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Extreme light confinement and low loss in triangle hybrid plasmonic waveguide

Qijing Lu [a], Chang-Ling Zou [b], Daru Chen [a], Pei Zhou [a], Genzhu Wu [a,*]

[a] Institute of Information Optics, Zhejiang Normal University, Jinhua 321004, China
[b] Key Laboratory of Quantum Information, University of Science and Technology of China, Hefei, Anhui 230026, China

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ABSTRACT

A low-loss triangle hybrid plasmonic waveguide to confine light at an ultra-deep subwavelength scale is proposed and numerically investigated. Compared to other hybrid slot plasmonic waveguides based on cylinder or square semiconductor nanowires, the novel hybrid plasmonic waveguide based on triangle semiconductor nanowire has not only stronger field confinement, but also lower propagation loss. Detailed study of this structure reveals that these advantages originate from the tip enhancement of the triangle semiconductor waveguide. This mechanism of the waveguide permits tolerance for structural imperfection in actual experiments, which is very feasible for experimental realization. The extreme confinement of light can lead to strong electric field around the tip of the triangle semiconductor waveguide, thus can greatly enhance the light-matter interaction. Various applications will benefit from this triangle hybrid plasmonic waveguide, such as the laser, waveguide (cavity) quantum electrodynamics and optomechanics.

1. Introduction

Surface plasmon-polariton (SPP) [1–3] is attracting more and more attentions due to that it offers the opportunity to confine and guide light beyond the diffraction limit. Thus, SPP-based devices have been studied extensively [4–7] and are regarded as the suitable candidates for guiding light in nano-photonic integrated circuits (PICs) [8,9]. Among them, various plasmonic waveguide structures have been proposed, such as self-assembled metallic nanowire [10], metal–insulator–metal [11,12], V-groove channel [13–15], and metal wedge [16–19]. However, there is a trade-off relation between the propagation loss and field confinement for these plasmonic waveguides, i.e., a deep subwavelength confinement of light is usually accompanied with a very short propagation distance.

Hybrid waveguide, such as dielectric-loaded SPP waveguide (DLSPPW) [20–24], possesses longer propagation distance, but with field less confinement. Recently, a new kind of hybrid waveguides with slot (gap) structures [25–35] (in this paper, this particular type of structure is denoted as hybrid plasmonic waveguide, HPW) which show relatively longer propagation distance and strong field confinement have been proposed to improve the trade-off relation between the light confinement and propagation distance. The HPW structure usually consists of a low-index dielectric nanoscale gap which separates the metal layer and high-index dielectric waveguide. The nanoscale gap shows the capacitor-like energy storage ability due to the discontinuity at the high-low index dielectric interface and the surface plasmon polaritons (SPPs) at the metal–dielectric interface. Various integrated photonic devices based on HPW have been proposed and demonstrated experimentally, including plasmonic nanolaser [36], highly efficient optical modulator [37], polarization beam splitter [38].

In this paper, we propose a new kind of HPW, which consists of a triangle semiconductor waveguide embedded in a low-index dielectric cladding above a silver substrate. Compared with the previously studied HPWs in Refs. [25,26], the new triangle HPW shows stronger field confinement and lower propagation loss. Our analysis revealed that the mechanisms of the extreme confinement of light are the additional lateral confinement and extreme field enhancement around the tip of the triangle semiconductor waveguide. Such triangle semiconductor waveguides can be well prepared in practical experiments [39,40], which indicates that the proposed structure is very potential for ultra-strong light-matter interactions in future.

2. Structure and basics

The schematic geometry of proposed triangle HPW is shown in Fig. 1, where a triangle semiconductor waveguide (Si) is separated from the metal (Ag) substrate by a nanoscale low-index dielectric

* Corresponding author.
E-mail address: wugenzhu@zjnu.cn (G. Wu).

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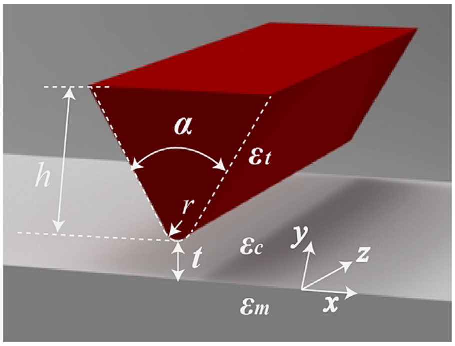

Fig. 1. Schematic illustration of the proposed HPW consisting of a triangle semiconductor waveguide on a silver substrate. The origin is defined at the vertex of the triangle semiconductor waveguide.

gap with height of t. The height and vertex angle of the triangular semiconductor wedge are denoted as h and α, respectively. The characteristics of the triangle HPW are investigated at the telecommunication wavelength $\lambda=1550$ nm, and the relative permittivities of the triangle semiconductor waveguide and silver substrate are $\varepsilon_t=12.25$ and $\varepsilon_m=-129+3.3i$ [25], respectively. The whole hybrid waveguide is immersed into low-index cladding material (SiO_2), with the permittivity $\varepsilon_c=2.25$.

