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Novel Dielectric Loaded Plasmonic Waveguide for Tight-Confined Hybrid Plasmon Mode

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Abstract

In this letter, a novel metal-dielectric waveguide structure is proposed to support hybrid long range surface plasmon polaritons with a highly confined mode field. The simulation results showed that our proposed structure has better mode confinement and propagation length compared to that of conventional dielectric-loaded surface plasmon polaritons waveguides. This structure offers greater flexibility for the design of SPPs waveguides by altering the trade-off between mode confinement and propagation length. The proposed structure has significant potential for application in highly

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Novel Dielectric-Loaded Plasmonic Waveguide for Tight-Confined Hybrid Plasmon Mode

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Received: 22 December 2012 / Accepted: 4 March 2013

Abstract In this letter, a novel metal-dielectric waveguide structure is proposed to support hybrid long range surface plasmon polaritons with a highly confined mode field. The simulation results showed that our proposed structure has better mode confinement and propagation length compared to that of conventional dielectric-loaded surface plasmon polaritons waveguides. This structure offers greater flexibility for the design of SPPs waveguides by altering the trade-off between mode confinement and propagation length. The proposed structure has significant potential for application in highly integrated photonic circuits.

Keywords Surface plasmon resonant · Optical waveguide · Dielectric-loaded plasmonic waveguide

In this paper, a novel metal-dielectric waveguide structure is proposed to support hybrid long range surface plasmon polaritons (LRSPPs) with a highly confined mode field. The simulation results showed that our proposed structure has better mode confinement and propagation length compared to that of conventional dielectric-loaded surface plasmon polaritons (DLSPPs) waveguides. This structure offers greater flexibility for the design of surface plasmon polaritons (SPPs) waveguides by altering the trade-off between mode confinement and propagation length. The proposed structure has significant potential for application in highly integrated photonic circuits.

The future development of optical communication systems will drive a requirement for high-density integration of photonics devices [1]. SPPs, which are electromagnetic waves (EMs) coherently coupled to electron oscillations and propagating at the interface between a dielectric and a metal conductor, can confine EMs at the subwavelength scale beyond the diffraction limit [2, 3] and therefore become ideal candidates for light guiding and confining in highly integrated optical circuits [4]. Recently, various plasmonic waveguides which provide nanoscale confinement have been proposed and investigated, such as a metal–insulator–metal waveguide [5], V-groove channel [6], and plasmonic wire waveguide [7]. These waveguides can significantly enhance the field confinement, but the associated decrease in the propagation length due increased absorption is often unacceptable. To achieve a long propagation length, the confinement will have to be relaxed but this will impact on the potential for high density integration. For example, in so-called long-range SPPs (LRSPPs), where guiding takes place by a thin metal film embedded in infinite homogeneous background dielectrics, it is possible to achieve a low propagation loss over a propagation length of a few millimeters [8]. However, as the LRSPPs mode size is in the order of a few micrometers, which causes significant bend loss in structures with tight

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bends or small radii with the optimal bend radius is as large as 10 mm [9], so that such devices are not suitable for high density photonic integration.

In order to optimize the tradeoff between the mode confinement and propagation length for SPPs [10], a DLSPPs waveguide with a reduced mode size (effective mode size of 1 μm) and a moderate propagation length at telecom wavelengths were recently proposed and shown to support a hybrid LRSPPs mode[11, 12]. The DLSPPs structure is very attractive as a plasmonic waveguide as it enables easy access to metal electrodes and thus offers the possibility of inducing electro- or thermo-optic effects in the waveguide components [12]. Recently, a hybrid LRSPPs waveguide consisting of a narrow metal film surrounded by low index dielectric regions has been theoretically analyzed, demonstrating a doubling of the propagation length (~756 μm) compared to that of a conventional structure (~356 μm) at expense of weaker mode confinement (i.e., the mode size increases 20 %) [13].

