Highly Confined Hybrid Plasmonic Modes Guided by Nanowire-Embedded-Metal Grooves for Low-Loss Propagation at 1550 nm

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***Abstract*—A waveguiding configuration consisting of a semiconductor nanowire embedded in a dielectric-coated V-shaped metal groove is presented. The modal properties of the fundamental quasi-TE hybrid plasmonic mode are investigated at the wavelength of 1550 nm. Simulation results reveal that by tuning the size of the nanowire, the hybridization between the dielectric mode, and plasmonic mode could be effectively controlled. Through appropriate design, the hybrid mode could be strongly localized in the nanowire and the gap regions on each side, featuring both tight-mode confinement and low propagation loss. Besides, the compromise between confinement and loss could also be balanced by controlling the angle or depth of the metal groove. Moreover, it is found that the hybrid mode could exist for a wide geometrical parameter range, even when the corresponding metal groove by itself does not support a guided channel plasmon polariton mode. The proposed hybrid structure is technologically simple and compatible with planar fabrication methods while avoiding alignment errors.**

***Index Terms*—Optical waveguides, optical planar waveguides, plasmons.**

I. Introduction

Surface plasmon polariton (SPP) structures combining the size of nanoelectronics and the speed of microphotonics are proposed as a promising solution for the next generation, highly integrated photonic components and circuits [1]. Although a wide range of SPP-based waveguides and components have been theoretically proposed, a less number of them have been experimentally demonstrated because of the huge loss caused by the metallic structure and the stringent practical fabrication requirements [2]. The long-range SPP (LR-SPP) waveguides are among one of the few candidates so far that have demonstrated the realization of complex photonic components and on-chip integrations [3], [4], mainly due to their ultralow propagation loss. However, their rather weak confinement with mode size comparable to that of the conventional low-index contrast dielectric waveguides renders great challenges for large-scale integrations. One of the promising candidate for efficient guiding and confining SPP waves at the subwavelength scale with relatively low propagation loss is the channel plasmon polariton (CPP) waveguides in the form of a V-shaped or U-shaped channel milled on a metallic substrate [5]–[10]. CPP waveguides could balance the tradeoff between the propagation loss and mode confinement to a certain extent. The subwavelength field confinement has enabled the realization of various integrated photonic components, including Y-splitters, Mach–Zehnder interferometers, waveguide-ring resonators, add-drop multiplexers, and Bragg grating filters [11], [12]. Another attractive advantage of the CPP waveguides and components is their compatibility with standard planar fabrication techniques (e.g., using the focused-ion beam (FIB) milling [11] or combined UV and nanoimprint lithography methods [13]). In contrast to other SPP counterparts that may require relatively strict fabrication condition and complicated fabrication procedures, CPP waveguides are relatively simple to make [11] and also offer compatibility with mass production [13], hence making them promising candidates for various applications.

On the other hand, recent advancement in novel plasmonic waveguiding configurations has led to the proposal and demonstration of a host of hybrid plasmonic structures [14]–[28], which combine the advantages of both semiconductor and plasmonic waveguides and enable light transmission in the deep subwavelength, low-index gap, promising to achieve long-range propagation with tight-mode confinement. Various types of active and passive plasmonic devices including nanolasers, couplers, splitters, and ring resonators have also been theoretically studied and experimentally demonstrated [29]–[36]. The characteristics of the hybrid mode can be shifted from dielectric-waveguide-mode-like toward SPP-like through tuning the hybridization between the SPP modes and the waveguide modes [14]. As the properties of the hybrid plasmonic modes are heavily influenced by those of the corresponding uncoupled SPP modes, employing a different metal nanostructure may result in dramatically modified modal behavior. However, the steps to

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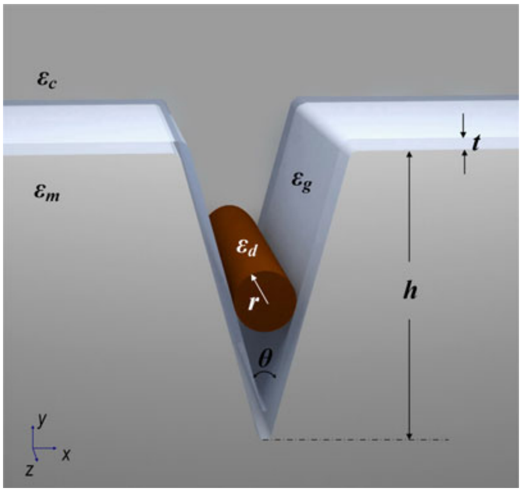

Fig. 1. Geometry of the hybrid metal groove waveguide.

