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Low-loss hybrid plasmonic waveguide based on metal ridge and semiconductor nanowire

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ABSTRACT

A novel hybrid plasmonic waveguide (HPW) based on a metal ridge and a semiconductor nanowire is proposed and analyzed theoretically. The high-index cylinder semiconductor nanowire is placed above a metal substrate with a semi-cylinder metal ridge and the low-index dielectric gap between them is introduced for nanoscale field confinement. Our simulations show that mode area as low as $\lambda^2/1600$ which is about three orders of the magnitude smaller than the diffraction-limit area in free space has been achieved for the proposed HPW. Compared with the early reported HPW with a high-index nanowire placed above a flat metal substrate without a semi-cylinder metal ridge, the proposed HPW has more tight lateral confinement and longer propagation distance, which also improves figure of merit (FOM). The propose HPW with truly nanoscale field confinement and low propagation loss has potential in applications such as low-threshold lasers.

1. Introduction

Optical waveguides [1,2] capable of transporting and manipulating light have been widely studied in recent years. Specially, optical waveguides with nanoscale field confinement are essential to achieve photonic integrated circuits (PICs) [3,4]. However, optical waveguides based on pure dielectric materials cannot achieve nanoscale field confinement due to the diffraction limit of light [5,6] when these optical waveguides are typically smaller than the order of wavelength. Plasmonic waveguides [7–13] become most feasible candidates for true subwavelength optical confinement beyond the diffraction limit due to the surface plasmon polaritons (SPPs), which are electromagnetic waves coupled to collective oscillations on the surface of a metal. A lot of plasmonic waveguides have been proposed based on SPPs, e.g., metal–insulator–metal (MIM) [14–16], insulator–metal–insulator (IMI) [17,18], metallic nanowire [19,20], cylindrical core–shell [21], channel plasmon polariton (CPP) [22,23], wedge plasmon polariton (WPP) [24–26], and long-range SPP (LRSPP) [27] waveguides. However, a typical challenge for most of reported plasmonic waveguides [7–27] is the trade-off between propagation distance and optical field confinement. For example, long propagation of a few centimeters can be achieved in LRSPP waveguides [27] but with loose confinement and diffused field. Strong mode confinement is performed in MIM waveguides [14–16] with the cost of a short propagation distance (several micrometers). Therefore, new plasmonic waveguides are still desired to obtain both strong field confinement and long propagation distance.

Recently, a so-called hybrid plasmonic waveguide (HPW) [28–33] has been proposed, which shows a relatively superior ability with both a relatively long propagation distance and nanoscale field confinement. HPW supporting hybrid mode usually consists of a high-index dielectric waveguide placed over a semi-infinite flat metal with a nanoscale low-index dielectric gap where most electromagnetic energy is highly confined. For example, due to the coupling between the SPP mode and the dielectric mode, a hybrid mode is highly confined in the nanoscale gap in a HPW with a cylinder semiconductor nanowire embedded in low-index dielectric above a flat metal substrate [28]. The nanoscale field confinement was achieved due to the discontinuity at the high–low index dielectric interface [6] which generates polarization charges interacting with the plasma oscillation at the metal–oxide interface. Various nanophotonic devices based on HPW have been demonstrated theoretically and experimentally, e.g., plasmonic laser [34], highly-efficient optical modulator [35], Y-splitter [36], etc.

In this paper, we propose a novel HPW to further enhance the lateral confinement of the guided mode. Compared with the HPW structure in Ref. [28], the proposed HPW structure employs a metal ridge (on the metal substrate) directly beneath the semiconductor nanowire, which forms a metal ridge hybrid plasmonic waveguide (MRHPW). The properties of the guided mode of the MRHPW are analyzed theoretically. Our simulation

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results show that the lateral confinement is improved obviously compared with the early reported HPW in Ref. [28]. More importantly, the proposed MRHPW shows a stronger field confinement and a low-loss propagation while figure of merit (FOM) of mode characteristic has also been improved. The dependence of modal characteristics of the proposed MRHPW on the metal ridge geometry is also discussed.

2. Structure and modal characteristics

The schematic structure of the proposed MRHPW is shown in Fig. 1. In contrast to the conventional HPW [28] which is shown in the inset of Fig. 1, a semi-cylinder metal ridge with radius of r is employed on the flat metal substrate. A high-index semiconductor (Si) nanowire with a diameter (d) embedded in a low-index cladding (SiO_2) is placed directly above the metal ridge with a gap of h. The media of metal ridge and substrate is assumed as Ag. The characteristics of the MRHPW are investigated at the telecommunication wavelength of 1550 nm and the permittivities of the Si, SiO_2, Ag are $\varepsilon_c=12.25$, $\varepsilon_d=2.25$, and $\varepsilon_m=-129+3.3i$, respectively. An finite-element-method (FEM)-based mode solver is used to investigate characteristics of the MRHPW. The characteristics of the HPW [28] are also analyzed for comparative investigation. Fig. 2 shows the normalized mode area (A_m/A_0) and propagation distance (L_m) of the MRHPW and HPW with different cylinder diameters. The propagation distance is defined as $L_m=\lambda/[4\pi \mathrm{Im}(n_{eff})]$ [28], where n_{eff} is the effective mode index. A_0 is defined as $\lambda^2/4$ which denotes the diffraction-limit mode area. The mode area is defined as the ratio of the total mode energy and peak energy density, which is given by

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

where W_m, $W(\mathbf{r})$ are electromagnetic energy and energy density respectively

$$W(\mathbf{r})=\frac{1}{2}\left(\frac{d(\varepsilon(\mathbf{r})\omega)}{d\omega}\left|E(\mathbf{r})\right|^2+\mu_0\left|H(\mathbf{r})\right|^2\right) \tag{2}$$

where $E(r)$, $H(r)$, $\varepsilon(r)$, ω, and μ_0 are the electric field, the magnetic field, the electric permittivity, the angular frequency, and vacuum magnetic permeability, respectively.