In this paper, a novel hybrid plasmonic waveguide offering lower loss but with a higher degree of mode confinement is proposed and investigated. The waveguide utilizes the dielectric configuration of DLSPPs but with an altered metallic structure to give a longer propagation length for the same mode confinement and a tighter mode confinement for the same propagation length, which offers greater flexibility in the design of SPPs waveguides by altering the trade-off between mode confinement and propagation length and hence has significant application potential in highly integrated photonic circuits.

Figure 1 shows a cross-sectional view of the proposed plasmonic waveguide, which consists of a thin metal film (with thickness *d* and width *g* in the central region, and thickness *h* at both sides) symmetrically embedded inside a dielectric ridge with thickness *H* and width *G* surrounded by air. For such a symmetrical configuration, the index matching condition is satisfied so that a hybrid LRSPPs mode is supported. As shown in Fig. 1, the dielectric material is chosen to be Si_3N_4, which has been commonly used by other authors. This dielectric material has a refractive index of $n_r=2.0$, and gold is used as the metal with refractive index $n_m=0.55+11.5i$ at the optical communication wavelength of $\lambda_0=1550$ nm. In the numerical simulations, the finite element method [14] is adopted to analyze the characteristics of the hybrid LRSPPs mode. The propagation length of the hybrid LRSPPs mode is calculated as $L_p=\lambda_0/[4\pi\ \mathrm{Im}(n_{eff})]$, where $\mathrm{Im}(n_{eff})$ is the imaginary part of the complex effective mode index n_{eff}. The key parameter demonstrating the mode confinement capability is the normalized mode area *S*, which is defined by the formula $S=S_{\mathrm{eff}}/S_0$. Here, S_0 is the diffraction limited mode area ($S_0=\lambda_0^2/4$), and the effective mode area S_{eff} is calculated using the following equations [15]:

$$S_{\mathrm{eff}}=\left(\iint W\left(\vec{r}\right)dS\right)^2\Big/\left(\iint W\left(\vec{r}\right)^2dS\right) \quad (1)$$

$$W\left(\vec{r}\right)=\frac{1}{2}Re\left\{\frac{d\left[w\varepsilon\left(\vec{r}\right)\right]}{dw}\right\}\left|E\left(\vec{r}\right)\right|^2+\frac{1}{2}u_0\left|H\left(\vec{r}\right)\right|^2 \quad (2)$$

where *r* is the coordinate, *ω* is angular frequency of the incident light, $\left|E\left(\vec{r}\right)\right|^2$ and $\left|E\left(\vec{r}\right)\right|^2$ are the intensities of electric and magnetic fields, respectively, $\varepsilon\left(\vec{2}\right)$ is the dielectric permittivity and μ_0 is the vacuum magnetic permeability.

Firstly, the relationship between the hybrid LRSPPs mode and the gold film thickness *h* was investigated for a conventional DLSPP plasmonic waveguide (i.e., $d=h$ in Fig. 1). Figure 2 gives the calculated L_p and *S* versus gold thickness.

As shown in Fig. 2, both the propagation length L_p and normalized mode area *S* of the hybrid LRSPPs mode increases as the thickness of the metal film decreases. As expected, since a larger normalized mode area corresponds to a lower degree mode confinement [15], there is a trade-off between the mode confinement and propagation length. For example, increasing the metal film thickness can result in a better field confinement, but will introduce higher transmission loss. Conversely a decrease in the metal film thickness can enhance the propagation length, but will degrade the mode confinement. In order to improve the trade-off conditions, e.g., to achieve longer propagation length for the same

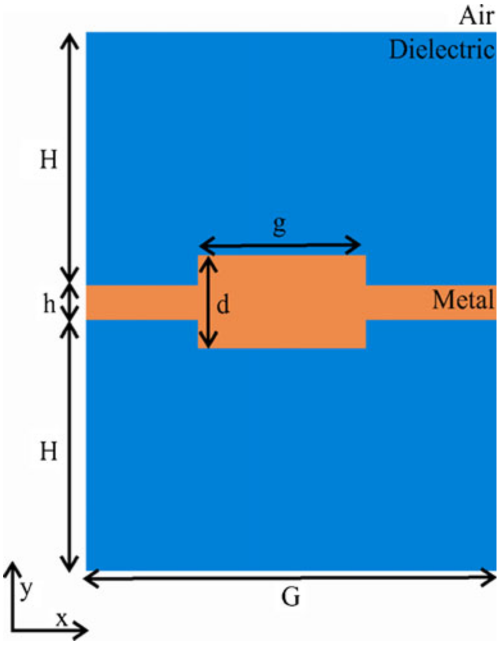

Fig. 1 (Color online) Schematic diagram of the cross-section of proposed DLSPPs waveguide. When *d* equals to *h*, i.e., $d=h$, the structure becomes a conventional DLSPPs waveguide