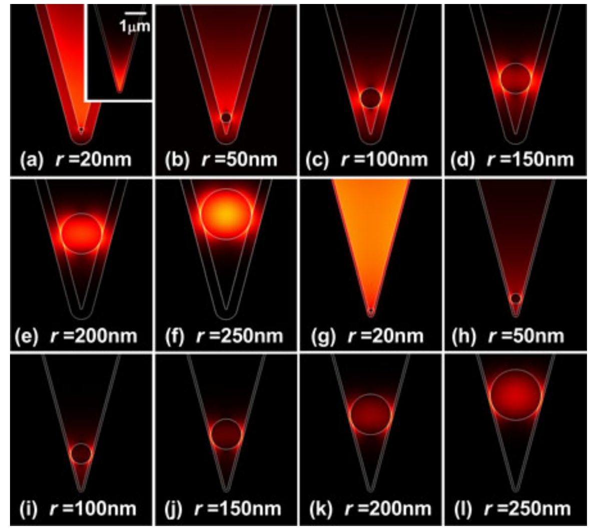

Fig. 2. $|E(x,y)|$ distributions of the fundamental quasi-TE plasmonic mode of hybrid V-groove waveguides with different GaAs nanowires: (a)–(f) $\theta = 30°$, $t = 100$ nm, (g)–(l) $\theta = 30°$, $t = 20$ nm.

fabricate complicated metallic nanostructures result in an extra complexity. Besides, for some of the hybrid structures, the accurate alignment between different layers or patterns could be challenging [15], [30], [37], and the fabrication errors may adversely affect the guiding capability of the hybrid modes.

In this paper, we propose a novel hybrid plasmonic waveguide by integrating high-index semiconductor nanowires with dielectric-coated metal groove plasmonic structures (also can be named as dielectric-loaded groove waveguides [38]–[40]). Through combining the strong mode confinement capability of the CPP waveguide with the hybrid concept, the formed hybrid plasmonic structure provides a new avenue to support highly efficient hybrid plasmonic modes, which feature both strong mode confinement and low-propagation loss at the telecom wavelength. The proposed straight-type waveguide could be fabricated using planar techniques. Similar to conventional CPP waveguides, the FIB method could be used to create the metal groove and the semiconductor nanowire is then placed inside the groove after a thin dielectric layer is coated on the metallic surface. Compared to many other plasmonic structures, fewer fabrication steps are needed and it is alignment-free, alleviating some of the undesirable fabrication imperfections. More complex passive photonic components based on such a waveguide may also be realized by employing micromanipulation process, which had been widely used to build versatile nanowire-based devices such as branch- [41] and loop-type structures [42] without damaging the nanowires.

II. Geometry and Modal Properties of the Proposed Hybrid Groove Waveguides

The proposed hybrid metal groove waveguide shown in Fig. 1 consists of a high-index dielectric nanowire separated from a V-shaped metallic substrate by a nanometer-scale-thick low dielectric constant gap. Here, the nanowire is assumed to be embedded inside the groove and supported in direct contact by the homogeneous low-index dielectric coating layer. The radius of the nanowire is r. The metal groove has a tip angle of θ and a depth of h. The thickness of the low-index dielectric coating layer is t. All the corners in the waveguiding structure are considered as rounded of a fixed 10-nm curvature radius for the inner corners, while the outer corners have a curvature radius of $(10 + t)$ nm to keep a constant gap width. The modal characteristics of the hybrid metal groove waveguides are investigated at $\lambda = 1550$ nm. The metallic substrate is assumed to be silver (Ag), the high-index dielectric is GaAs, and the low-index dielectric gap layer is silica (SiO_2) with air as the cladding. The permittivities of air, SiO_2, GaAs, and Ag are $\varepsilon_c = 1$, $\varepsilon_g = 2.25$, $\varepsilon_d = 12.25$, and $\varepsilon_m = -129 + 3.3i$ [43], respectively. The modal properties are investigated by means of the finite-element method using COMSOL. The eigenmode solver is used with the scattering boundary condition, which is a commonly employed approach to mimic the necessary open boundary [14]. Convergence tests are done to ensure that the numerical boundaries and meshing do not interfere with the solutions.

