Hybrid wedge plasmon polariton waveguide with good fabrication-error-tolerance for ultra-deep-subwavelength mode confinement

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Abstract: A novel hybrid plasmonic waveguide consisting of a high-index dielectric nanowire placed above a triangular metal wedge substrate is proposed and analyzed theoretically. The strong coupling between the wedge plasmon polariton and the dielectric nanowire mode results in both the ultra-tight confinement and low propagation loss. Compared to the previous studied hybrid surface plasmon polariton structures without the metal wedge substrate, stronger field enhancement in the low-index gap region as well as improved figure of merit (FOM) could be realized simultaneously. Results of the modal properties considering certain fabrication imperfections show that the proposed structure is also quite tolerant to these errors.

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OCIS codes: (240.6680) Surface plasmons; (130.2790) Guided waves; (250.5300) Photonic integrated circuits.

References and links

1. Introduction

Surface plasmon polariton (SPP) waveguides leveraging the electromagnetic waves coupled to electron oscillations at the metal/dielectric structures have become a hotly studied area in nanophotonics, due to their prospect of deep-subwavelength light guiding [1]. Many novel structures, such as metal slot waveguides [2–5], channel SPP (CPP) waveguides [6,7] and wedge plasmon polariton (WPP) waveguides [8–11], have been proposed, numerically analyzed and experimentally demonstrated. These waveguides could provide tight confinement of light but suffer pretty high propagation loss, which poses challenges for further device integration. Recently, several hybrid plasmonic waveguides have been considered to achieve sub-wavelength mode confinement with relatively low loss [12–17], which could have great impact on realizing optical interconnects at deep sub-wavelength scales. Instead of guiding the light purely by the SPP along the metal/dielectric interface, dielectric index contrast near the metal surface also play an important role in confining the wave in these hybrid SPP waveguides. Although the overall geometrical sizes of their structures are comparable to those of some dielectric nanophotonic devices, these hybrid waveguides offer unique advantages such as large field enhancement, strong light-matter interaction, and lower crosstalk, which make them appealing building blocks for novel integrated nanophotonic components. Plasmonic nanolasers [18,19] and various functional passive devices, such as directional couplers [20,21], Y-switches [22] and ring-resonators [21], based on such structures had been intensively studied.

The hybrid plasmonic waveguides are designed based on plasmonic waveguide structures with additional high refractive index dielectric nanostructures placed very close to the metal surface. The optical signal is guided not only at the metal/dielectric interface but also by the index contrast between the high and low index dielectric structures near the metal surface as well. By tuning the hybridization between the SPP modes and the waveguide modes, the characteristics of the hybrid mode can be shifted from dielectric-like toward SPP-like [12]. So far, the studied hybrid plasmonic waveguides are designed based on the traditional traveling SPP along the flat metal/dielectric surface [12], the long-range SPP (LR-SPP) mode of thin
metal stripes [14], the dielectric-loaded SPP (DLSPP) mode [16], the plasmonic nanowire mode [17], or the plasmonic edge modes of truncated metal films [15,19]. The properties of the hybrid plasmonic modes are heavily influenced by those of the corresponding SPP modes. For example, the long-range hybrid SPP mode of the symmetric hybrid plasmonic waveguide also could possess ultra-low propagation loss similar to that of the traditional LRSPP waveguides [23]. As significantly improving the transmission loss while maintaining a highly confined mode is the goal for most of the hybrid waveguide designs, the compromise between the mode confinement and loss still exists. Reduced effective mode area is realized when the gap between the high-index structure and the metal surface is shrunk. The hybrid plasmonic waveguide is shown to be able to achieve ultra-deep-subwavelength mode area with a very small gap width in [12]. However, limited by the mode confinement capability of the corresponding SPP modes involved, further downscaling of the hybrid mode area seems difficult as the gap width is already minimized for practical implementations.

To circumvent the above problem and find an alternative approach to reduce the mode area, here we propose a novel hybrid plasmonic waveguide that employs a triangular metal wedge as the substrate. By exploiting the extraordinary confinement property of the wedge plasmon polariton (WPP) [8–11] at the top corner of the wedge and the advantages of the hybrid structures [12], a novel hybrid WPP waveguide is proposed. Simulation reveals that, compared to the previously demonstrated flat metallic substrate based hybrid plasmonic waveguide, the hybrid WPP waveguide could achieve even stronger mode confinement with similar propagation length. Such ultra-deep-subwavelength confinement could enable various applications such as ultra-compact integrated photonic components, manipulation of particles by optical forces [24], and more.

