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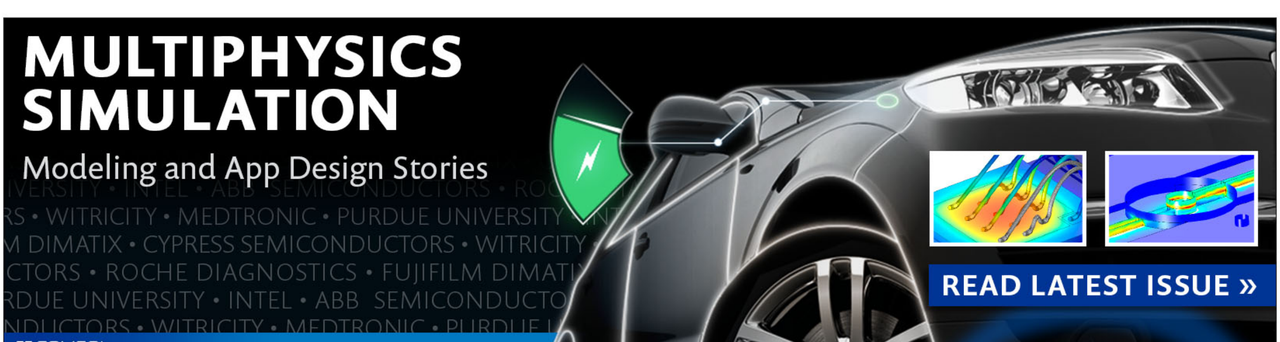

Excitation of short range surface plasmon polariton mode based on integrated hybrid coupler

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The short range surface plasmon polariton (SRSPP) mode, which has an antisymmetric field profile on the two sides of a thin metal film, has been excited efficiently based on an integrated vertical hybrid coupler. The coupler is composed of an Au (SRSPP) waveguide and a SiN_x (dielectric) waveguide. Highly efficient coupling between the SRSPP mode and conventional dielectric waveguide mode was demonstrated. A compact (less than 90 μm long) polarizer with a low TE insertion loss and high TM extinction ratio up to 30 dB was realized by utilizing different characteristics of the TE and TM modes in the hybrid coupler. © *2010 American Institute of Physics*. [doi:10.1063/1.3499269]

Surface plasmon polariton (SPP) is a transverse-magnetic surface electromagnetic excitation that propagates along an interface between a metal and a dielectric medium.[1] A thin metal film embedded in a dielectric can support both a long range SPP (LRSPP) and a short range SPP (SRSPP) mode since there is coupling between the SPP modes on the both sides of the metal film.[2] Compared with the LRSPP, the SRSPP has much higher transmission loss and a more compact mode size. Recently, it was reported that the SRSPP is promising as a biosensor to detect surface refractive index change[3–5] and for enhancement of the internal quantum efficiency of silicon nanocrystals.[6,7] However, due to its antisymmetric distribution of mode field, the SRSPP is hard to excite with presently integratable methods,[8] which limits its applications in integrated optical devices.

Recently, our group theoretically demonstrated that the SRSPP mode can be excited efficiently based on a vertical hybrid coupler composed of a thin metal film and dielectric waveguide, which developed an integrated route to excite a SRSPP mode.[9] In this paper, fabrication and measurement results of a vertical SRSPP-SiN_x hybrid coupler are presented. Highly efficient coupling between the SRSPP and a SiN_x waveguide fundamental TM mode has been observed with a coupling length as short as 30 μm, which is promising for realizing highly integrated SRSPP-dielectric hybrid devices. A compact (less than 90 μm long) polarizer with a low TE insertion loss and high TM extinction ratio up to 30 dB was realized by utilizing different characteristics of the TE and TM modes in the hybrid coupler.

Figure 1(a) shows the schematic structure of the vertical hybrid coupler, which is composed of an Au strip (SRSPP waveguide) and a SiN_x strip (dielectric waveguide) surrounded by SiO_2. The cross section of the hybrid coupler and the detailed structure parameters are illustrated in Fig. 1(b).