The waveguide configuration firstly considered here, has a deep enough metal groove (sufficiently large to avoid the edge effects) with a tip angle of 30°, to ensure that the structure without the GaAs nanowire could support bound CPP modes [5], [9], [44]. In such a case, as the fundamental hybrid plasmonic mode results from the coupling between the CPP mode and the dielectric mode, and is denoted as the hybrid CPP mode. We note that the dielectric mode could also be coupled with higher order CPP modes under certain geometries, but here we will only focus our discussions on the properties of the fundamental hybrid CPP mode. Simulation results of the electric field for the fundamental quasi-TE hybrid mode with different geometries are shown in Fig. 2. For configurations with a relatively thicker SiO_2 layer (e.g., $t = 100$ nm), increasing the GaAs nanowire radius from 20 to 250 nm results in an evolution of the hybrid mode behavior from CPPlike to dielectric-like. When the nanowire is small ($r = 20$ nm), the field is mainly guided at the bottom of the metal groove [see the inset of Fig. 2(a)] similar as conventional CPP waveguides. As the nanowire gets larger, the mode field begins shifting toward where the nanowire sits (e.g., $r = 50$ nm). A further increase in the size of the nanowire results in more field concentrated in both the nanowire and the adjacent gap layer (e.g., r = 100, 150 nm), corresponding to the strongest coupling between the CPP and dielectric mode. Finally, almost all of the energy could be stored inside the nanowire when r reaches certain values (e.g., r = 200 and 250 nm), where the corresponding mode loss is very low. While for the case of a thin silica layer (e.g., t = 20 nm), the trend of the mode behavior with various nanowires is almost the same as that of the thick layer. The only difference is that when the nanowire is relatively large, the hybrid mode no longer displays either dielectric- or CPP-like properties, but gets strongly confined in the low-index gap, as clearly seen in Fig. 2(j)–(l). Simulation also illustrates that further reduction of the thickness of the SiO_2 layer (e.g., t = 10 nm) would result in more pronounced field enhancement in the gap and smaller mode area, indicating tighter mode confinement could be achieved. Besides, for all the studied cases, when the nanowire is rather large, the quasi-TM mode could also be supported by the structure, which has dielectric-like modal properties with relatively low-propagation loss due to the less overlap of the mode profile with the metal sidewalls.

The modal properties including the modal effective index N_{eff}, propagation length L_p, and normalized mode area A_{eff}/A_0) of the fundamental hybrid plasmonic mode of our proposed structures with different GaAs nanowires and SiO_2 layers are shown in Fig. 3 as r varies from 20 to 250 nm. The propagation length is given by $L_p = \lambda/[4\pi \mathrm{Im}(n_{\mathrm{eff}})]$. A_0 is the diffraction-limited mode area in free space and defined as $\lambda^2/4$. The effective mode area A_{eff} is calculated using

$$A_{\mathrm{eff}} = \left(\iint W(\boldsymbol{r}) dA\right)^2 \Big/ \left(\iint W(\boldsymbol{r})^2 dA\right) \qquad (1)$$

