

Communication

Power Loss Reduction of Angled Metallic Wedge Plasmonic Waveguides via the Interplay between Near-Field Optical Coupling and Modal Coupling

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Abstract: Coupled metallic-wedge nano-plasmonic (CWP) waveguides were predicted as the best building blocks, which can realize ultra-compact and broadband integrated optical circuits (IOCs) due to the localized near-field distributions at the dielectric/metal interfaces. Our simulation results show that the manipulations of the near-field distribution and the near-field modal coupling in CWP waveguides can effectively minimize the power loss by varying the wedge angles, which can avoid the loss from the metallic structure and thereby improving the practical application in IOCs.

Keywords: plasmonic waveguides; wedge angle; propagation characteristics; modal coupling; near-field coupling



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1. Introduction

Surface plasmon polariton (SPP) is a bounded optical mode at the dielectric/metal interface, which naturally localizes lightwaves at nanoscales and thereby increasing the light-material interactions [1-3]. In other words, the intrinsic ohmic loss impedes the longrange propagation in nanoplasmonic waveguides [4,5]. The power loss of nanoplasmonic waveguides can be decreased by tailing the field distribution of the SPP waves, which results in a trade-off between the modal size and power loss. Metallic V-shaped groove, wedge and coupled wedges structures [6–9] have been proposed to overcome the optical diffraction limit of waveguides while keeping the relatively low power losses, which is mainly due to the folded electromagnetic fields near the metallic nano-trench structure [10]. To demonstrate that the power losses are sufficient low, the nanoplasmonic waveguide based passive optical devices were investigated theoretically and experimentally [11–15]. In general, the insertion losses of SPP-based passive optical devices can be higher than 3 dB, which limited the practical application in integrated optical circuits (IOCs). Fortunately, the nanoplasmonic waveguides were also used as sensors [16-18] even though the intrinsic loss of metals cannot be avoided. It is noted that the figure of merit of plasmonic sensors is related to the field distribution and modal confinement [19–21]. In other words, it is worthwhile to control the near-field distribution and modal characteristics of plasmonic waveguides.

At the dielectric/metal interface, the modal field of a SPP wave consists of two opposite exponential decay functions along the normal vector of the metal surface. It can be predicted that the penetration depths in the dielectric and metal determine the modal size and power loss of the SPP wave, respectively. The penetration depths $(1/\text{Re}[\beta_1] \text{ and } \beta_1)$

 $1/\text{Re}[\beta_2]$) are related to the permittivity values of the dielectric and metal, which can be calculated by using the simple equation as follows:

$$\beta_i = (\omega/c) \sqrt{-\varepsilon_i^2/(\varepsilon_1 + \varepsilon_2)},\tag{1}$$

where ω is the angular frequency, *c* is the light speed in a vacuum, ε_1 is the permittivity of dielectric, ε_2 is the permittivity of metal and subscript *i* can be 1 or 2. In the optical telecommunication wavelength ranges, the real part of the permittivity values of noble metals is far larger than that of the dielectric materials. Therefore, the weak and strong dielectric responses result in the long penetration depth in the dielectric and the short penetration depth in the metal, respectively. Fortunately, the effective dielectric responses in dielectric materials and metals can be manipulated via the near-field optical coupling, which results in the position-dependent wave impedance of the supported SPP wave at nanoscales and thereby influencing the light-material interaction strength (power loss) [22]. The concept can be used to explain that why the power loss of SPP waves is related to the metallic wave-guiding structure. In other words, it is possible to reduce the propagation loss and increase the field confinement via manipulating the metallic wave-guiding structure.

In this study, we found that the near-field optical coupling [22] and modal coupling both influence the spatial distortion of the modal field, which can be used to manipulate power loss of the CWP waveguide. Our simulation results show that the lowest power loss and modal index can be simultaneously obtained when the wedge angle of the CWP waveguide decreases from 90° to 60°. In other words, the proposed CWP waveguide is the best building block for the realization of ultra-compact and broadband IOCs [23].

2. Simulation Layout and Methodology

The modal index, power loss and modal field distribution of the CWP waveguide are calculated by using the finite-difference time-domain (FDTD) method, fast Fourier transform technique and curving fitting process [9,22]. To effectively excite the fundamental mode and higher order modes of the CWP waveguides, an electrical dipole is used to effectively excite the SPP waves supported in the CWP waveguides. The perfectly matched layers (10 layers) [22] are used as the efficient absorbing boundaries in order to minimize the reflections from the outgoing electromagnetic waves at the six computational boundaries. The excitation wavelength of the electrical dipole is fixed at 1550 nm, which is widely used in the optical telecommunication wavelength range. Figure 1 presents the structure of the CWP waveguide and the related physical sizes. The width and height of the CWP were fixed at 600 nm and 1080 nm, respectively, which resulted in a longer propagation length when the wedge angle was 90° [9]. The wedge angle is varied from 90° to 15° . The metal is Au, Ag, Cu or Al. The used conditions (gird sizes and time step) in the FDTD simulations follow our previous report [22]. It is predicted that the optical modes and field distributions of the SPP waves are related to the wedge angle, which can be used to manipulate the power loss and modal index.



Figure 1. 3D view of the coupled metallic wedge nanoplasmonic (CWP) waveguide. SPP donates surface plasmon polariton. Metal can be Ag, Au, Cu or Al.