2. Geometry and modal properties of the proposed hybrid WPP waveguides

The schematic of the proposed hybrid WPP waveguide is shown in Fig. 1, which consists of a high-index dielectric nanowire embedded in a low-index cladding near the metallic wedge substrate. Here we assume the nanowire is placed directly above the wedge with a gap width of $h$ away from the top edge of the wedge. The metal wedge tip has an angle of $\theta$ and a curvature radius of $r$, while the wedge height is $h_w$. The diameter of the nanowire is $d$. The characteristics of the hybrid WPP waveguides are investigated at $\lambda = 1550$nm. The metallic substrate is assumed to be silver (Ag), the high-index dielectric is silicon (Si), and the cladding is silica (SiO$_2$). The permittivities of SiO$_2$, Si and Ag are $\varepsilon_c = 2.25$, $\varepsilon_d = 12.25$ and $\varepsilon_m = -129 + 3.3i$ [25], respectively. The modal properties are investigated by means of the finite-element method (FEM) using COMSOL™. The eigenmode solver is used with the scattering boundary condition. Convergence tests are done to ensure that the numerical boundaries and meshing do not interfere with the solutions.

We first consider waveguide configurations with nontruncated metal wedges (i.e. $h_w \rightarrow \infty$). To avoid singularities in simulations, the tip of the top corner are rounded with a
10nm curvature [26]. $|E(x,y)|$ distributions of the fundamental plasmonic mode of the hybrid WPP waveguides are shown in Fig. 2, where the diameter of the nanowire is fixed at 200nm and the distance $h$ is set at 5nm. The metal wedge tip-angle is chosen at 20deg, 60deg, 100deg, 140deg and 180deg, respectively. We note that the extreme case of 180deg corresponds to the hybrid plasmonic waveguide with flat metallic substrate as investigated in [12]. It is shown that for all the above cases, the low-index nanogap between the dielectric nanowire and the metal wedge could effectively confine a large portion of the field due to the slot effect [12,16,27]. A metal wedge with smaller $\theta$ would result in stronger field enhancement in the gap region, especially near the wedge tip. At larger $\theta$, the field enhancement is less obvious, and more electric field is distributed along the metal surface, leading to an increased mode area. These phenomena suggest that in order to suppress the mode area and enhance the mode confinement, a metal wedge with a sharper tip is preferred.

Fig. 2. (a)-(e) $|E(x,y)|$ distributions of the fundamental plasmonic mode of hybrid WPP waveguides with different tip-angles ($h = 5nm$), where the extreme case of $\theta = 180deg$ corresponds to the hybrid plasmonic waveguide in [12] (The top tip of the metal wedge are rounded with a curvature of 10nm. Note that the field distributions are normalized so that the surface integrals of the power flow in the cross section are equal); (f) $|E(x,y)|$ distributions along y direction at the center position of the nanowire.

The modal effective index ($N_{eff}$), propagation length ($L_p$), normalized mode area ($A_{eff}/A_0$) and figure of merit (FOM) of the SPP mode of our proposed structures with different tip-angles are shown in Fig. 3 as $\theta$ varies from 20deg to 180deg. The propagation length is given by $L_p = \lambda/[4\pi\text{Im}(n_{eff})]$. $A_0$ is the diffraction-limited mode area and defined as $\lambda^2/4$. The effective mode area ($A_{eff}$) is calculated using $A_{eff} = (\int |W(r)|^2 dA)/(\int |W(r)|^2 dA)$, where, to accurately account for the energy in the metal region, the electromagnetic energy density $W(r)$ is defined as [5,28]:

$$W(r) = \frac{1}{2} \text{Re}\{\frac{d[\omega c(r)]}{d\omega}\}|E(r)|^2 + \frac{1}{2} \mu_0 |H(r)|^2,$$

(1)

where $E(r)$ and $H(r)$ are the electric and magnetic fields, $\epsilon(r)$ is the electric permittivity and $\mu_0$ is the vacuum magnetic permeability. FOM is defined as the ratio of $L_p$ to $D_{eff}$ [29], where $D_{eff}$ is the effective mode size defined as the diameter of $A_{eff}$.

Figure 3(a) illustrates that the mode effective index decreases monotonically with increased tip-angles, indicating a gradually weakened confinement at larger $\theta$, which is consistent with the trend of increased effective mode area as shown in Fig. 3(b). While the propagation length is shown to increase first before it decreases when the metal wedge shifts towards flat metallic surface, which indicates the existence of an optimized tip angle (~140 deg) with respect to $L_p$. When $\theta$ is around 140 deg, the corresponding hybrid WPP waveguide could achieve longer propagation length with much smaller mode area compared to the
previous hybrid plasmonic waveguide [12]. This indicates that ultra-deep subwavelength mode confinement could be simultaneously realized along with relatively low transmission loss based on our proposed structure. Calculations of the figure of merit at various tip-angles show that the overall performance of the proposed hybrid WPP structure could be better than that of the hybrid plasmonic waveguide with a flat metallic substrate in most cases. On the other hand, similar to hybrid plasmonic waveguides [12], $N_{eff}$ decreases while $L_p$ and $A_{eff}$ increase at larger gap width. The propagation lengths in Fig. 3 are comparable to those of the dielectric-loaded plasmonic waveguides but with much stronger confinement, which could be used to realize various devices such as plasmonic Bragg grating and other wavelength-selective structures, as well as active devices including nanolasers. We also note that $L_p$ could be increased to even hundreds of microns by further increasing the gap widths at the expense of weaker field confinement. Our results indicate that between 20 to 40% of the total power resides in the high-index nanowire for the geometrical parameters in Fig. 3, indicating sufficient modal overlap for possible applications like nanolasers [18,19].

