Hybrid Plasmonic Waveguiding Model in a V-shaped Silicon Groove

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Abstract ─ A modified V-shaped silicon groove waveguide, embeded with metal nanowire,which is coated with a low refractive index layer was proposed. Finite element method (FEM) is used to numerically simulate the characteristics of the hybrid plasmonic mode at the wavelength of 1550nm. The simulation results show that the hybrid plasmonic mode can be confined to the dielectric layer on the surface of the metal nanowire. Meanwhile, factors on the modal properties are analyzed. Low loss and strong mode confinement can be realized by adjusting the size of the dielectric and metal nanowires as well as the angle of the V-shaped groove. The overall performance of the proposed model is superior to that of traditional hybrid plasmonic waveguides.

Index Terms ─ Finite element method, hybrid plasmonic waveguide, Modal analysis, V-shaped silicon groove.

I. INTRODUCTION

Surface plasmon polaritons (SPPs) have been widely used as information carriers for designing and preparing nano-waveguide structures. By the advantage of excellent conductivity and the breakthrough of diffraction barrier, surface plasmon waveguides (SPWs) has become one of the ideal design schemes for the new-generation optoelectronic integrated chips. A key issue in designing SPWs is how to get the balance between mode confinement and propagation length [1-2].

Up to present, researchers have made a variety of innovative improvements in the structure of optical waveguides, and have proposed a series of surface plasmonic waveguide structures, e.g., shapes, film, slit, cylinder, strip and V-shaped groove were designed; material patterns, dielectric-metal-dielectric (DMD), metal-dielectric-metal (MDM) and hybrid pattern were proposed [3-9].

Among the above plasmonic waveguide structures, the V-shaped groove structure has been shown that a strong lateral confinement on the SPP at the bottom of the groove resulted in low transmission loss in the optical communication bands [10-14]. In addition, the silicon waveguides are well compatible with complementary metal oxide semiconductors (CMOS), and it can be used as the basic module for the transmission, confinement and process of optical signals in photonic integrated circuits. The mode confinement ability of SPP structure can be further enhanced by combining metal waveguides with silicon devices [15-17]. However, SPPs mode transmits on the nanowire surface, the propagation constant is denoted as $\beta = 2\pi \, neff / \lambda$ [18], and the propagation length can be defined as $Lp = 1/2Im(\beta)$ [18]. Therefore, the propagation length of the metal-high refractive index dielectric was higher than that of the metal-low refractive index dielectric structure. In other words, the hybrid SPPs mode is confined to the low refractive index layer more efficiently. For the above reasons, based on the traditional structure [19-20], a modified waveguide model consisting of a metal nanowire covered with a dielectric film of low refractive index in a V-shaped silicon groove is proposed. FEM is used to numerically analysis the symmetrical hybrid SPP mode transmission due to its flexibility in geometrical modeling [6]. Furthermore, the factors on the modal properties are analyzed to facilitate the feasibility design of the waveguide structure, such as the size of the dielectric and metal nanowires, the angle of the V-shaped groove, et al.

II. GEOMETRY OF THE PROPOSED HYBRID V-GROOVE WAVEGUIDE AND THEORETICAL ANALYSIS

Based on the analysis above, the hybrid plasmonic waveguide model is proposed as shown in Fig. 1. In order to increase transmission distance, the V-shaped silicon groove waveguide was embedded with the metal

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nanowire, which is coated with low refractive index dielectric layer.

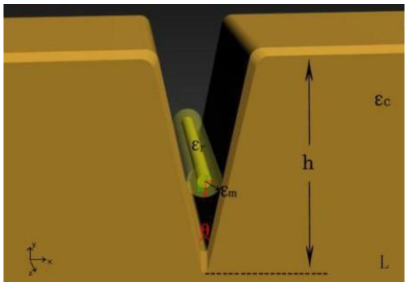


Fig. 1. Geometry of the proposed hybrid groove waveguide. The silicon slice (height h = 600 nm, width L = 800 nm, ε_c = 12.25) is used as the V-groove substrate with the angle (θ), and the silver nanowire (the radius is denoted by r, ε_m = -129+3.3i) [9] is coated with low-index dielectric SiO_2 (the radius is denoted by R), thus, the thickness of the SiO_2 (ε_r = 2.25) layer is denoted by $d = R - r$.

The surface plasmon mode transmits on the nanowire surface along z-axis. The vector field $\mathbf{\Phi}$ can be expressed as:

$$\mathbf{\Phi}(x,y,z)=\mathbf{\Phi}(x,y)e^{-j\beta z}=\left(\mathbf{\Phi}_t(x,y)+\mathbf{\Phi}_z(x,y)e^{-j\beta z}\right), \quad (1)$$

where, $\mathbf{\Phi}_t(x,y)$ and $\mathbf{\Phi}_z(x,y)$ are respectively represented by the horizontal and vertical field components. In this case, the wave equation is degenerated into two-dimensional cross section, which can be shown as:

$$\nabla^2\mathbf{\Phi}+\left(n^2-neff^2\right)(2\pi/\lambda)^2\mathbf{\Phi}=0, \quad (2)$$

where n and $neff$ denote the refractive index of material and the modal effective refractive index, respectively.
The mode characteristics are analyzed by wave equation. The propagation length can be defined as:

$$L_p = 1/2Im(\beta). \quad (3)$$

The modal properties also include the normalized mode area A_{eff}/A_0, which can be defined by the ratio of a mode's total energy density per unit length and its peak energy density. Here,

$$A_{eff}=\left[\int_{A\infty}W(r)\,dA\right]^2 \Big/ \int_{A\infty}W(r)^2\,dA; A_0=(\lambda/2)^2, \quad (4)$$

where $W(r)$ represents the effective energy density [18].