To realize the hybrid coupler, a Si wafer with 15 μm thick SiO_2 ($n_{sub}=1.446$) on the surface was selected as the substrate. On the substrate, a layer of SiN_x ($n_d=1.92$) with a thickness of $T_d=180$ nm was deposited by plasma-enhanced chemical-vapor deposition (PECVD). After standard UV lithography, reaction ion etching and photoresist removal, SiN_x strips with a width of $W_d=5$ μm were obtained. Then, a $D=1.29$ μm thick SiO_2 ($n_{cml}=1.448$) layer was deposited by PECVD on the SiN_x strips to complete the fabrication of the SiN_x waveguide section. After that, Au strips with width $W_{Au}=8$ μm were fabricated above the SiN_x waveguide by cover-lithography, magnetic sputtering and lift-off process. Finally, a 5 μm thick SiO_2 ($n_{sup}=1.448$) layer was deposited by PECVD as the superstrate. A photo of the completed SRSPP-SiN_x coupler is shown in Fig. 1(c), where the wider and shorter strip is the SRSPP waveguide, and the narrower

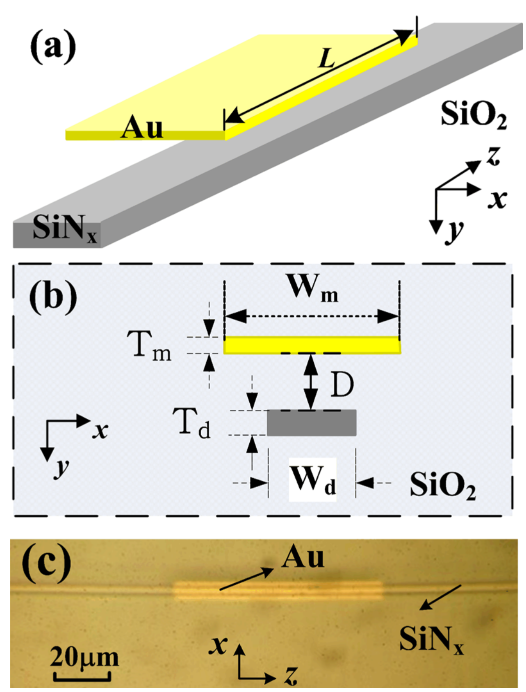

FIG. 1. (Color online) (Color online) (a) Schematic structure of a SRSPP-SiN_x vertical coupler with Au strip (wider and shorter) and SiN_x strip (narrower and longer) embedded in SiO_2. (b) Cross section of this vertical coupler in the *x-y* plane. (c) Photo of the hybrid coupler in the *x-z* plane under an optical microscope.

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and longer one is the SiN_x waveguide. Here, samples with different thicknesses and lengths of Au strip were fabricated to study the coupling characteristics between the SRSPP and SiN_x waveguide mode.

In contrast with the LRSPP mode, the SRSPP mode is difficult to directly observe at the facet of the Au strip because of its high transmission loss and antisymmetric mode pattern. Therefore, an indirect method was adopted by measuring the output power P_{out} of the SiN_x strip with different lengths of Au strip L. According to the simulation results,[9] the P_{out}-L curve indicates the coupling characteristics between the SRSPP mode and SiN_x waveguide mode, as well as the excitation of SRSPP mode. Here the chip was cut into 2.5 mm long pieces for easier measurement though the length L of the vertical hybrid coupler is only tens of micron. The measurement system consists of a laser emitting at a wavelength of 1.55 μm, a polarization controller, an input tapered lens fiber, a precise fiber alignment system controlled by computer, an output tapered lens fiber, and a power meter.

By fixing the input and output fiber to the center of both facets of the SiN_x waveguide, the SRSPP-SiN_x hybrid coupler was measured. First, with TE polarization as the input, it was found that the variance of the output power when changing the Au strip length (L) and the thickness (T_m) of Au strip was rather small. Taking the coupler with T_m=27 nm for example, the coupling loss between the tapered fiber and SiN_x waveguide TE mode is around 2.23 dB and the TE mode transmission loss of the coupler is as low as 2.02 dB/mm. For a 100 μm long coupler, the TE insertion loss (here determined only by the transmission loss[9,10]) is about only 0.2 dB. Such low TE insertion loss is consistent with the theoretical prediction that there is no coupling between the SRSPP and the TE mode of SiN_x waveguide.[9] Therefore, when studying the coupling between the SRSPP mode and the TM mode of SiN_x waveguide, the output power of latter (P_{TM}) could be normalized by that of the TE mode (P_{TE}) to eliminate the influence of the alignment between input/output fiber and the SiN_x waveguide. Then a TM input was use to measure P_{TM}/P_{TE} with different L and T_m.

Figure 2 shows the measurement and simulation results of the P_{TM}/P_{TE} (decibel) output from SiN_x arm versus the length of the Au arm L, which was normalized by the output power ratio P_{TM0}/P_{TE0} (=2.51 dB) of a single SiN_x waveguide (equivalently L=0 μm). When T_m=27 nm, the red square marks shown in Fig. 2(a) illustrate that the P_{TM}/P_{TE} curve declines rapidly along L with strong dips, which corresponds to the highly efficient energy coupling between the SRSPP mode supported by the Au strip and the TM mode of the SiN_x waveguide. Two dips appear for the samples with length around L=30 μm and L=90 μm, respectively, both of which indicate that the power has almost completely transferred from the SiN_x waveguide to the Au strip, and the coupling length is as short as about 30 μm. The SRSPP mode has been excited efficiently for a length around L=30 μm and L=90 μm.