where the electromagnetic energy density $W(\boldsymbol{r})$ is defined the same as in [14], [45], [46]. Fig. 3(a) illustrates that N_{eff} increases monotonically when r gets bigger. Such a trend gets more pronounced for relatively large GaAs nanowire with thinner SiO_2 layer, due to the stronger interaction between the plasmonic and dielectric mode, while the propagation length and mode area are shown to decrease first before they increase with increased r. Extended propagation length and, correspondingly, larger mode area are observed when the GaAs nanowire is either very small or very large. When the GaAs nanowire has a moderate size, strong coupling between the CPP mode and dielectric mode occurs, where relatively short propagation length with small mode area is expected. Under such conditions, between 30% and 40% of the total power could be squeezed into the gaps on both sides of the GaAs nanowire, indicating tighter mode confinement achieved in the low-index gap region than the conventional hybrid plasmonic waveguide [14]. While on the other hand a substantial portion of the total power could also be stored in the high-index GaAs nanowire, and such power ratio could be further increased, even up to nearly 90% (e.g., r = 250 nm), by employing a larger nanowire, which is also higher than the corresponding conventional hybrid waveguide on flat metal substrate. Such property may faciliate sufficient

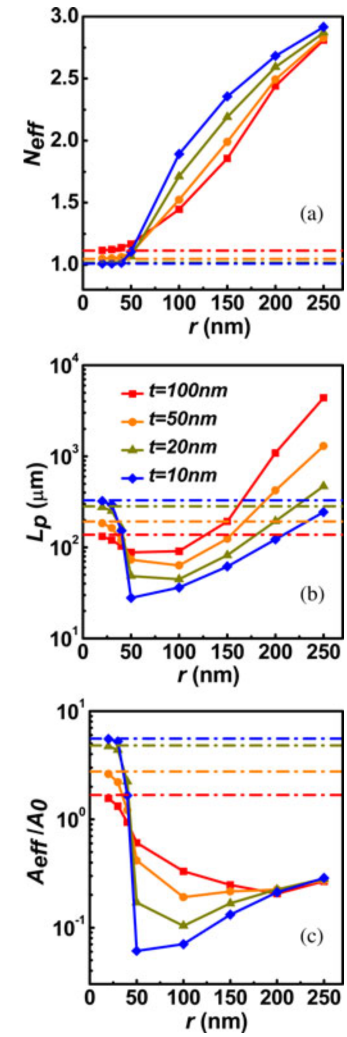

Fig. 3. Dependence of the modal properties of the fundamental hybrid CPP mode on the radius of the GaAs nanowire. (a) Modal effective index N_{eff}. (b) Propagation length L_p. (c) Normalized mode area A_{eff}/A_0. Dash-dotted lines correspond to the CPP modes supported by the metal grooves with different SiO_2 coating layers.

modal overlap with the gain medium, beneficial for possible applications like nanolasers [29], [33]. As also seen in Fig. 3(b) and (c), for the considered range of geometry parameters, subwavelength mode confinement could be achieved along with relatively long-range propagation distance (around tens to hundreds of microns), indicating nice guiding properties of the fundamental hybrid CPP mode.

The effects of metallic groove angle and groove depth on modal properties are then investigated. Fig. 4 shows the calculated results of the L_p and A_{eff}/A_0 with different θ and h. It is illustrated that the waveguide with a deep metal groove has lower propagation loss with a sharper θ, at the cost of a larger mode area. Furthermore, for relatively large h (e.g., >1 μm for $\theta = 16^\circ$), the modal properties of the quasi-TE hybrid mode quickly reach those under infinitely large h, indicating robust waveguiding characteristics against the variation of the metal groove when the groove is not too shallow. On the other hand, when h is very small, the hybridization between the dielectric nanowire mode and the SPP along the top edges becomes

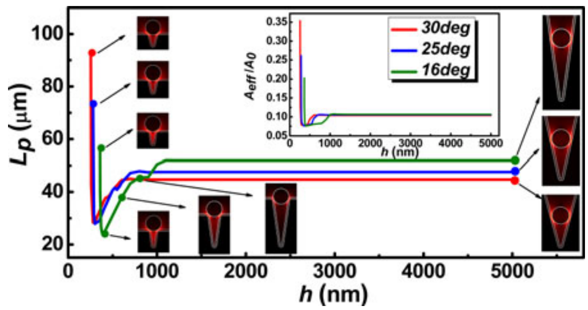

Fig. 4. Propagation length L_p of the studied hybrid plasmonic mode supported by the waveguide with different h and θ ($r = 100$ nm, $t = 20$ nm), where the inset shows the corresponding normalized mode area ($A_{\text{eff}}\ /A_0$) and the electric field distributions for different waveguiding structures.

