Coupling between long range surface plasmon polariton mode and dielectric waveguide mode

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Coupling of TM mode between long range surface plasmon polariton (LRSPP) mode and conventional dielectric waveguide mode is demonstrated numerically with finite element method. The characteristics of a hybrid coupler, which consists of the LRSPP waveguide and conventional single mode dielectric waveguide, are analyzed. The high efficient coupling shows a possible route for integrating the SPP device and conventional dielectric optical devices together and a method to excite LRSPP mode with dielectric waveguide. Because the coupling just occurs on TM mode, this kind of the hybrid coupler can be used as polarization mode splitter and combiner. © *2007 American Institute of Physics.* [DOI: 10.1063/1.2719169]

Surface plasmon polariton (SPP) is transverse-magnetic surface electromagnetic excitation that propagates in a wave-like fashion along the interface between metal and dielectric medium.[1,2] It is considered as one of the routes to integrated optical devices. In particular, metal strip guided long range surface plasmon polariton (LRSPP) mode attracts much attention for its low loss[3,4] and capability of carrying optical signals and electrical signals simultaneously.[5] Meanwhile, the combination of the SPP with the conventional optical devices[6,7] is worthy of expectation in the communication and sensor field.

Both of the 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, the high loss of SPP makes them impractical. In this letter, high efficient coupling between a metal strip (LRSPP waveguide) and a conventional single mode dielectric waveguide is demonstrated theoretically. A hybrid coupler consisted of LRSPP and dielectric waveguide is proposed. Compared with the pure LR-SPP coupler[8,9] reported recently, proposed hybrid coupler has not only the advantages of the pure LRSPP coupler but also lower loss and other functions, such as exciting LRSPP mode in the integrated devices (instead of the "end-fire method"[10]), realizing high performance TE/TM mode splitter and combiner for use in optical communications and optical sensors, and so on. More importantly, the high efficient coupling between the LRSPP mode and the dielectric waveguide mode provides us a route for integrating the SPP device to conventional dielectric optical devices, and shows great potential for realizing compact, low loss, and low cost functional devices based on the planar circuit fabrication technique.

Figure 1(a) shows the simulation model for proposed lateral hybrid coupler. The propagation direction is along z axis. Different from the conventional dielectric coupler or pure LRSPP coupler,[8,9] the right arm is a metal strip (LRSPP mode waveguide) and the left arm is a dielectric waveguide. The two arms have the same width W, but different film thicknesses T_m and T_d to get similar effective index for high coupling efficiency. D stands for the distance between the

two arms. Instead of calculating the mode field of individual LRSPP waveguide and single dielectric waveguide to get coupled modes by solving the coupled-mode equations,[11] we calculate the coupled eigenmodes, even and odd eigenmodes, directly to analyze the coupling between two arms.[8,9,12] These two coupled eigenmodes are supported by the proposed hybrid coupler and solved by using the software FEMLA,[13] which implements the finite element method (FEM) to solve Maxwell's equations and can be adopted to calculate the SPP mode. The energy transfer between two arms results from the existence of the two coupled eigenmodes and their different transmission speeds. The coupling is just for TM mode because LRSPP is TM polarized.

Here, we assume a Au ($\varepsilon_m = -132 + i \times 12.65$) strip is embedded in SiO$_2$ ($n_s = 1.444$) at $\lambda_0 = 1.55$ μm,[14] with width of $W = 2$ μm and thickness of $T_m = 70$ nm. For the left arm, the dielectric waveguide can be derived from ion exchange,[15] polymer film or other method, and its refractive index is assumed as $n_d = 1.54$ here. We find that the even and odd eigenmodes can be obtained only when T_d around 393 nm. At this time, the effective index of individual LRSPP mode and dielectric waveguide mode are close. Otherwise, neither even nor odd mode can be gotten, and coupling does not occur. This conclusion is consistent with the well known coupled-mode theory.[11] By the way, the $1/e$ spot sizes of the
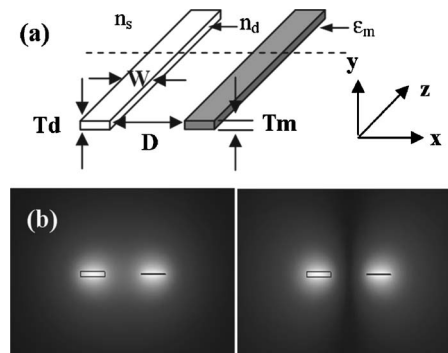

FIG. 1. (a) Parallel hybrid coupler, dark arm (right) stands for metal strip and white arm (left) stands for dielectric waveguide. The widths of the two arms are the same. (b) Amplitude of magnetic field of even and odd eignmodes supported by the hybrid coupler in the *x-y* plane. The brighter is larger in field amplitude.