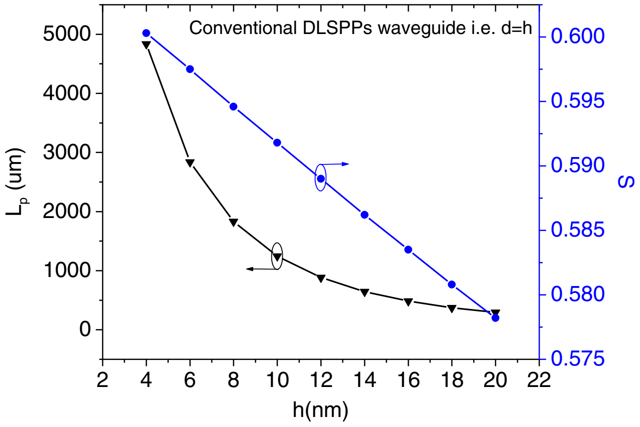

Fig. 2 (Color online) The propagation length L_p and normalized mode area S versus thickness h of the metal film. In this case, H=400 nm, G=600 nm

degree of mode confinement (or alternatively, a tighter field confinement for the same propagation length), a patterned metal film thickness structure is proposed, where $d \neq h$ in Fig. 1, and is analyzed.

In our simulation, two sets of fixed parameters are used for our proposed structure: H=400 nm, G=600 nm, h=4 nm, g=300 nm and H=400 nm, G=600 nm, h=10 nm, g=300 nm, respectively, corresponding to typical values for such dimensions commonly used by other authors to satisfy the requirements of highly integrated photonic devices needing both tight mode field confinement and long propagation length [11]. Figure 3 shows simulated results of the dependence of the hybrid LRSPPs mode of the proposed structure (L_p and S) on the geometric parameter d. The results for the conventional structure (d=h) are also provided in Fig. 3 for comparison.

From Fig. 3, it can be seen that for the same value of L_p, the value of S is lower (i.e., better mode confinement) for our proposed structure as long as d>h. However for the simulation with a larger value of h (h=10 nm, the red curve in Fig. 3), we find that the advantage of the proposed structure is lower as h increases, and in fact beyond a value of L_p=1,246 μm, the proposed structure has a higher value of S (i.e., worse mode confinement).

An alternative view is that for the same value of S, the value of L_p is higher for our proposed structure while d>h. For example for S=0.58, the value of L_p is 1037 μm (violet curve in Fig. 3) for our proposed structure, which is far longer than that of 349 μm for the conventional structure. However, for the simulation with a larger value of h (red curve in Fig. 3), it is found that the merit of the proposed structure is reduced as h increases, i.e., for h=10 nm, at S=0.58, the value of L_p is only marginally higher that for the conventional structure. Also, we know that beyond a value of S=0.5918, the proposed structure actually has a lower value of L_p.

In addition, the influence of the dimension g on the hybrid LRSPPs mode of the proposed structure (L_p and S) was investigated and simulation results are as shown in Fig. 4. In this simulation, two sets of parameters were selected with H=400 nm, G=600 nm, h=4 nm, d=20 nm and H=400 nm, G=600 nm, h=10 nm, d=20 nm. The corresponding results for the conventional structure are also provided in Fig. 4 for comparison.