Fig. 2(a) shows that the normalized mode area (A_m/A_0) of the proposed MRHPW (solid curves) is smaller than that of the early reported HPW [28] (dashed curves) over the entire range of cylinder diameter (d), which indicates the proposed MRHPW has a stronger field confinement, in particular for the small cylinder diameter (d). Here, the radius of semi-cylinder metal ridge is 10 nm. For example, the normalized mode area (0.00142, i.e., $\lambda^2/1600$) of the MRHPW is about one quarter that the normalized mode area of the early reported HPW [28] when they have the same parameters of $d=200$ nm and $h=2$ nm, which is about three orders of the magnitude smaller than the diffraction-limit area in free space. What is more, Fig. 2(b) shows that the proposed MRHPWs have longer propagation distances than the early reported HPW [28].

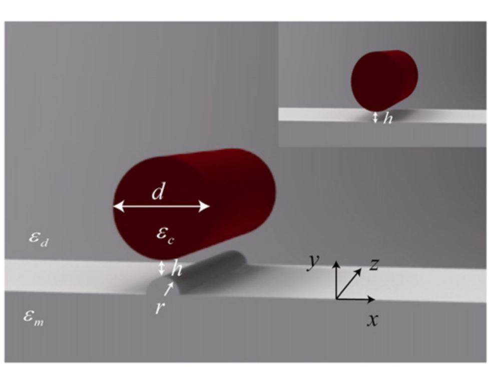

Fig. 1. Schematic structure of the proposed MRHPW and the early reported HPW (inset). The origin ($x=y=0$) is defined at the center of the cylinder.

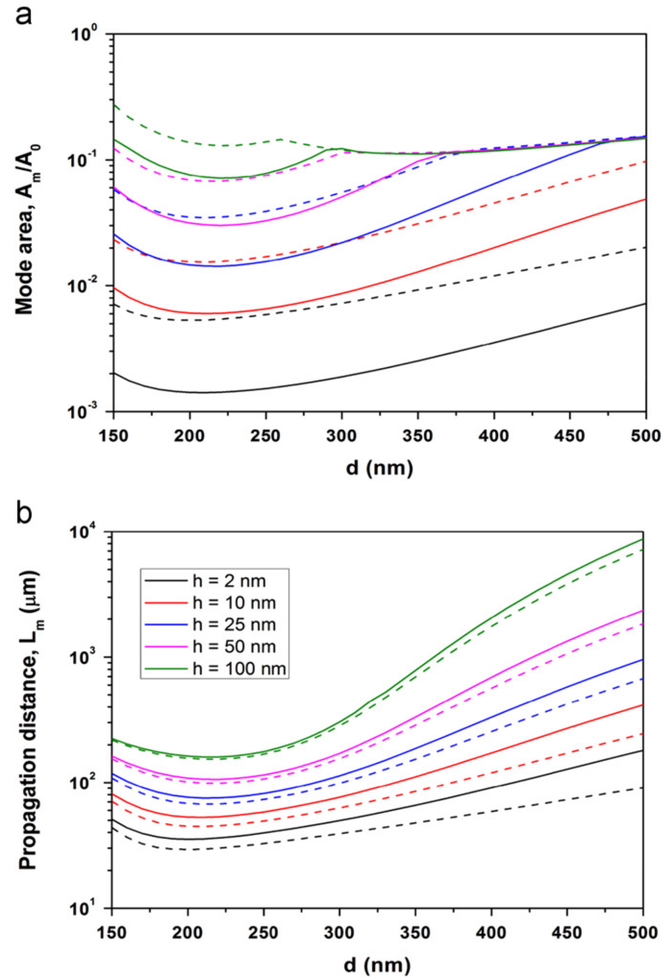

Fig. 2. (a) mode area (A_m/A_0) and (b) propagation distance (L_m) of the MRHPW (solid curves) and conventional HPW (dashed curves). Here, the radius of the semi-cylinder metal ridge is 10 nm.

To present a fair comparison of the MRHPW and the early reported HPW for field confinement, we fix the diameters of the cylinder semiconductor as 200 nm and the radius of the semi-cylinder metal as 10 nm while varying the gap width (h). Figure of merit (FOM) [37] illustrated by a parametric plot of normalized propagation distance (L_m/λ) versus normalized mode area (A_m/A_0) is shown in Fig. 3, which provides a more convictive comparative tool than a single-valued FOM, e.g., $L_m/(A_m^{1/2})$. We can find that the propagation distance of the MRHPW is about two times larger than that of the conventional HPW [28] in the case of the same mode area.

To further show the better performance of the MRHPW than the early reported HPW [28], we analyze the normalized energy density ($W(\mathbf{r})A_0/W_m$) [28] and the effective mode size which are shown in Fig. 4. The effective mode size (D_{eff}) is defined as the diameter of the mode area [26]. The normalized energy density ($W(\mathbf{r})A_0/W_m$) actually denotes the reciprocal relationship of the peak normalized energy density and the normalized mode area (A_m/A_0), i.e., the value of $W(\mathbf{r})A_0/W_m$ represents that of A_0/A_m.