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TE, TM dielectric waveguide modes, and the LRSPP mode are rather close to each other (about 3.5 μm) for the above arm sizes.

The amplitude of magnetic field for these two eigenmodes is shown in Fig. 1(b), when the arm distance $D=3$ μm. It can be seen that the patterns of the eigenmodes are similar to those of the modes supported by the pure dielectric coupler[11] and LRSPP coupler.[9] For the even mode, the magnetic field has the same direction in all the position with more concentrated field near the waveguide due to the higher effective index ($n_{eff}=\beta_r/k_0$, β_r is the real part of mode propagation constant β and k_0 is the vacuum wave number). While the odd mode has opposite field direction on the two arms and has a dip ($|H|=0$) at the center of the coupler, and it spreads farther outside the guiding region with lower effective index.

Coupling between the LRSPP mode and dielectric waveguide (TM) mode of hybrid coupler can be revealed by these two eigenmodes. Any TM mode supported by the hybrid coupler can be expressed in terms of a linear superposition of the even and odd eigenmodes,

$$\mathbf{H}(x,y,z) = a_e\mathbf{H}_e(x,y)e^{i\beta_e z} + a_o\mathbf{H}_o(x,y)e^{i\beta_o z}, \tag{1a}$$

$$\mathbf{E}(x,y,z) = a_e\mathbf{E}_e(x,y)e^{i\beta_e z} + a_o\mathbf{E}_o(x,y)e^{i\beta_o z}, \tag{1b}$$

where $\mathbf{H}_e$, $\mathbf{H}_o$ and $\mathbf{E}_e$, $\mathbf{E}_o$ are the magnetic fields and electronic fields of even, odd eigenmodes when $z=0$, $\beta_e=\beta_{er}+i\beta_{ei}$, $\beta_o=\beta_{or}+i\beta_{oi}$ are the corresponding complex propagation constants, and a_e, a_o are the corresponding mode amplitudes. The eignmode fields and propagation constants can be calculated by FEM. We consider launching the individual TM mode $\mathbf{H}_d$ ($\mathbf{E}_d$) of dielectric (left) arm as the input. Therefore, the amplitudes of the even and odd eigenmodes can be derived from[11]

$$a_i = \frac{1}{2}\int (\boldsymbol{E}_d \times \boldsymbol{H}_i^*)\cdot\hat{z}dA \quad (i=e,o), \tag{2}$$

where the integral is taken over the entire mode cross section with $dA=dxdy$. For all the modes, the fields have been normalized,

$$\frac{1}{2}\int (\boldsymbol{E}_j \times \boldsymbol{H}_j^*)\cdot\hat{z}dA = 1 \quad (j=e,o,d). \tag{3}$$

Thus, the magnetic field supported by the hybrid coupler can be expressed as

$$\mathbf{H}(x,y,z) = a_e e^{-\beta_{ei}z}\boldsymbol{H}_e(x,y)e^{i\beta_{er}z} + a_o e^{-\beta_{oi}z}\boldsymbol{H}_o(x,y)e^{i\beta_{or}z}. \tag{4}$$

Therefore, according to Eq. (4), we depict how energy couples from one arm (left) to the other (right). Figure 2 shows the intensity of the magnetic field along the dotted line in the inset, rather near the top surface of the strips. Because LRSPP mode has its maximum field value on the surface,[3] the dotted line does not cross the arm centers. When $z=0$, the coupler mode is identical to the mode guided by dielectric waveguide and with no energy guided by Au strip. When $z=L_c/2$ [$L_c=\pi/(\beta_{er}-\beta_{or})$ (Ref. 11)], the coupler mode has symmetric shape with equal energy on both arms. When $z=L_c$, almost all of the energy is guided by the Au strip and the dielectric waveguide mode transforms to
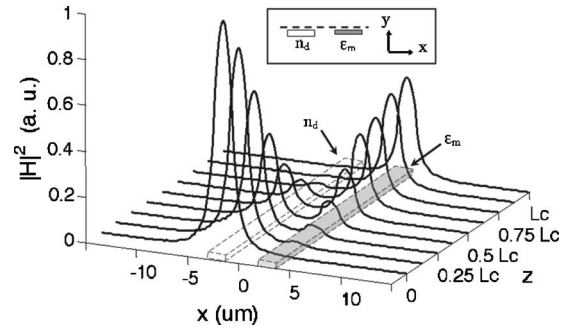

FIG. 2. Intensity of magnetic field (TM polarized) (sampled along dotted line in the inset) when energy couples from dielectric waveguide (left) to LRSPP waveguide (right) along propagation direction z when $D=3$ μm. The inset shows the x-y plane cross section of the hybrid coupler and the dotted line rather near the top surface of strips.