![Fig. 3](image1.png)

Fig. 3. Dependence of the modal properties of the fundamental plasmonic mode of the proposed hybrid WPP waveguide on the tip-angle of the metal wedge: (a) the modal effective index ($N_{eff}$) and the propagation length ($L_p$); (b) the normalized mode area ($A_{eff}/A_0$) and figure of merit (FOM). Solid line: $h = 2$nm; dashed line: $h = 5$nm; dash-dotted line: $h = 10$nm.

Then we consider more realistic waveguide configurations with metal wedges truncated at a certain height. The dependence of modal properties on the metal wedge height at different tip-angles are shown in Fig. 4 (a)-(c). Unlike the traditional WPP waveguides [9], there is no critical height below which the mode is no longer guided for our proposed waveguides. At relatively large $h_w$ (e.g. >300nm), the modal properties of the hybrid WPP waveguides quickly reach those under infinitely large $h_w$ as shown in Fig. 3. Thus, the waveguide’s characteristics are robust against the variation of the metal wedge height when the wedge is not too shallow. On the other hand, when $h_w$ is very small, the coupling between the dielectric nanowire and the bottom flat metal substrate becomes more obvious. This results in more complex mode properties, such as the non-monotonical changes of the curves shown in Fig. 4. The mode eventually approaches that from a flat metal surface [12] as the metal wedge gradually diminishes.

![Fig. 4](image2.png)

Fig. 4. Dependence of the modal properties of the fundamental plasmonic mode of the proposed hybrid WPP waveguide on the wedge height: (a) the modal effective index ($N_{eff}$) and the propagation length ($L_p$); (b) the normalized mode area ($A_{eff}/A_0$) and figure of merit (FOM). Dashed-lines correspond to the hybrid WPP waveguides with infinite metal wedge heights.
To fabricate such a waveguide, the focused-ion beam (FIB) technique could be used to form the metal wedge with high accuracy and the Si nanowire can then be placed after depositing a thin SiO$_2$ layer on the wedge. Another approach might be using a reverse step by positioning the Si nanowire on a SiO$_2$ substrate and then covering the nanowire with a SiO$_2$ cladding first. The metal will later be deposited after milling a V-shape groove in the upper silica layer, similar as the fabrication process for the WPP waveguide in [10]. Considering the practical fabrication issues for the proposed hybrid WPP waveguide, while the size of the dielectric nanowire and the gap width $h$ could be controlled with high precision [18], the curvature radius of the metal tip may vary [8–11] and the accurate alignment between the metal wedge and the nanowire is also difficult. Therefore, we further investigate in detail the impact of the above common fabrication imperfections on the modal properties. In Fig. 5, the effects of the tip radius and the misalignment between the wedge and the wire on the propagation length and effective mode area are shown at different tip angles. It is noted that for metal wedges with larger tip-angles (e.g. $>$60deg), the variation of $r$ causes little changes in $L_p$ and $A_{eff}$. When $r$ increases from 10nm to 20nm, the changes in $L_p$ and $A_{eff}$ are only $\sim$2% and $\sim$5%, respectively. However, when $\theta$ is small (e.g. 20deg), the difference of the modal properties at various $r$ becomes more obvious, especially when the radius is very small (e.g. $<$5nm). Figure 5(b) shows that, for all the considered tip-angles, a $\pm$ 10nm misalignment in the horizontal direction only result in a less than 3% fluctuation for $L_p$ and a no more than 5% variation for $A_{eff}$. The modifications in the mode profile are also negligible. The above results clearly indicate that the proposed hybrid WPP waveguide is quite tolerant to fabrication errors, especially at larger tip-angles, which is beneficial for its implementations.

Fig. 5. Dependence of the modal properties on (a) the metal tip curvature radius $r$ and (b) the misalignment $\delta x$ ($r=10$nm). Solid line: $L_p$; dashed line: $A_{eff}/A_0$, when $h=5$nm.

To couple to the proposed hybrid plasmonic waveguide with a deep-subwavelength mode size, coupling schemes for the traditional wedge plasmon polariton modes by means of the continuously geometrically deformed metal surface [9] could be adopted, while a reversed configuration could be used to convert the hybrid WPP mode to the conventional hybrid plasmonic mode (i.e. the hybrid mode on the flat metal surface as in [12]).

3. Conclusions

In this paper, we have proposed and studied a novel hybrid plasmonic structure based on the wedge plasmon polariton waveguide. The combination of the unique properties of WPP and the advantages associated with the hybrid plasmonic structures provide us a new avenue to further improve some of the key characteristics of the waveguide. By optimizing the waveguide geometry, ultra-deep-subwavelength mode confinement could be achieved while maintaining relatively long propagation distance. Simulation results reveal the structure is also quite tolerant to fabrication errors.

Acknowledgments

This work was supported by 973 Program (2009CB930701), NSFC (60921001/61077064) and PCSIRT, SEM, and the Innovation Foundation of BUAA for PhD Graduates.