The triangle HPW is uniform along z-axis, therefore the confined propagation eigenmode can be characterized by the propagation constant $k=N_{hyb}k_0$, where $k_0=2\pi/\lambda$ is the wave number in vacuum. The effective mode index N_{byb} and corresponding mode profile in the cross section can be solved numerically by finite element method, with the commercial available software (COMSOL Multiphysics). The eigenmode solver is applied with the scattering boundary condition and a convergence analysis is done to ensure that the numerical boundaries do not interfere the solutions [25]. Since the metal absorbs electromagnetic wave energy, the light decays when propagating along the waveguide. Therefore, N_{byb} is a complex number. We can introduce the propagation distance of hybrid mode as

$$L_m=\lambda/[4\pi \mathrm{Im}(N_{hyb})] \tag{1}$$

The ability of light confinement in this HPW can be characterized by the mode area:

$$A_m=\frac{W_m}{\max\{W(r)\}}=\frac{1}{\max\{W(r)\}}\iint W(r)d^2r, \tag{2}$$

where W_m is the electromagnetic energy and $W(r)=\left\{\frac{d[\omega\varepsilon(r)]}{d\omega}|E(r)|^2+\mu_0|H(r)|^2\right\}/2$ is the energy density, with $E(r)$, $H(r)$, $\varepsilon(r)$, ω, μ_0 being the electric field, magnetic field, dielectric permittivity, angular frequency, and vacuum magnetic permeability, respectively.

In our realistic model, the tip of the triangle semiconductor waveguide is rounded with radius of curvature r for two reasons: (i) the waveguides fabricated in practical experiment always have a round corner with nonzero radius. (ii) The sharp corner will give rise to field singularity in numerical simulation [41,42].

3. Properties

From the field distribution of the hybrid mode in the proposed waveguide structure (Fig. 2(a)), we can see great field enhancement in the gap between the silver film and triangle semiconductor waveguide. Here, the waveguide height $h=200$ nm, the vertex angle $\alpha=100°$, radius of curvature $r=10$ nm and $t=2$ nm. For a comparison, we also calculated the hybrid modes in the cylinder and square HPWs, as shown in Fig. 2(b) and (c), with the same

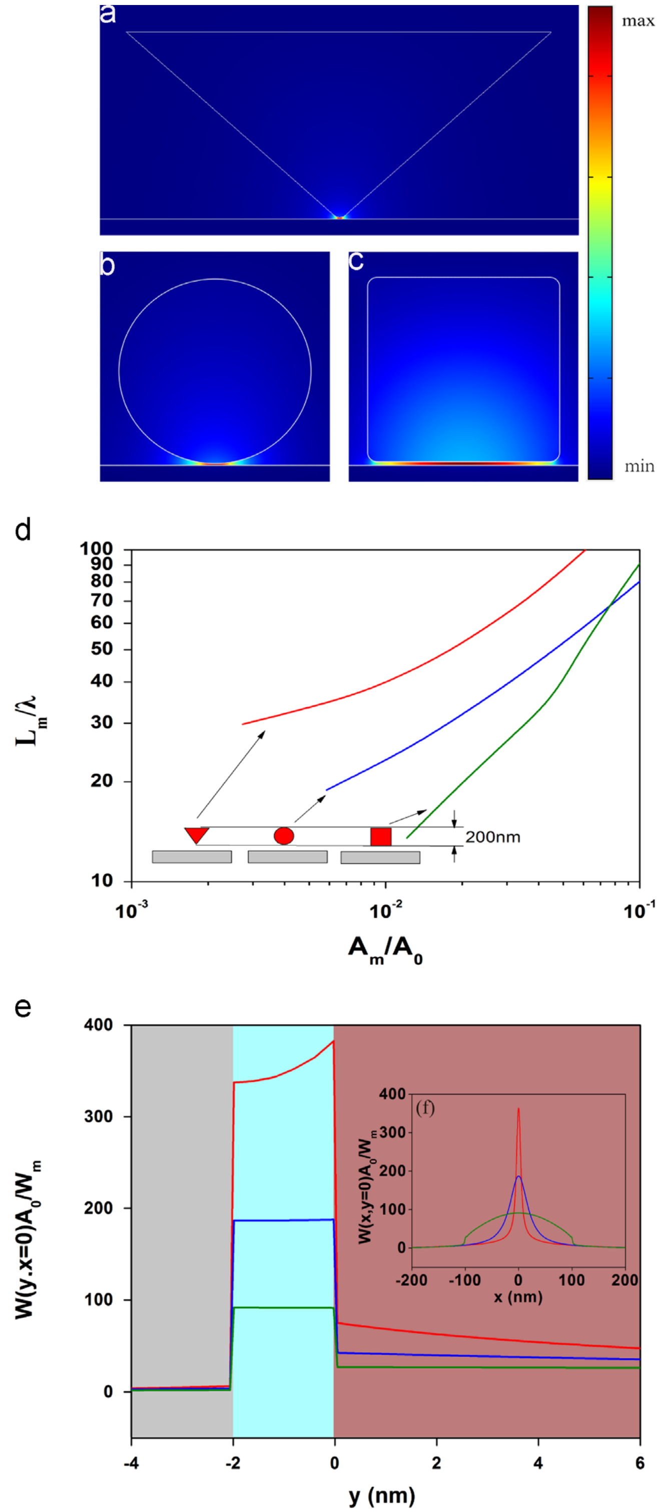

Fig. 2. (a)–(c) The field distributions of hybrid modes at the cross section of the triangle, cylinder and square HPWs, respectively. (d) The normalized propagation distance L_m/λ versus the normalized mode area A_m/A_0 for the hybrid modes in triangle (red line), cylinder (blue line) and square (green line) HPWs when gap t varies from 2 to 40 nm. (e) and (f) Normalized energy densities along $x=0$, $y=0$ ($t=2$ nm) of the hybrid modes in triangle, cylinder and square HPWs, respectively. The shaded gray, green and wine areas in (e) represent silver, low-index dielectric, and semiconductor regions, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

height of semiconductor waveguide, which have been studied previously in Refs. [25,26] (The corners of the square semiconductor waveguide are all rounded with a 10 nm curvature to avoid