3. Results and Discussion

Figure 2 presents the normalized instantaneous electric field distributions along the propagation direction of the CWP waveguides with the different wedge angles from 90° to 15° . In the spatial range from 0 μ m to 5 μ m, the random variations in the amplitude originate from the interference between the guided mode and non-guided mode [24]. Therefore, the power loss and modal index of the CWP waveguide can be obtained by analyzing the electric field distribution from 5 μ m to 40 μ m (see Figure S1). When the wedge angle of the CWP waveguide is higher than 60° , the peak intensities of the x-directed electric filed (E_X) exponential decay along the propagation direction, which can be used to calculate the power loss of the waveguides. When the wedge angle of the CWP waveguide is lower than 45° , the interference beats can be observed in the instantaneous E_X distributions, which indicates that the fundamental mode and higher order modes can be simultaneously supported in the sharp CWP waveguides. In other words, the strength of the interference beats can be used to evaluate the modal overlap between CWP modes. In addition, the coupled fundamental mode and higher order mode has a reduced propagation loss due to the decreased modal index (field confinement) when the wedge angle is 15°. Figure 3 presents the power loss and modal index of the fundamental mode supported in the CWP waveguide with the different wedge angles from 90° to 15°. The trend of the power loss values is similar to the trend of the modal index values, which indicates that the stronger field confinement effect (larger modal index) corresponds to the higher power loss from the metal.



Figure 2. The distributions of instantaneously x-directed electric field (E_X) of the CPW waveguide along the propagation direction with the different wedge angles from 90° to 15°. Metal is Au.



Figure 3. Propagation characteristics of the CWP waveguide with the different wedge angles from 90° to 15° . (a) Power loss; (b) Modal index. Metal is Au.

Figure 4 presents the modal distributions of the CWP waveguide with the different wedge angles from 90° to 15° . The modal fields are extended from the two corners in the top region to the bottom region when the wedge angle decreases from 90° to 60° . The trend in the field confinements is consistent with the trends in the power loss and modal index values when the wedge angles decrease from 90° to 60° (see Figure 3). There is a significant change in the modal field from an extended field distribution to a localized field distribution when the wedge angle decreases from 60° to 45° , which can be used to explain the large increase in the modal index from 1.03 to 1.11. In contrast, the modal fields are more concentrated at the top corners when the wedge angle decreases from 45° to 15° . It is noted that the modal fields of the CWP waveguides near the side walls are more distorted in the smaller wedge angles, which means that modal fields consist of the fundamental mode and higher order modes. The spatial distortion of modal fields near the side walls (see Figure 4c-f) is proportional to the strength of the interference beats in the distributions of instantaneously E_X of the CWP waveguide (see Figure 2c–f). In other words, the spatial distortion of fields near the side walls can be used to confirm the existence of higher order modes in the CWP waveguides [25]. The strength of modal fields near the side walls increases with the decrease in the wedge angle from 45° to 15°, which means that the modal fields can be delocalized by decreasing the wedge angle and thereby reducing the modal index of the CWP waveguides. It is noted that the mode mainly distributes in the top region when the wedge angle is 60° (see Figure 4c). To evaluate the spatial distortion of modal field near the top corners and side walls, the differential of electric energy density of the CWP waveguide is plotted in Figure 5. Figure 6 presents the differential of electric energy density in the whole region and the region of top corners. Then trend of the differential of electric energy density values in the top corners region is proportional to the trend of the power loss values of the CWP waveguides (see Figure 3a), which indicates that the stronger field localization (spatial distortion of modal field) near the top corners results in the higher power loss. When the wedge angles are larger and smaller than 60° , the CWP waveguide can support a fundamental mode and a hybrid mode, respectively. It can be concluded that 60° is close to the transition wedge angle for the generation of the higher order modes in the CWP waveguide. In other words, the interplay between the near-field optical coupling and the modal coupling [26-28] can be used to explain the lowest power loss of the CWP waveguide at the transition wedge angle.



Figure 4. Modal distributions of the CWP waveguides with the different wedge angles from 90° to 15° . (a) 90° ; (b) 75° ; (c) 60° ; (d) 45° ; (e) 30° ; (f) 15° . Metal is Au. The length of scale bar is 600 nm.



Figure 5. The differential of electric energy density of the CWP waveguide with the different wedge angles from 90° to 15°. (a) 90°; (b) 75°; (c) 60°; (d) 45°; (e) 30°; (f) 15°. Metal is Au. The length of scale bar is 600 nm.



Figure 6. The differential of electric energy density (E_D) of the CWP waveguide with the different wedge angles from 90° to 15°. Metal is Au.

Figure 7 presents the power loss values and modal index values of the CWP waveguides for the different metals (Al, Cu, Ag and Au). The modal index and power loss are mainly related to the real part of dielectric constant and the extinction coefficient of the used metals, respectively. At the wavelength of 1550 nm, the real part of dielectric constant and the extinction coefficient of Al, Cu, Ag and Au are -232.67 (15.33), -109.04 (10.45), -103.32 (10.17) and -93.07 (9.66), respectively [29]. In other words, the low negative dielectric response and small extinction coefficient are the desired parameters for the used metallic material in the CWP waveguide in order to satisfy the requirements of modal field confinement at nanoscales and long-range propagation simultaneously.



Figure 7. The power loss values and modal index values of the CWP waveguide for the different metals (Al, Cu, Ag and Cu). The wedge angle is 60°.

4. Conclusions

In summary, we have theoretically investigated the interplay between the near-field optical coupling and the modal coupling of the coupled metallic-wedge nano-plasmonic (CWP) waveguide with the different wedge angles at the wavelength of 1550 nm. At the transition wedge angle of 60°, the lowest power loss of the CWP waveguide can be explained as due to the lowest modal index and the lowest spatial distortion. In addition, power loss and modal index of the CWP waveguide are intrinsically related to the extinction coefficient and dielectric response of the used metal.

Supplementary Materials: The following supporting information can be downloaded at: https: //www.mdpi.com/article/10.3390/photonics9090663/s1, Figure S1: (a) E_X -Y plot and the fitting curve. (b) Modal wavelength spectrum.

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