LRSPP mode completely. Therefore, besides end-fire method,[10] such high efficient coupling is a good method to excite LRSPP in the integrated devices.

The energy transfer shown in Fig. 2 results from the different transmission speeds of even and odd eigenmodes. The effective indices of the two modes are shown in the inset of Fig. 3(a) as a function of arm distance D. So coupling length L_c can be calculated by $L_c=\pi/(\beta_{er}-\beta_{or})$, and shown as the dashed curve in Fig. 3(b). It is noticeable that near the odd mode cutoff distance ($D=1.5$ μm), the coupling length is less than 200 μm. This is of great potential for realizing compact optical components.

The attenuation constants (β_i/k_0) of even and odd eigenmodes are shown in Fig. 3(a). This results in lower output power (transmission loss is 1.3–2.3 dB when $D=1.5$–3 μm) from the right metal arm, as that shown in Fig. 2. In the region of $D<6$ μm, the curves are identical to that of the pure LRSPP coupler.[8,9] However, in the region of $D>7$ μm, the coupling becomes weak and the situation is different. Even mode trends to the mode guided by the dielectric waveguide, and its propagation loss decreases, while odd mode trends to the LRSPP mode with increased loss. For
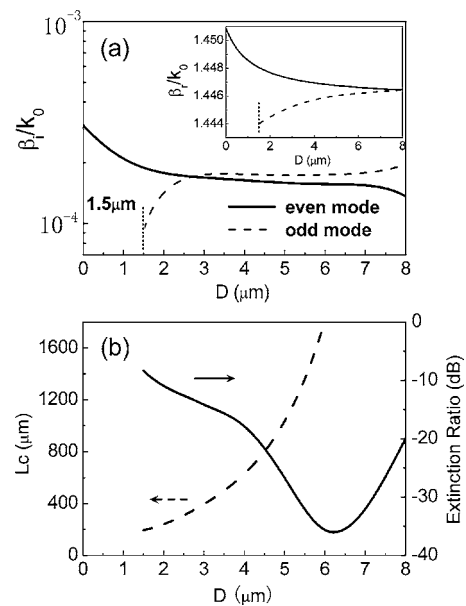

FIG. 3. (a) Normalized attenuation constants (β_i/k_0) and effective index (β_r/k_0) (inset) of even and odd modes. (b) Coupling length (dashed curve) and extinction ratio (solid curve) of hybrid coupler vs arm distance D.

the same Au strip size, the hybrid coupler has lower loss than pure LRSPP coupler. That is because about half of the fields are concentrated near the lossless dielectric waveguide. Loss of the hybrid coupler can be further reduced by thinning the thickness of the Au strip (adjusting the dielectric waveguide parameters simultaneously to match the effective index) with somewhat increasing mode size and coupling length L_c.

Although the two arms of the hybrid couplers are completely different, the field patterns of even mode (symmetric) and odd mode (antisymmetric) are rather close to those of coupler consisted by two identical arms. Therefore the extinction ratio (E.R.), which is defined as the ratio of maximum output power on the right arm and minimum power on the left when the input is launched from the left, is[11,12]

$$\text{E.R.} = \left(\frac{a_e e^{-\beta_{ei} L_c} - a_o e^{-\beta_{oi} L_c}}{a_e e^{-\beta_{ei} L_c} + a_o e^{-\beta_{oi} L_c}} \right)^2. \tag{5}$$

The cross-talk is considered resulting from the amplitude difference of even and odd eigenmodes. Figure 3(b) estimates the extinction ratio of the hybrid coupler with Eq. (5). The solid curve shows that the extinction ratio is comparative low when the arm distance D is small. This is for two reasons. First, the input mode is assumed as the individual dielectric waveguide mode to excite the even and odd eignmodes. When D is small, the field intensity on the output (right) arm is not zero at the input end for the comparative large input field size. Second, when near odd mode cutoff point ($D=1.5$ μm), the odd mode spreads farther outside the guiding region compared with even mode. So the amplitude of even mode a_e is larger than that of odd mode a_o, which leads to lower extinction ratio.[12] On the other hand, we find that the extinction ratio goes bad also in the large D region and this is different from the conventional dielectric coupler, whose extinction ratio goes better with increasing D.[11] This is easy to understand from Figs. 3(a) and 3(b) that the differences of the attenuation constants and coupling length L_c both increase with D. This enlarges the amplitude difference of even ($a_e \exp(-\beta_{ei} L_c)$) and odd mode ($a_o \exp(-\beta_{oi} L_c)$). According to Eq. (5), the extinction ratio will decrease with large D. In fact, for large arm distance D (i.e., $D>6$ μm for the selected structure parameters), the coupling length L_c and the propagation loss are too large to be used. A compact and comparative low loss hybrid coupler can be realized by adjusting D to a suitable value. If the hybrid coupler is embedded in thermo-optic materials, we can control the coupling of the TM mode with altering the effective index of the LRSPP mode by electrical signals like LRSPP couplers.[5]

