Vertical coupling between short range surface plasmon polariton mode and dielectric waveguide mode

Ruiyuan Wan, Fang Liu, Xuan Tang, Yidong Huang, and Jiangde Peng

View online: http://dx.doi.org/10.1063/1.3111001
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/94/14?ver=pdfcov
Published by the AIP Publishing

Articles you may be interested in
Compact and broadband directional coupling and demultiplexing in dielectric-loaded surface plasmon polariton waveguides based on the multimode interference effect

Excitation of short range surface plasmon polariton mode based on integrated hybrid coupler
Appl. Phys. Lett. 97, 141105 (2010); 10.1063/1.3499269

Extremely high efficient coupling between long range surface plasmon polariton and dielectric waveguide mode
Appl. Phys. Lett. 95, 091104 (2009); 10.1063/1.3212145

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

Vertical coupling of long-range surface plasmon polaritons
Vertical coupling between short range surface plasmon polariton mode and dielectric waveguide mode

Ruiyuan Wan, Fang Liu,a) Xuan Tang, Yidong Huang, and Jiange Peng

Department of Electronic Engineering, State Key Lab of Integrated Optoelectronics, Tsinghua University, Beijing 100084, China

(Received 10 November 2008; accepted 23 February 2009; published online 7 April 2009)

Coupling performance between a short range surface plasmon polariton (SRSPP) mode and a conventional dielectric waveguide mode is demonstrated numerically. Simulation results show that the coupling length, as short as tens of microns, can be realized because the field of SRSPP extremely concentrates to the metal surface. SRSPP-based hybrid coupler provides not only an approach to realize highly compact functional devices, such as the TE-pass polarizer with high performance, but also an integratable route for efficiently exciting SRSPP mode, which is very useful in the SRSPP-based biosensor or SRSPP-assisted emission enhancement devices. © 2009 American Institute of Physics. [DOI: 10.1063/1.3111001]

Surface plasmon polariton (SPP) is a transverse-magnetic surface electromagnetic excitation that propagates along an interface between metal and dielectric medium.¹ For a thin metal film embedded in dielectrics, the SPPs on the upper and lower metal-dielectric interfaces couple and form a symmetric mode and an asymmetric mode.² The symmetric mode with field extending into the dielectrics has comparatively lower loss and is referred to as long range SPP (LRSSP).² The metal strip guided SPP modes had been studied³ and various LRSSP-based optical devices had been shown.⁴,⁵ However, the asymmetric mode, referred to as short range SPP (SRSSP) mode, receives less attention than the LRSSP mode due to its much higher propagation loss and unclear applications. Besides, for the SRSSP mode, the π phase difference between the field on the two metal film surfaces makes it nearly impossible to be excited with present integratable method.⁶,⁷

Recently, it was reported that the SRSSP mode is promising for the biosensor to detect the refractive index change in ultrathin layer with high sensitivity⁸ and the enhancement in internal quantum efficiency of silicon nanocrystals.⁹,¹⁰ Therefore an integratable excitation method for the SRSSP mode is required for its further applications. Our group has proposed the hybrid coupler structure and demonstrated the high efficient coupling between the LRSSP mode and the dielectric waveguide mode.¹⁰,¹¹ In this paper, based on a vertical hybrid coupler structure, it is theoretically demonstrated that the SRSSP mode also can be excited by using coupling property with the conventional single dielectric waveguide mode. This not only provides an efficient route for exciting SRSSP mode within a rather short length, which is very useful for the integratable SRSSP biosensor of ultrathin layer detection and the light sources with SRSSP-assisted emission enhancement structure, but also makes it possible to realize some highly compact functional devices, such as the TE-pass polarizer with much shorter length, high extinction ratio (ER), and comparatively low insertion loss (IL) due to the characteristics of the SRSSP mode.

Figure 1 shows the proposed vertical hybrid coupler. The two arms have different width, Wm and Wd, and different film thicknesses, Tm andTd, to get similar effective index for high efficient coupling. D stands for the separation between the two arms. Coupling occurs only for TM mode because SRSSP is TM polarized. Here, we assume that the Au (εm = -132 + i × 12.65) strip is surrounded by SiO₂ (n₁ = 1.444) at λ = 1.55 μm, with fixed thickness of Tm = 15 nm and width of Wm = 2 μm. SiNₐ (n₂ = 2) (Ref. 12) waveguide is chosen for the dielectric arm with Td = 220 nm and Wd = 1 μm.

