra transmission loss on the metal strip can be avoided because of the lossless input and output arms. The three-arm hybrid coupler is promising for realizing TE/TM mode splitter or combiner with low loss, high performance, as well as the possibility of electrical control.

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