The measurement results match the simulation results (shown as the blue dots in Fig. 2) well. Due to our proper design, the intensities of eigenmodes are evenly distributed around two waveguides [shown in the inset of Fig. 2(a)], resulting in high coupling efficiency and thus the large amplitude in coupling curve. Such a short coupling length and high loss (the slope of the curve) indicate that a SRSPP has

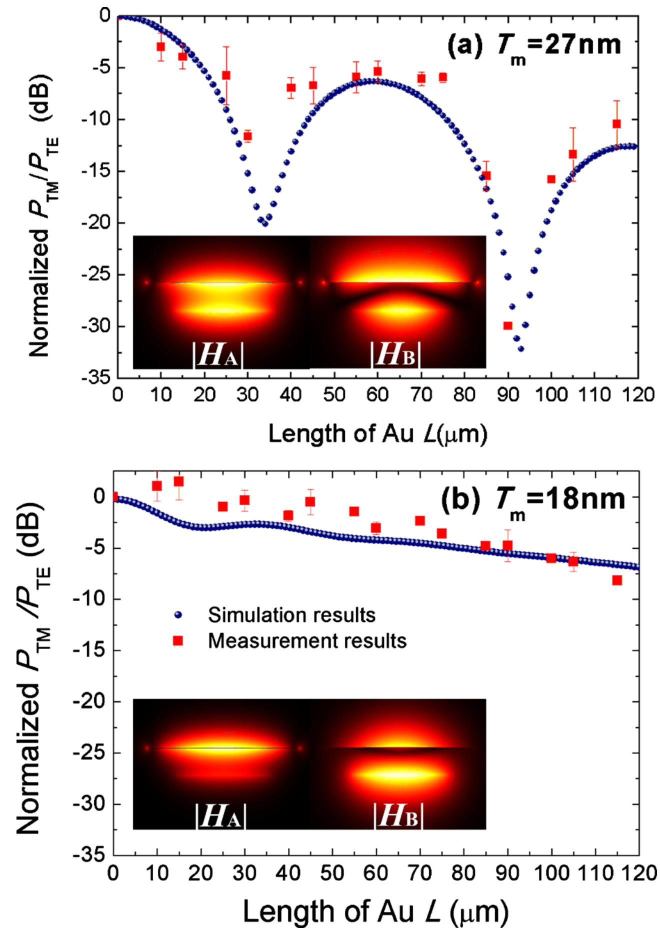

FIG. 2. (Color online) The measured (red squares with error-bar) and simulated (blue dot) output P_{TM}/P_{TE} ratio as a function of SiN_x arm vs the length of Au arm L when the thickness of Au (a) T_{Au}=27 nm, (b) T_{Au}=18 nm. Here, all the input was applied on the SiN_x arm. The insets are the simulated pattern of corresponding magnetic field $|H|$ of the two coupled TM eigenmodes.

been excited instead of a LRSPP mode when T_m is only 27 nm. Based on this experimental result, a highly compact polarizer (90 μm long) has been realized with a TE insertion loss as low as 0.18 dB and a TM extinction ratio as high as 30 dB at wavelength of 1.55 μm. Similar to the wavelength dependence of a LRSPP hybrid coupler (shown as Fig. 5 in Ref. 11), this SRSPP coupler-based polarizer also has a large bandwidth, which will be discussed in detail in another paper.

As a comparison, Fig. 2(b) shows that there is little coupling between the SRSPP and the TM mode of a SiN_x waveguide when T_m=18 nm. In this case, the eigenmodes have a large asymmetric field distribution on the two arms [as shown in the inset of Fig. 2(b)], and the SRSPP mode could not be excited efficiently, which is accompanied by a smaller slope in the P_{TM}/P_{TE} curve. Therefore, the experimental results confirm that the higher the SRSPP-SiN_x coupling efficiency is, the stronger the ripple will be in the P_{TM}/P_{TE}-L curve accompanied by a larger TM loss.

Furthermore, the output power distribution of a SiN_x waveguide for different coupler lengths L has been measured. The black solid-dot curve in Figs. 3(a)–3(e) shows the corresponding normalized TM output power profile when scanning the output fiber along the x-direction. There are two obvious peaks in the output power profile in Figs. 3(a)–3(e).