As shown in Fig. 4, the performance of the hybrid LRSPPs mode is highly dependent on the value of g. The tightest mode confinements can be achieved at g=300 nm for both values of h selected. As in Fig. 3, a lower value of h is better. For example, for the same value of S=0.578, the

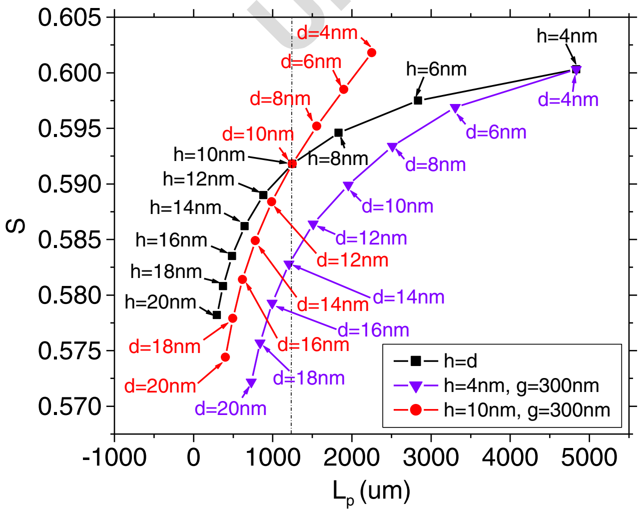

Fig. 3 (Color online) The normalized mode area S as a function of the propagation length L_p for the conventional and proposed structure

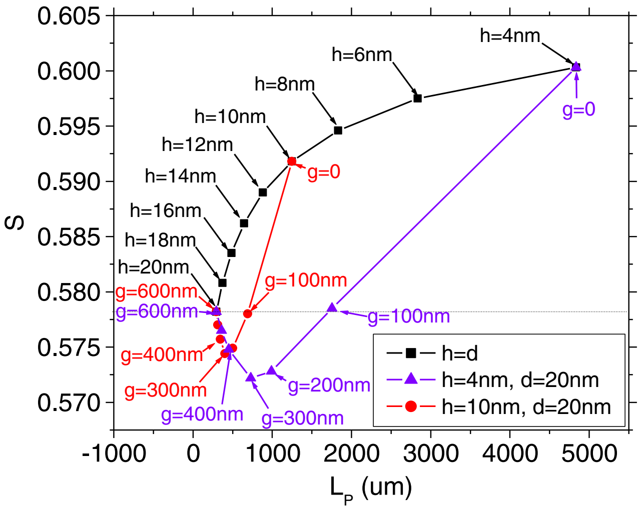

Fig. 4 (Color online) The normalized mode area S versus the propagation length L_p for the conventional and proposed structure

structure with h=4 nm, g=100 nm, and d=20 nm has a propagation length of Lp=1753 μm compared to a value of Lp=689 μm for the structure with h=10 nm, g=100 nm, and d=20 nm. It should be noted that both proposed structures have substantially longer propagation lengths than of the value of 295 μm for the conventional structure.

Based on the results shown in Figs. 3 and 4, we have shown that the proposed DLSPPs waveguide offers a degree of flexibility in the design of SPPs that can achieve both a long propagation length and tight mode confinement simply by appropriately selecting the parameters g, h, and d.

In future optical communications systems, in order to achieve high-integration density, it is essential to develop ultracompact photonic devices and subsystems. However, photonic subsystems with a high integration density are restricted by the crosstalk between the adjacent waveguides, as well as the parameter of coupling length.

Figure 5a shows the calculated coupling length L_c as a function of separation distance D for two parallel waveguides for different configurations: two horizontally parallel waveguides and two vertically parallel waveguides. The parameters used in the simulation are set as H=400 nm, G =600 nm, h=10 nm, d=20 nm, and g=300 nm. For comparison purposes, the coupling lengths for the conventional structures with d=h=10 nm was also provided in Fig. 5a. The coupling length is given by $L_c=\pi/(\beta_s-\beta_a)$, where β_s and β_a are the propagation constants of the symmetric and anti-symmetric modes of the two adjacent waveguides, respectively. Figure 5b–e are the simulated amplitude distributions of E_y based on our proposed structure. Figure 5b and c show the amplitude distributions of E_y for symmetric and anti-symmetric modes with D=200 nm between two horizontally parallel waveguides, and the corresponding results for two vertically parallel waveguides are shown in Fig. 5d and e, respectively.

