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Abstract. A hybrid surface plasmon waveguide (HSPWG) with a convex rib added on the metal surface is further investigated and analyzed theoretically. The high mode confinement and long propagation distance can be realized simultaneously by optimizing the waveguide geometry. Our designed structures can provide mode area and propagation distance achieving close to $\lambda^2/512$ and 2200 μm respectively, which are better than the performance of the traditional HSPWG. Our structures are excellent, promising candidates for improving plasmonic devices in the fields of ultrafast modulators and low-threshold nanolaser. © 2016 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: [10.1117/1.JNP.10.016005](https://doi.org/10.1117/1.JNP.10.016005)]

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1 Introduction

Surface plasmon waveguides (SPWGs) have been of great interest for many years due to their excellent performance of confining the optical mode to subwavelength scale and minimizing the optical mode size by enabling the use of transverse magnetic polarization modes.¹ These modes show several features such as a high proportion of mode energy localized at the interface of the dielectric layer and the metal surface and the ability of guiding mode far beyond the diffraction limit.

Although there exists excellent remarkable features, SPWGs exhibit a tradeoff between the mode confinement and propagation loss which is the result from ohmic loss² in the metal surface. To address this issue, a so-called hybrid SPWG (HSPWG), which consists of a low-index dielectric gap embedded between the high-index dielectric and the metal layer, is theoretically proposed³ and experimentally demonstrated.⁴ This new SPWG is capable of achieving large energy localization in the gap region and small propagation loss. This is because the transmission mode of HSPWG is emerged by coupling the optical mode of the high-index dielectric and the traditional surface plasmon mode created at the interface of the low-index dielectric and the metal layer.

Owing to these excellent characteristics, a variety of modified HSPWG structures such as long-range HSPWG,⁵ ridge HSPWG,⁶ V-groove HSPWG,⁷ and graphene HSPWG⁸ is further investigated by many research groups. These modified HSPWG structures are potentially excellent candidates exploited as directional couplers⁹ and polarization rotators.¹⁰ However, comparing with the traditional HSPWG,^{3,4} all these HSPWG structures are complicated in fabrication when achieving strong energy confinement and small propagation loss. In order to solve this issue, a modified HSPWG called convex rib HSPWG (CRHSPWG), where a convex metal rib waveguide is placed on the metal surface below the high-index dielectric cylinder waveguide, is theoretically reported.¹¹ Its mode is two-dimensionally confined at the gap region between the

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high-index dielectric and the convex rib metal surface. However, its propagation distance is maintained at $38\ \mu\text{m}$, which is less than that of HSPWG with the same value of the gap height.

In this paper, the eigenmode of the CRHSPWG structures with varied gap heights and rib widths is studied using the finite element method (FEM). The trend of mode properties with varying structural parameters is shown, and the waveguide geometries leading to high mode confinement and long propagation distance are presented. The simulation results show that our structure has longer propagation distance and smaller mode confinement than that of HSPWG³ at proper range of gap region. Therefore, our designed structure has promising, excellent performance of long propagation transmission and strong energy confinement.

2 Structures and Fabrication

This section describes the geometry and fabrication methods of CRHSPWG. The schematic of our proposed structure is shown in Fig. 1. It consists of a submicro-Ag convex rib with width w added on the Ag surface and a cylinder Si waveguide with diameter d surrounded by SiO₂ background.

The gap region which helps to confine the electromagnetic field in a small area is the low-index SiO₂ area embedded between the high-index Si cylinder and the Ag convex rib. The gap height h is the distance from the lower edge of the Si waveguide to the upper edge of the Ag convex rib, whereas h_r is the height of convex rib fixed at 50 nm. Throughout this paper, relative permittivities of these materials are $\epsilon_{\text{Si}} = 12.25$, $\epsilon_{\text{SiO}_2} = 2.25$, and $\epsilon_{\text{Ag}} = -129 + 3.3i$ ¹² at the telecommunication wavelength $\lambda = 1550\ \text{nm}$.

To fabricate such a waveguide, the metal rib can be formed by the focused-ion beam technique with relatively high precision, as demonstrated in the conventional hybrid plasmonic waveguide.⁴ After that, the low-index SiO₂ layer is deposited on the metal rib as the gap of the waveguide, and then the high-index Si waveguide can be realized by the vapor-liquid-solid method.¹³ Although the size of the Si waveguide, the gap height, and the metal size can be controlled with high accuracy,⁴ our waveguide also suffers from misalignment between the Si waveguide and the metal rib. However, compared with those modified HSPWGs,^{5–10} our waveguide has fewer high-index nanowire layers and less complicated structures in the gap region such as wedge⁵ or V-groove metal,⁷ which may cause less fabrication error tolerances in the real fabrication process.