The coupling between the two arms of the hybrid coupler discussed above is just for TM mode. As shown in Fig. 4, different from TM mode, there is almost no influence from the Au strip on the amplitude of magnetic field $|\mathbf{H}|$ of TE mode guided by the dielectric waveguide mode. Neither even nor odd mode does exist, namely, no coupling can occur for TE mode. If TE and TM modes are guided simultaneously by the dielectric waveguide (left) arm, TE mode will propagate through the left arm directly without feeling the LRSPP waveguide, while TM mode can be coupled to the right arm.
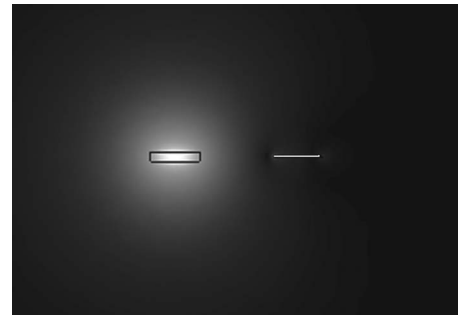

FIG. 4. Amplitude of TE polarized magnetic field supported by the hybrid coupler.

Thus, TE and TM modes can be separated with high extinction ratio at proper coupling length. It is easy to understand that polarization splitter and combiner can be realized with this hybrid coupler.

In conclusion, we demonstrate numerically the high efficient coupling between LRSPP mode and conventional dielectric waveguide TM mode. The characteristics of the hybrid coupler, which consists of dielectric waveguide and Au strip, are analyzed. Based on this hybrid coupler, it is possible to excite LRSPP mode efficiently with dielectric waveguide and realize a kind of compact, high performance, and electrical controlled TE/TM mode splitter or combiner. We expect that the high efficient coupling between LRSPP mode and conventional dielectric waveguide mode provides us a route for integrating the SPP device with conventional dielectric optical devices together and realizing functional devices.

[1] H. Raether *Surface Plasmons* (Springer, Berlin, 1988), p. 4–13.
[2] A. V. Zayats, I. I. Smolyaninov, and A. A. Maradudin, Phys. Rep. **408**, 131 (2005).
[3] P. Berini, Phys. Rev. B **61**, 10484 (2000).
[4] T. Nikolajsen, K. Leosson, I. Salakhutdinov, and S. I. Bozhevolnyi, Appl. Phys. Lett. **82**, 668 (2003).
[5] T. Nikolajsen, K. Leosson, and S. I. Bozhevolnyi, Appl. Phys. Lett. **85**, 5833 (2004).
[6] M. Hochberg, T. Baehr-Jones, C. Walker, and A. Scherer, Opt. Express **12**, 5481 (2004).
[7] P. S. Davids, B. A. Block, and K. C. Cadien, Opt. Express **13**, 7063 (2005).
[8] R. Charbonneau, C. Scales, I. Breukelaar, S. Fafard, N. Lahoud, G. Mattiussi, and P. Berini, J. Lightwave Technol. **24**, 477 (2006).
[9] H. S. Won, K. C. Kim, S. H. Song, C. H. Oh, P. S. Kim, S. Park, and S. I. Kim, Appl. Phys. Lett. **88**, 011110 (2006).
[10] R. Charbonneau, P. Berini, E. Berolo, and E. Lisicka, Opt. Lett. **25**, 844 (2000).
[11] W. P. Huang, J. Opt. Soc. Am. A **11**, 963 (1994).
[12] K. L. Chen and S. Wang, Appl. Phys. Lett. **44**, 166 (1984).
[13] COMSOL AB, Sweden, FEMLAB Electromagnetics Module Manual, 3.0 edition, 2003.
[14] E. D. Palik, *Handbook of Optical Constants of Solids* (Academic, Orlando, 1985), p. 286–297.
[15] R. V. Ramaswamy, and R. Srivastava, J. Lightwave Technol. **6**, 984 (1988).