From Fig. 5a, it can be seen that for both a conventional structure and our proposed structure, the coupling lengths increase almost exponentially for both cases as D increases. However, for the case of vertically parallel waveguides, the coupling length of our proposed structure is higher than that of conventional structure, which illustrates that the crosstalk is lower, in other words, high-density independent function photonic elements are more easily integrated for our proposed structure. For the case of a horizontally parallel waveguide, our proposed structure has similar coupling lengths compared to a conventional structure. Furthermore, for both our proposed structure and a conventional structure it is noted that: (1) the coupling length for the vertically parallel waveguides is higher than that for horizontally parallel waveguides at the same waveguide's separation, which indicates that highly integrated photonic elements are more easily achieved for the vertical configuration; (2) the coupling length for the horizontally parallel waveguides is significantly lower than that of SPPs waveguide reported in [16], which is typically 10 μm.

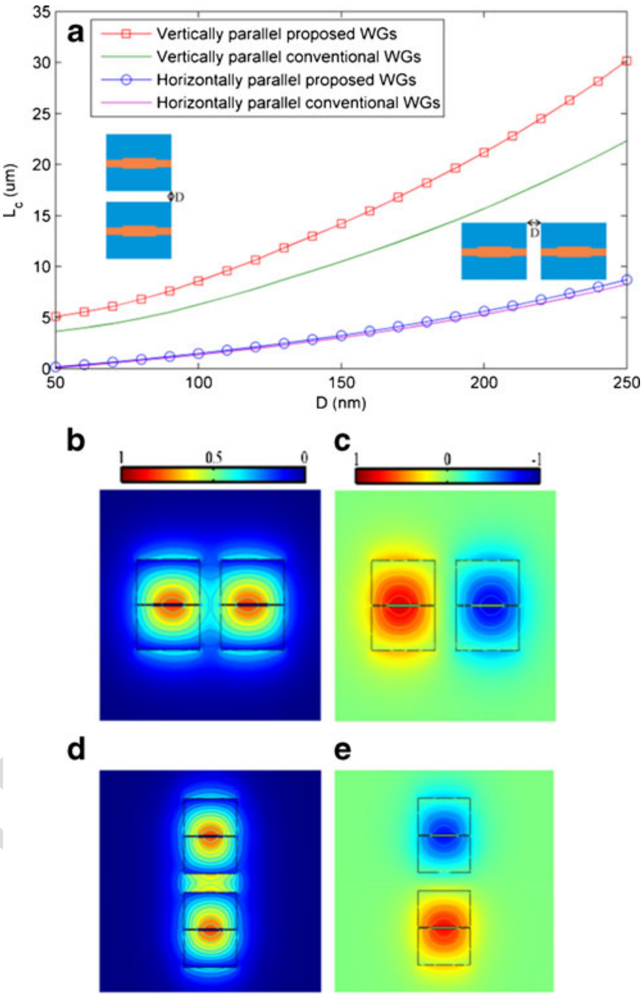

Fig. 5 (Color online) **a** The calculated coupling lengths versus the separation between the two horizontally and vertically parallel hybrid plasmonic waveguides. Amplitudes of E_y for the symmetric mode (**b**) and the anti-symmetric mode (**c**) with D=200 nm between two horizontally parallel waveguides based on our proposed structure. Amplitudes of E_y for the symmetric mode (**d**) and the anti-symmetric mode (**e**) with D=200 nm between two vertically parallel waveguides based on our proposed structure

In conclusion, we have proposed a novel dielectric-loaded plasmonic waveguide structure which supports hybrid LRSPPs with a high degree of mode confinement and long propagation length. Our investigations show that the proposed structure provides a better trade-off between the propagation length and mode confinement, compared to the conventional DLSPPs configuration. The proposed structure can significantly improve the propagation length for the same mode confinement capacity, or can realize a much tighter field confinement for the same propagation length. The structure offers flexible solutions for the development of compact hybrid plasmonic devices by the appropriate selection of structural parameters.

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