The proposed coupler has two bounded TM polarized eigenmodes, mode A and B, which were calculated by using software FEMLAB.¹³ Their complex amplitudes of x-directional magnetic fields (Hx) are shown in Fig. 2, where D = 1.2 μm. Figures 2(a) and 2(c) show the 2-dimensional mode pattern of real part of Hx for mode A and B, respectively. The corresponding line profiles of field distribution across the center of two arms are also illustrated. It can be seen from both the 2D mode pattern and line profiles of field that the field surrounding the upper Au arm is antisymmetric distribution, which clearly shows the modal property of SRSSP. The eigenmode A and B arise from the in-phase and opposite-phase coupling between SRSSP and the dielectric waveguide mode, respectively.

Different from the LRSSP-based coupler,¹⁰,¹¹,¹⁴ in the case of the SRSSP, the imaginary part of the field can be comparable with the real part and should be taken into account. This is for the reason that the SRSSP mode, with field much more concentrated to the metal strip, has comparatively high loss. Figures 2(b) and 2(d) show the imaginary

![Image](image_url)

FIG. 1. Vertical hybrid coupler, white arm (upper) stands for metal strip and dark arm (lower) stands for dielectric waveguide. The right lower inset shows the x-y plane cross-section of the hybrid coupler and the dashed line crosses the center of two arms.

---

¹Electronic mail: liu_fang@mail.tsinghua.edu.cn.
part of mode A and B, respectively. By comparing (b) and (c), it can be seen that the imaginary part of mode A looks like the real part of mode B, but with smaller magnitude.

With above eigenmodes, any TM mode supported by the hybrid coupler can be expressed as follows:

\[
\mathbf{H}(x,y,z) = a_A e^{-\beta_A x} \mathbf{H}_A(x,y) e^{-\beta_A z} + a_B e^{-\beta_B x} \mathbf{H}_B(x,y) e^{-\beta_B z}.
\]  

(1)

Here, \(\mathbf{H}_A\) and \(\mathbf{H}_B\) are the complex magnetic fields of eigenmodes A and B \((z=0)\), respectively, and \(\beta_A = \beta_{A_0} - i \times \beta_{A_0}\) and \(\beta_B = \beta_{B_0} - i \times \beta_{B_0}\) are the corresponding complex propagation constants. Both of them can be calculated by software FEMLAB. At the input end, the incident field \(\mathbf{H}_0\) \((E_d)\) of individual dielectric (lower) arm is considered as a single TM mode, then the corresponding mode coupling complex coefficients \(a_A\) and \(a_B\) can be derived from

\[
a_m = \frac{1}{2} \int (E_d \times H_m)^2 dA = |a_m| e^{i\theta_m} \quad (m = A, B).
\]  

(2)

According to the unconjugated version of Eq. (11-16) in Ref. 15, all the modes are normalized and orthonormalized. Where \(|a_m|\) and \(\theta_m\) represent the magnitude of amplitude and coupling initial phase of corresponding eigenmode, respectively. Different from low-loss modes, here the phase part of the coupling coefficient \(\theta_m\) is no longer just 0 or \(\pi\), which results in complex initial amplitude of the eigenmode \(a_m\). According to Eq. (1), the intensity of the magnetic field supported by the coupler can be expressed as

\[
I(x,y,z) = \sum_m |b_m|^2 |\mathbf{H}_m(x,y)|^2 + 2b_A b_B \Re \{\mathbf{H}_A(x,y) \mathbf{H}_B^*(x,y) e^{-i\Delta \beta} \},
\]

\[
(b_m = a_m e^{-\beta_m z}, \quad m = A, B, \quad \Delta \beta = \beta_{A_0} - \beta_{B_0} \}.
\]  

(3)

According to Eq. (3), we can depict how energy couples from the lower arm to the upper arm. Figure 3 shows the intensity of the magnetic field along \(z\) direction and the real part of \(\mathbf{H}_z\) at the coupling distance \(z=L_c\). It is clearly shown that the TM mode in the lower dielectric arm transfers gradually to the SRSPP mode in the upper metal arm. This coupling characteristic provides not only a method to excite SRSPP mode, but also an approach to realize highly compact functional devices. At the coupling distance \(z=L_c = \pi/(\beta_{A_0} - \beta_{B_0})\), Eq. (3) can be simplified as

\[
I(x,y,z_c)^2 = |b_A \mathbf{H}_A(x,y) - b_B \mathbf{H}_B(x,y)|^2.
\]  

(4)

According to the field pattern in Fig. 2, Eq. (4) indicates that most of the energy has been coupled to the upper Au arm when \(z=L_c\).