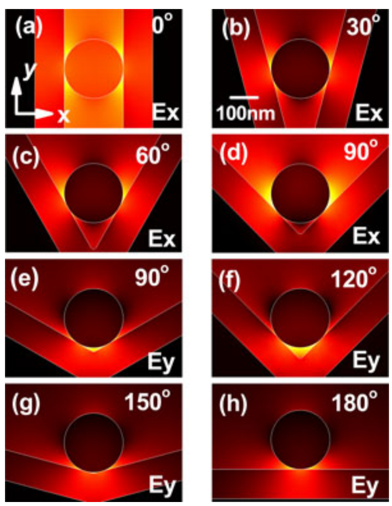

Fig. 5. Field distributions of the dominant electric component when θ changes from 0° to 180°: E_x for the quasi-TE mode and E_y for the quasi-TM mode. ($r = t = 100$ nm).

more pronounced, resulting in more field localized in the metal structure, and thus increased the propagation loss. Further reduction of the groove depth causes the mode shifted toward cutoff, where the effective index of the mode approaches that of the air cladding's, with dramatically reduced propagation loss and increased mode area (also see the field distributions in the inset).

Simulations also demonstrate that hybrid modes could be supported by the proposed waveguide configuration with a much larger range of groove angles, even when the corresponding metal structure does not support guided CPP modes. Here, the electric field distributions of the fundamental hybrid modes are shown in Fig. 5 with groove angle increasing from 0° to 180°, where the extreme case of 0° corresponds to a hybrid plasmonic structure with a nanowire placed between two parallel vertical metal walls separated by SiO_2 buffer layers. Similar configurations, which can be called hybrid metal–insulator–metal waveguides, have been investigated both theoretically and experimentally in previous study [37], [47]–[51]. On the other hand, when the angle reaches 180°, the structure turns into a conventional hybrid plasmonic waveguide with a flat metallic substrate. Fig. 5 illustrates that when θ is small (e.g., $<90°$), the hybrid mode is quasi-TE-like with E_x as the dominant electric component. On the other hand, for large angles (e.g., $>90°$), the fundamental mode exhibits a quasi-TM-like behavior. Here, as the metal groove structure may not support a CPP mode with large tip angles, the hybrid mode might be better named as a hybrid trench mode instead of a hybrid CPP mode. At certain critical angles (e.g., $\sim 90°$), the hybrid groove waveguide could support both quasi-TE and quasi-TM hybrid plasmonic modes. The aforementioned results illustrate that when θ varies within the range of 0°–180°, the fundamental hybrid mode undergoes a polarization change, indicating a transformation of hybrid TE mode to hybrid TM mode. On the other hand, for more realistic configurations with a finite groove depth and a sharp angle (supporting hybrid quasi-TE mode), polarization rotation could also be realized by continuously decreasing the groove depth.

Recent work has demonstrated that in contrast to the conventional CPP waveguides, metal grooves with finite metal thickness could support not only short-range CPP modes [52] with even stronger mode confinement but also long-range ones with ultralow-propagation loss [44]. Therefore, we expect that employing such a finite thick metal groove may provide new possibilities for further improvement of the hybrid mode's properties, e.g., by coupling to the short-range CPP modes for tighter mode confinement or further reducing the propagation loss by hybridization with the long-range CPP modes, which may be the focus of our futurestudy.

III. Conclusion and Discussion

In this paper, we have proposed and investigated a novel metal groove-based hybrid plasmonic structure. The coupling between the nanowire dielectric mode and the SPP mode supported by the metallic sidewalls results in a tightly confined hybrid plasmonic modes with relatively low transmission loss. The proposed novel structure could be realized using simple fabrication procedures and avoid some of the fabrication imperfections that may occur in other hybrid plasmonic waveguide structures. Such compact waveguides with nice optical performance could enable various types of integrated photonic components as well as their applications.

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