3 Results and Discussions

For evaluating the performance of our designed CRHSPWG structures, mode properties such as the propagation distance and the normalized mode area are illustrated through varying the diameter of Si waveguide and the gap region. The propagation distance is defined as the distance where the initial normalized power of the guided mode decreases to $1/e$, which can be computed as $L = \lambda/4\pi \text{Im}(N_{\text{eff}})$, where $\text{Im}(N_{\text{eff}})$ is the imaginary part of the complex guided mode's

Fig. 1 Schematic of a CRHSPWG: (a) cross-sectional view, and (b) three-dimensional view.

effective index. In order to demonstrate the mode confinement capability, the normalized mode area M_{eff}^3 is computed as

$$M_{\text{eff}} = \frac{A_{\text{eff}}}{A_0}, \quad (1)$$

$$A_{\text{eff}} = \frac{W_m}{\max[W(r)]} = \frac{\iint W(r) d^2 r}{\max[W(r)]}, \quad (2)$$

where A_{eff} is defined as the ratio of total mode energy W_m and the maximum energy density $\max[W(r)]$, and A_0 is the diffraction-limited mode area in free space expressed as $\lambda^2/4$. $W(r)$ can be calculated as

$$W(r) = \frac{1}{2} \left\{ \frac{d[\varepsilon(r)\omega]}{d\omega} |E(r)|^2 + \mu_0 |H(r)|^2 \right\}, \quad (3)$$

where $E(r)$ and $H(r)$ are the electrical field and magnetic field of the guided mode, respectively. In addition, to compare with the mode properties of HSPWG,³ the same method—FEM—is employed to analyze CRHSPWG structures and the same results of HSPWG are obtained using our codes, which further validates our models.

The dependence of mode properties of CRHSPWG on d and h when setting w at 50 nm is shown in Fig. 2. The variation of the guided mode's property in CRHSPWG follows that of HSPWG, while gradually increasing d from 100 to 500 nm with different h . As illustrated in Fig. 2, owing to the small gap region of CRHSPWG, we can find some ranges of d and h where our designed waveguide can provide an order of smaller mode area or longer propagation distance than that of HSPWG. More specifically, the smallest mode area and the longest propagation distance of CRHSPWG approach to $\lambda^2/512$ and 2000 μm , while keeping $d = 200$ nm, $h = 10$ nm and $d = 500$ nm, $h = 10$ nm, respectively. For small diameter d and gap height h (e.g., $d = 150$ nm, $h = 10$ nm), high electromagnetic energy is localized at the interface of Ag and SiO_2 , as shown in Fig. 2(c), which is resulted from the surface plasmon

Fig. 2 Mode properties versus d and h while setting w at 50 nm: (a) normalized mode area, and (b) propagation distance. (c) and (d) Normalized electromagnetic energy distributions for typical structures: (c) $[d, h] = [150, 10]$ nm, and (d) $[d, h] = [450, 50]$ nm.

polarization (SPP)-like mode emerged in CRHSPWG. On the other hand, for large diameter d and gap height h (e.g., $d = 450$ nm, $h = 50$ nm), the cylinder-like mode is supported by CRHSPWG where a large part of energy exists in Si waveguide as illustrated in Fig. 2(d).

To gain a deeper understanding of the hybrid mode in CRHSPWG, the mode character is calculated using the coupled-mode theory,³ as shown in Fig. 3. An approximation hybrid mode and its mode character are calculated by a set of equations:

$$\varphi_{\pm}(d, h) = a_{\pm}(d, h)\varphi_{\text{cyl}}(d) + b_{\pm}(d, h)\varphi_{\text{spp}}, \quad (4)$$

$$b_{\pm}(d, h) = \sqrt{1 - |a_{\pm}(d, h)|^2}, \quad (5)$$

$$|a_{\pm}(d, h)|^2 = \frac{n_{\text{hyb}}(d, h) - n_{\text{spp}}}{[n_{\text{hyb}}(d, h) - n_{\text{cyl}}(d)] + [n_{\text{hyb}}(d, h) - n_{\text{spp}}]}, \quad (6)$$