The effective indices of the eigenmode A and B and the coupling length \(L_c\) are shown in the inset of Fig. 4, as a function of \(D\). It can be seen that \(L_c\) of SRSPP-based coupler could be diminished to less than 25 \(\mu\m\), which is about 1/10 of LRSPP-based coupler.10,14

It can be noticed from Fig. 3 that output power from the upper metal arm is lower than the input power because of the high loss of mode A and B, demonstrated by attenuation constant \(\beta/k_0\) (Fig. 4). When \(D<1 \mu\m\), the coupling length \(L_c\) is relatively short [19–31 \(\mu\m\) when \(D = 0.7–1 \mu\m\) (inset of Fig. 4)]. In this case, the transmission loss within \(L_c\) is comparatively low. When \(D>1.2 \mu\m\), the coupling becomes weak and \(L_c\) increases dramatically, which results in high transmission loss over 10 dB. Therefore, compared with LRSPP-based coupler, high efficient coupling should be operated under much smaller \(D\) due to the tightly bounded SRSPP mode. Both smaller arm separation and shorter coupling length are significant for realizing highly compact optical components. Here, we ignore the coupling between LRSPP mode and dielectric waveguide mode because the significantly large effective index difference between LRSPP mode and SRSPP mode supported by thin metal strip makes

FIG. 2. Complex amplitudes of \(H_x\) of two TM eigenmodes in \(x-y\) plane. (a) and (b) shows real and imaginary part of mode A. (c) and (d) shows real and imaginary part of mode B. The line profiles are corresponding 1D field distribution along the dash line shown in inset of Fig. 1.

FIG. 3. Intensity of TM polarized magnetic field (sampled along dashed line in the inset of Fig. 1) as a function of propagation length \(z\) when \(D = 1 \mu\m\). The left upper inset shows the TE mode directly passing through the dielectric arm. The line profile is the real part of \(H_z\) at the coupling distance \(z=L_c\).

FIG. 4. Attenuation constants \((\beta/k_0)\) of mode A (solid curve), mode B (dashed curve), and TE mode (dot-dashed curve) vs arm separation \(D\). Inset shows corresponding effective index of each mode as well as coupling length (dotted curve).
it difficult to get effective coupling for LR-SPP mode to
dielectric waveguide which has been designed to couple with
the SR-SPP mode.

Coupling characteristics between the two arms of the
hybrid coupler discussed above is just for TM mode. For the
TE mode guided by dielectric arm, no coupling can occur.
The influence of Au arm can be ignored for relatively large
D, while when D becomes smaller, the influence of Au arm
gets noticeable. In the region of D < 0.6 μm, the attenuation
of TE mode increases and the effective index decreases dra-
matically, and the cutoff distance is found at D = 0.25 μm
(Fig. 4).

According to the coupling and loss characteristics ana-
yzed above, a compact polarizer can be realized. Let us
consider that TE and TM modes are input into the dielectric
arm simultaneously, the TE mode will pass directly through
the dielectric arm (inset of Fig. 3), while the TM mode will
be filtered rapidly within a very short transmission length
due to the coupling between two arms. Therefore, high TM
ER and low TE IL can be realized.

At the output end z = L, coupling coefficient between the
coupled mode and individual dielectric waveguide TM mode
\[a_L = \frac{1}{2} \int \left[ E_d \times H(x,y,L) \right]^2 dA \]
\[= \sum_m |a_m|^2 e^{-\beta_m L} e^{(2\beta_m - \beta_{mL})}, \quad (m = A,B). \] (5)

Therefore the total loss of TM mode is determined by
−20 lg |a_L|. For TE mode, the similar formula could be cal-
duced. Here loss of TM mode approximately represents the
ER, and that of the TE mode represents the IL.16

Using Eq. (5), the ER of TM mode with D = 0.8 and
1.15 μm as a function of the coupler length L were calcu-
lated, respectively (Fig. 5). It can be seen that the ER curve
of TM mode increases rapidly along L with a strong ripple.
The ripple indicates the coupling between the dielectric
mode and SR-SPP mode or the interference of eigenmodes A
and B. The peak corresponds to the position where the TM
mode transforms almost to the SR-SPP mode. The period of
the beat is in close agreement with 2L. However, as seen in
Eq. (2) and (5), the difference in the phase of complex
coupling coefficients (Δθ = θ_A − θ_B) resulting in nonzero coupling
induced phase difference between two eigenmodes. There-
fore the position of first peak appears at \[z = (\pi + 2\Delta \theta) / (\beta_A \neq \beta_B),\] which is a little longer than Lc.