III. MODAL CHARACTERISTICS OF THE PROPOSED HYBRID V-GROOVE WAVEGUIDE

FEM method is carried out to simulate the plasmon characteristics with a wavelength at 1550 nm. The wave equation (2) is solved by combining the boundary condition of the above proposed model. Simulation results of the electric field energy flux density S_z for the fundamental hybrid plasmonic mode are shown in Fig. 2. Compared with different geometries, energy began to spread from the bottom of the groove to the surface of the metal nanowire, and was ultimately confined to the vicinity of the lower refractive index layer. Moreover, from Table 1, it is found that the proposed hybrid V-groove waveguide has the maximum value of the energy, which implies that the proposed waveguide structure has higher mode field confining ability for the strongest coupling between the channel plasmon polaritons (CPPs) mode and dielectric mode.

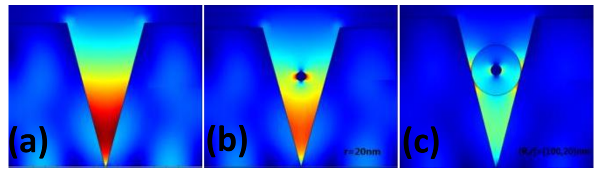


Fig. 2. S_z distributions of the fundamental mode of hybrid groove waveguide with different geometries: (a) conventional V-groove waveguide (θ = 30^0), (b) V-groove waveguide with metal nanowire (θ = 30^0, r = 20 nm), and (c) the proposed hybrid V-groove waveguide (θ= 30^0, [R, r] = [100, 20] nm).

Table 1: The maximum value of the electric field energy flux density S_z

Modal	(a)	(b)	(c)
S_z (V/m)	9.9814e7	1.4776e8	2.7261e8

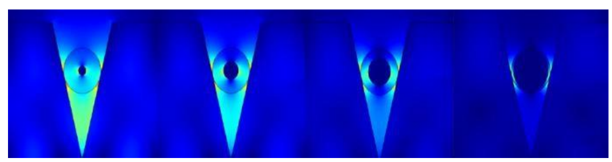


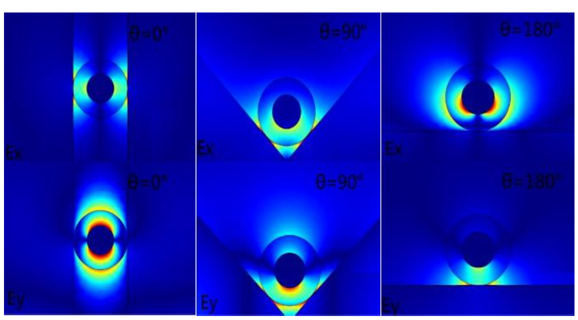
Fig. 3. S_z distributions of the fundamental mode with different r = 20, 40, 60, 90 at θ = 30^0 and R = 100 nm.

The influence of different thickness of the dielectric layer on the fundamental hybrid plasmonic mode is shown in Figs. 3 (a)-(b). For configurations with a relatively radius of the dielectric layer and nanowire (e.g., R = 100 nm), as the radius r of the nanowire increases, one can find that the distribution of energy gradually shifted from the entire groove area to the dielectric layer. Moreover, from Table 2, the maximum value of the electric field energy flux density S_z has increased with the decrease in the thickness of dielectric layer, which shows that the hybrid plasmonic mode can be confined to the thinner dielectric layer.

Table 2: The maximum value of the electric field energy flux density S_z

S_z (V/m)	r = 20 (nm)	r = 40 (nm)	r = 60 (nm)	r = 80 (nm)
R = 100 (nm)	2.7261e8	3.2873e8	4.3811e8	7.9982e8

It is of practical significance to investigate the influence of groove angle on the fundamental hybrid plasmonic mode. For configurations with [R, r] = [100, 60] nm, the electric field distribution of the fundamental plasmonic modes are shown in Fig. 4. While $\theta = 0^0$ (e.g., Fig. 4 (a)), the proposed structure is similar to a DMD hybrid plasmonic waveguide structure [9]. While $\theta = 180^0$ (Fig. 5 (c)), the proposed structure is similar to a hybrid waveguide structure consisting of a dielectric base and metal nanowire [18]. Through comparing the maximum energy electric field components (E_x and E_y) in Table 3, it can be seen that the hybrid mode appears as a symmetric quasi-TM mode with E_x as the dominant electric field components for $\theta < 90^0$. However, a further increase in the groove angle results in the confinement of symmetric quasi-TM mode. With more energy penetrating into the metal area, E_x decreases with the energy loss. When $|E_x|_{max}$ and $|E_y|_{max}$ are comparable for $\theta = 90^0$, both the symmetric quasi-TE and quasi-TM hybrid modes are supported. The value of $|E_x|_{max}$ continuously decreased along with the increased the groove angle from $\theta > 90^0$ to $\theta < 180^0$. It can be obtained that the hybrid mode appears as a symmetric quasi-TE mode with E_y as the dominant electric field components, indicating a transformation of the quasi-TE mode to quasi-TM mode, and polarization rotation can be realized by adjusting the groove angle.