where $\varphi_{\pm}(d, h)$ is the strength of the hybrid mode, $a_{\pm}(d, h)$ and $b_{\pm}(d, h)$ are the amplitudes of the cylinder mode $\varphi_{\text{cyl}}(d)$ in Si waveguide and of the SPP mode φ_{spp} in Ag-SiO₂ interface, respectively. In Eq. (6), $n_{\text{hyb}}(d, h)$ and n_{spp} are the mode effective indices of $\varphi_{\text{cyl}}(d)$ and φ_{spp} , respectively. It is obvious that when $n_{\text{hyb}}(d, h) > n_{\text{spp}}$, which leads to the mode character $|a_{\pm}(d, h)|^2 > 0.5$, a large portion of energy is located in the cylinder Si waveguide, which makes our hybrid mode a cylinder-like mode. On the contrary, a large amount of energy exists in Ag-SiO₂ interface, which lets our hybrid mode be SPP-like mode. From Fig. 3, one can easily tell that the critical diameter d is obtained at 200 nm when setting $|a_{\pm}(d, h)|^2 = 0.5$ and increasing h can accelerate hybrid mode to be more cylinder-like mode. These can be used to theoretically explain why our CRSPWG mode properties are changed when varying d and h as plotted in Fig. 2.

Figure 4 displays the dispersion relation of CRHSPWG with different d and h . Due to the bounded nature of SPP mode, the guided mode of CRHSPWG excitations corresponds to the dispersion curve lying to the right of the respective light line of SiO₂. On the other hand, the guided mode's dispersion curve lying to the left of light line of Si has more property of cylinder mode when the frequency or diameter d becomes larger. The gap height h also plays an enhanced role in the determination of dispersion curves while h is small (e.g., $h = 200$ nm).

In order to further investigate the gap region's influence in the performance of CRHSPWG, the dependence of mode properties of CRHSPWG with varied w and h is compared with the HSPWG, as shown in Fig. 5. The diameter of Si waveguide d is set at 450 nm, where the tight mode confinement and long propagation distance are obtained from Fig. 2. For a small h (e.g., $h < 25$ nm), there exists a range of w where the normalized mode area of CRHSPWG is smaller than its HSPWG counterpart due to the smaller gap region of CRHSPWG. As further increasing h to 50 nm, the enlarged gap region starts to hold pure cylinder-like modes, which leads more areas to be nearly stable. Moreover, it is interesting to note that for a small w (e.g., $w < 30$ nm), the radiation loss occupies the main part of the propagation loss, which is smaller than that of

Fig. 3 Mode character versus d and h while setting w at 50 nm.

Fig. 4 Dispersion relation with different d and h , where k_{mode} is the wave number of guided mode.

Fig. 5 Mode properties versus w and h while setting d at 450 nm: (a) normalized mode area, and (b) propagation distance.

Fig. 6 Schematic of a taper coupler structure based on CRHSPWG, where the cladding Ag layer is not depicted for xoz plane.

HSPWG with the same parameters. However, for a large h (e.g., $h > 25$ nm), we can find a range of w where the propagation distance of CRHSPWG is longer than its HSPWG counterpart, owing to the smaller interface of Ag in SiO₂ layer. As w is further increased, the metal loss surmounts the radiation loss in CRHSPWG and leads to a shorter propagation distance than its HSPWG counterpart.

To achieve the goal of on-chip telecommunication applications, our CRHSPWG is used to connect two identical dielectric waveguides, which leads to the coupling between the surface plasmon mode and the photonic mode in communication. Therefore, an experimentally demonstrated coupler structure¹⁴ is designed to support highly efficient coupling between CRHSPWG and Si photonic waveguides on the same silicon-on-insulator (SOI) chip, as shown in Fig. 6. This structure consists of SOI waveguide, CRHSPWG, and metallic tapered coupler, which is capable of converting photonic mode in SOI waveguide to surface plasmonic mode. In future research, we will further calculate the parameters of couplers and prepare for fabrication.

4 Conclusion

In this paper, we further investigate the CRHSPWG based on FEM method. To better understand the performance of our structures, the simulation results are compared with those of the traditional hybrid plasmonic waveguides. Our simulation results show that through varying the gap region, waveguide structures have the capability of supporting longer propagation distance and smaller mode area than those of HSPWG³ with the same value of h . More specifically, h and d of CRHSPWG play critical roles in determining whether the characteristics of guided coupled mode behave as the SPP-like mode or cylinder mode. While setting h and d in a suitable range, varying w efficiently reduces the mode area or increases the propagation distance. In addition, a tapered coupling structure based on CRHSPWG is further designed to realize on-chip telecommunication in lab fabrication. Therefore, changing the gap region of HSPWG remains the most critical issue for obtaining long propagation transmission and high energy confinement in the fields of ultrafast modulators and low-threshold nanolaser.

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