Compared with conventional SPP-based TE-pass wave-
guide polarizer,16,17 the proposed polarizer can have shorter
device length, high ER, and comparatively low TE IL. Since
the SR-SPP mode has much higher loss than general SPP
modes, the ER for TM mode increases rapidly along L. In
addition, due to the concentrated field of SR-SPP mode, small
arm separation D can be adopted to achieve extremely short
coupling length. It is noticeable in Fig. 5 that the ER is high
up to 20 and 30 dB at the first peak position when D = 0.8
and 1.15 μm, with the transmission length is only about 25
and 50 μm, respectively. Benefit from such short device
length, the IL of TE mode can be comparatively low. Take
D = 1.15 μm, for example, the IL of TE mode is only about
0.1 dB when L = 50 μm (Fig. 5). Therefore, TE-pass polar-
izer with high performance and rather short length could be
realized. Furthermore, it is estimated that device size can be
further reduced with thinner metal thickness, since increased
loss for TM mode caused by more concentrated field of SR-
SPP mode make it easier to obtain high ER in shorter length,
so long as we decreased D to maintain the strong coupling.

In conclusion, we demonstrate numerically the high ef-

ciency coupling between SR-SPP mode and conventional
dielectric waveguide TM mode. The proposed coupler has
rather compact size because the field of SR-SPP extremely
concentrates to the metal surface. Simulation results show
that the length of SR-SPP-based coupler can be as short as
tens of microns. This provides not only an approach to real-
ize highly compact functional devices, such as the TE-pass
polarizer with much shorter length, high ER, and compara-

tively low IL, but also an integratable route for efficiently
exciting SR-SPP mode, which solves the bottleneck for the
SR-SPP-based integratable biosensor and SR-SPP-assisted
emission enhancement devices.

This work is supported by the 973 Program of China
under Contract No. 2007CB307004. The authors would like
to thank Professor Wei Zhang, Xue Feng, and Yi Rao, as well
as Mr. D. Ohnishi, H. Takatsu, and A. Kamisawa of ROHM
Corporation for their helpful comments.

\[1^H. \text{Raether}, \textit{Surface Plasmons} \textit{(Springer, Berlin, 1988)}, \text{pp. 4–13.} \]
\[2^J. \text{J. Burke and G. I. Stegeman, Phys. Rev. B} \textit{33}, 5186 \text{(1986).} \]
\[3^P. \text{Berini, Phys. Rev. B} \textit{61}, 10484 \text{(2000).} \]
\[4^T. \text{Nikolaansen, K. Leosson, and I. Bozhevolnyi, Appl. Phys. Lett.} \textit{85}, 5833 \text{(2004).} \]
\[5^R. \text{Charbonneau, C. Scales, I. Breukelaar, S. Fafard, N. Lahoud, G. Mat-
iussi, and P. Berini, J. Lightwave Technol.} \textit{24}, 477 \text{(2006).} \]
\[7^J. \text{J. T. Hastings, Opt. Express} \textit{15}, 17661 \text{(2007).} \]
\[8^X. \text{Hu, Y. Huang, W. Zhang, and J. Peng, Appl. Phys. Lett.} \textit{89}, 081112 \text{(2006).} \]
\[9^X. \text{Tang, Y. Huang, Y. Wang, W. Zhang, and J. Peng, Appl. Phys. Lett.} \textit{89}, 241116 \text{(2008).} \]
\[10^F. \text{Liu, Y. Rao, Y. Huang, W. Zhang, and J. Peng, Appl. Phys. Lett.} \textit{90}, 141101 \text{(2007).} \]
\[12^M. \text{M. Tilleman, D. Haronian, and D. Abraham, J. Microlithogr., Micro-
fabr., Microsystems} \textit{5}, 023001 \text{(2006).} \]
\[13^COMSOL AB, PLEMLAB RF module model library, 3.3 edition, Sweden, \textit{2006.} \]
\[15^W. \text{S. Snyder and J. D. Love, \textit{Optical Waveguide Theory} \textit{(Cambridge, Lon-
don, 1983)}, pp. 212–214.} \]
\[17^P. \text{S. Davids, B. A. Block, and K. C. Cadien, Opt. Express} \textit{13}, 7063 \text{(2005).} \]