(a) (b) (c)

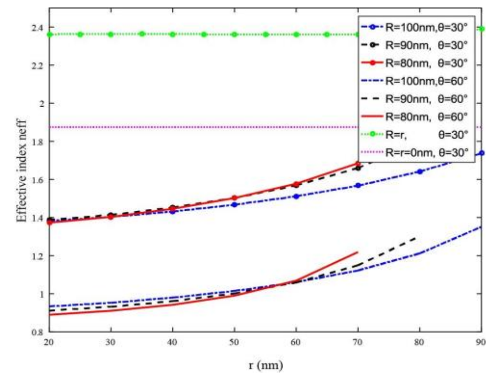
Fig. 4. Field distributions of the dominant electric component E_x and E_y on various angle.

Table 3: The maximum value of the electric field energy

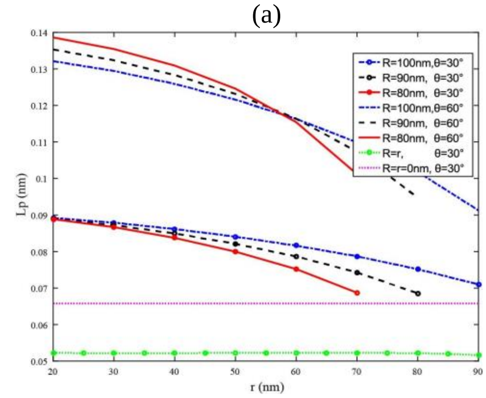
	$\theta = 0^0$	$\theta = 90^0$	$\theta = 180^0$
$\lvert E_x\rvert_{max}$ (V/m)	4.0724e8	3.2086e8	1.6468e8
$\lvert E_y\rvert_{max}$ (V/m)	1.4162e8	3.2585e8	5.7815e8

Next, comparison is carried out between the proposed CPPs, V-groove waveguide with metal nanowire ($R = r$) and conventional V-groove waveguide ($R = r = 0$) [8-11]. Simulation results reveal that the proposed CPPs model has low effective refractive index (n_{eff}), long-distance transport (L_p) and strong mode confinement (A_{eff}/A_0) in Figs. 5 (a)-(c). One can further prove the strongest coupling between the plasmonic and dielectric mode.

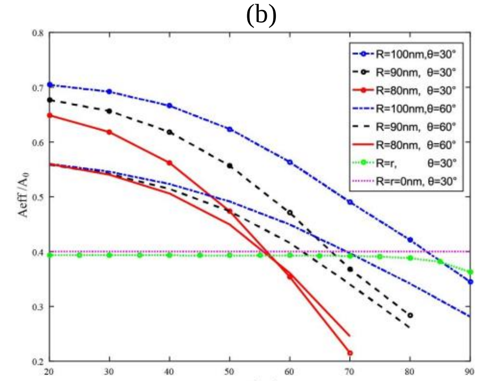
Further, these factors of R, r and θ on the impact of the modal properties have been investigated. For configurations with θ (e.g., $\theta = 30^0$), Figs. 5 (a)-(c) illustrates that the value of n_{eff} increases monotonically; the value of L_p and A_{eff}/A_0 decreases when r gets bigger with the same R. Correspondingly; the value of n_{eff}, L_p and A_{eff}/A_0 have the same trend when R gets smaller with the same r. Meanwhile, compared with different angles, performance gets better in accordance with bigger θ. So the hybrid plasmonic waveguide model with low loss and strong mode confinement can be realized by adjusting the values of the R, r and θ.



(a)



(b)



(c)

Fig. 5. Dependence of the modal properties of the fundamental hybrid mode with the different R and r; (a) the effective refractive index (n_{eff}), (b) the propagation length (L_p), and (c) normalized the effective area (A_{eff}/A_0).

IV. CONCLUSION

In this paper, a novel hybrid silicon groove waveguide model is proposed. FEM is used to numerically simulate the electric field energy for the fundamental hybrid plasmonic mode. Compared with conventional groove waveguide, more energy are confined on the low refractive index dielectric layer because of the strong coupling between plasma mode and dielectric mode. Meanwhile, these factors of R, r and θ on the impact of the modal properties have been investigated. The proposed model with low loss and strong mode confinement can be realized by adjusting the values of the R, r and θ, and polarization rotation of the hybrid mode can be achieved by changing the θ. Therefore, the proposed hybrid waveguide structure is compatible with traditional fabrication technologies, and has the potential to be used in highly integrated waveguide circuits.

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