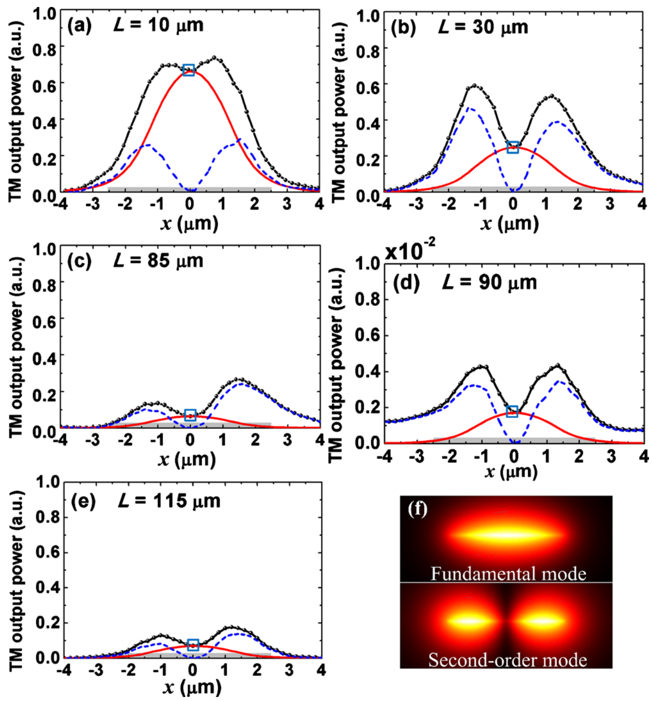

FIG. 3. (Color online) Measured TM output power profile (black solid-dotted curve) along the x-direction of the SiN_x waveguide, which can be fit by the combination of the fundamental (red solid curve) and second-order mode (blue dashed curve), when the coupler length (the length of Au strip) is L=(a) 10, (b) 30, (c) 85, (d) 90, and (e) 115 μm. The power profile in Fig. 3(d) is amplified 100 times to show the power distribution clearly. The blue box in the black solid-dotted curve at $x=0$ μm labels the corresponding output power shown in Fig. 2. And (f) shows the simulated TM magnetic field $|\boldsymbol{H}|$ pattern of the fundamental and second-order mode of the SiN_x waveguide.

which can be approximately divided into fundamental and second-order TM modes, shown as the red solid and blue dashed curve, respectively. The second-order TM mode was excited because of the imperfect symmetry of the SiN_x waveguide and an offset between the center axis of the input fiber and the SiN_x waveguide. If the output tapered fiber was fixed at the center of the SiN_x waveguide, the output power of the fundamental mode can be measured at $x=0$, shown as the black dot in the blue square in Figs. 3(a)–3(e). Therefore, we can derive its dependence on the coupler length L and study the coupling characteristics between the SRSPP and the fundamental TM mode (corresponding to the measurement results in Fig. 2) with the minor influence of the second order TM mode. Of course, the higher order TM mode can be removed if the parameters of the SiN_x waveguide are adjusted to only support fundamental TM mode.

In conclusion, a vertical SRSPP hybrid coupler has been fabricated and measured. High coupling efficiency between the SRSPP and the SiN_x waveguide's TM mode has been observed with a coupling length as short as 30 μm. Meanwhile, a highly compact polarizer has been realized with a TM extinction ratio as high as 30 dB within a 90 μm length. These indicate that the SRSPP mode has been excited efficiently using an integratable approach, and it is promising to make use of this mode for highly compact optoelectronic functional devices, such as a SRSPP-assisted light emitting device,[6,7] highly sensitive refractive index detection of a ultrathin layer,[12] and so on.

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[1]J. J. Burke and G. I. Stegeman, Phys. Rev. B **33**, 5186 (1986).
[2]P. Berini, Phys. Rev. B **61**, 10484 (2000).
[3]P. Berini, New J. Phys. **10**, 105010 (2008).
[4]J. Guo, P. D. Keathley, and J. T. Hastings, Opt. Lett. **33**, 512 (2008).
[5]M. Vala, J. Dostálek, and J. Homola, Proc. SPIE **6585**, 658522 (2007).
[6]X. Hu, Y. Huang, W. Zhang, and J. Peng, Appl. Phys. Lett. **89**, 081112 (2006).
[7]X. Tang, Y. Huang, Y. Wang, W. Zhang, and J. Peng, Appl. Phys. Lett. **92**, 251116 (2008).
[8]W. K. Burns and G. B. Hocker, Appl. Opt. **16**, 2048 (1977).
[9]R. Wan, F. Liu, X. Tang, Y. Huang, and J. Peng, Appl. Phys. Lett. **94**, 141104 (2009).
[10]T. Nakano, K. Baba, and M. Miyagi, J. Opt. Soc. Am. B **11**, 2030 (1994).
[11]F. Liu, R. Wan, Y. Li, and Y. Huang, Appl. Phys. Lett. **95**, 091104 (2009).
[12]R. Wan, F. Liu, and Y. Huang, Opt. Lett. **35**, 244 (2010).