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PLASMON WAVE PROPAGATION PROPERTY OF METAL WEDGE PLASMONIC WAVEGUIDES COVERED BY A PROTECTIVE OXIDE LAYER

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Abstract. *Guiding plasmon waves is based on dielectric/metal interfaces. The wedge-shaped interface shows an excellent capacity in the tight lightwave confinement at deep-subwavelength propagation mode size. Several types of metals have also been investigated for guiding plasmon waves. Among them, the Ag metal shows a plasmon wave guiding ability superior to other metals, however, it is sensitive to the operating medium and is easily oxidized. To overcome these drawbacks, the Ag wedge covered by a protective thin oxide layer is proposed. Numerically investigated results show that the propagation length of the Ag wedge covered by a protective thin silicon dioxide layer can be enhanced by a factor of 7.5 while its figure of merit is at least 1.7 times larger than that of the Au wedge waveguide. The advantage of the proposed interface is potential for developing plasmonic waveguide components.*

Keywords: surface plasmon polariton; wedge plasmonic waveguide; protective oxide layer covered metal layer.

Classification numbers: 68.47.Gh; 73.20.Mf.

I. INTRODUCTION

Guiding lightwaves by the conventional dielectric waveguides is limited by the optical diffraction effect. To overcome this problem, optical waveguides guiding lightwaves based on surface plasmon polariton (SPP) have been introduced and intensively studied in recent years [1–3]. SPP waveguides can be found in applications such as fundamental elements in integrated nanophotonic circuits including lightwave guiding at nanoscale, optical switches, optical modulators, and optical sensors [1–12]. Various types of SPP waveguide have been proposed for improving the propagation length while keeping the propagation mode area at subwavelength size such as metallic nanowires [13], metal strips [14], and wedge-shaped waveguides [15,16]. Among these waveguides, the wedge-shaped SPP waveguides show an excellent capability of the tight lightwave confinement around the apex of metallic wedge [3]. Furthermore, several types of metals for guiding SPP waves have also been investigated [17–20]. The Ag metal shows a surface wave guiding ability superior to other metals; however, it is unstable to the operating medium and is easily oxidized. To protect the Ag metal layer, an Au metal layer inert to operating medium is proposed for covering on the Ag wedge waveguide [4]. The investigated results show that the propagation length of SPP using the Au/Ag double-layer structure with an appropriate thickness of the Au covering layer can be increased by a factor of 2.5 compared to that of using the only Au metallic structure at the same propagation mode area. However, lightwave guiding based on metals such as Au is limited due to Ohmic loss.

To solve this problem we propose a waveguide structure that consists of an Ag wedge covered by a thin protective oxide layer. We will investigate the effect of the oxide layer on the propagation properties of the waveguide. To confirm the performance of the proposed waveguide, we compare its propagation characteristics with the other metal wedge waveguides and previously published works.

II. THE BACKGROUND OF STUDY

The SPP is a surface electromagnetic wave propagating along the metal/dielectric interface, which is the result of the strong coupling between light and collective oscillation of free electrons at the metal surface. The advantage of SPP is its exhibition at remarkable mode confinement capabilities at a deep-subwavelength scale. The ability of SPP wave propagation and confinement of a dielectric/metal interface depends on the complex dielectric function $\varepsilon(\omega)$ as well as the complex refractive index of metal, $N(\omega) = \sqrt{\varepsilon} = n(\omega) + ik(\omega)$, here, ω is angular frequency of lightwave [21]. $k(\omega)$ is called the extinction coefficient and determines the optical absorption of electromagnetic waves propagating through medium. For convenience in comparison, four commonly-used metals and their complex refractive indexes at the optical communication wavelength in plasmonics, Ag, Au, Cu and Al, are listed in Table 1 [22]. The propagation lengths (LSPP) and figure of merit (FoM) of wedge plasmonic waveguides based on these metals are also calculated and shown in Table 1. Figure 1 (a) shows the cross-section of conventional metal wedge plasmonic waveguide. The wedge plasmonic waveguide is formed by depositing a thin metal layer on a silicon waveguide (SW) which can be fabricated by using the anisotropic wet etching property of single crystal silicon in potassium solution [16, 23]. Therefore, the apex angle of SW is 70o. The height of SW is also kept constant to be 0.5 μm for all investigations. This size is chosen to satisfy the single mode condition of SW [24]. LSPP is obtained by $L_{SPP} = \lambda/[4\pi \mathrm{Im}(\beta)]$, here, β is the propagation constant along the waveguide, y-axis (Fig. 1) [21]. The figure of merit FoM as a trade–off between the propagation attenuation and the mode confinement, which is defined by $FoM = LSPP/\sqrt{(A_{eff})}$ [25]. Here, Aeff is the effective propagation mode area, which is defined by [4, 26]

$$A_{eff} = \iint \frac{W(r)}{maxW(r)} dA, \tag{1}$$

where $W(r)$ is the electromagnetic energy density defined as:

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

where, $E(r)$ and $H(r)$ are the electric and magnetic fields, $\varepsilon(r)$ is the electric permittivity and μ_0 is the vacuum magnetic permeability.

These characteristics of the plasmonic waveguide are numerically investigated by solving the Helmholtz equation using the boundary mode analysis problem in the finite element method based COMSOL Multiphysics [26]. By solving the Helmholtz equation, we can obtain the spatial field distributions and the modal characteristics of the propagating wave in the device. The propagation properties of the device are evaluated at a telecommunication wavelength of 1.55 μm. The material of the support and the dielectric waveguide is single crystal silicon which has the refractive index of 3.4757. The gap medium is air with the index of 1.0.

Table 1. Complex refractive indexes and SPP propagation length calculated at the optical communication wavelength of 1.55 μm of commonly-used metals in plasmonics.

Metals Oxide\ Physical parameters	Refractive index (n)	Extinction coefficient (k)	LSPP (μ)m)	FoM (10^3)
Ag	0.15	11.57	300	59
Au	0.24	11.26	75	15
Cu	0.26	9.8	66	13.7
Al	1.42	15.1	44	8.6

From the results shown in Table 1, it is clear that the propagation length of Ag wedge waveguide is larger than that of the other wedge waveguides. In these investigations, we used a wedge waveguide consisting of a single crystalline silicon wedge covered by a metal layer of 200 nm. Compared with the second good metal, Au, its propagation length is larger than a factor of 4. However, Ag is easily oxidized in the operating medium, such as air or aqueous environments [4]. The refractive index of AgO_x film depends on the component ratio x [27]. Thus, the above investigated results show that Ag has the SPP wave guiding ability is superior to the other plasmonic metals; however, the sensitivity to the operating medium degrades the performance of Ag wedge waveguide.

In the following investigation, we assume that the metal films on SW are oxidized. Thus, the structure of waveguide is shown in Fig. 1 (b), which is composed of an oxidized metal layer on the metal film in Fig. 1(a). Table 2 shows the complex refractive index of oxides of Ag, Cu and Al [22]. These oxides are fabricated by different methods, including reactive sputtering, thermal oxidation, and sintering, electrodeposition [4, 22, 27–29]. The propagation lengths and figure of merit of respective plasmonic waveguides are also calculated and shown for comparison. In the calculations, we assumed that a 5 nm thin oxide layer are deposited respectively on a 195 nm metal layer for three metals, Ag, Cu and Al which are easily oxidized in environment. It is clear that the Ag-based plasmonic waveguide also shows LSPP and FoM superior to the remaining plasmonic waveguides

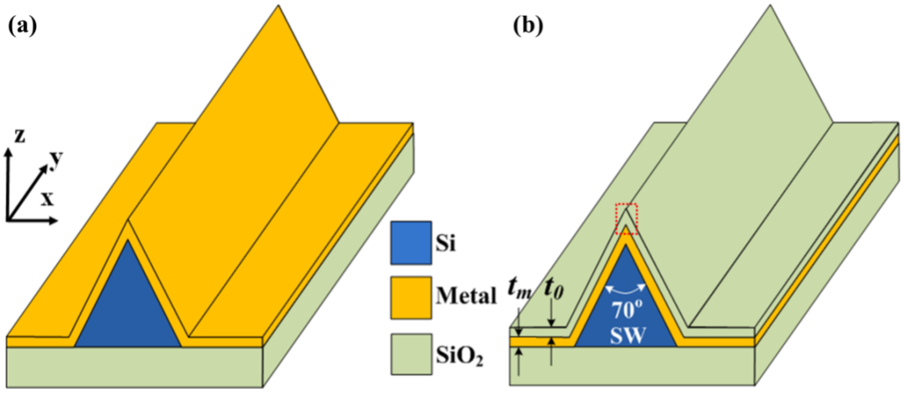

Fig. 1. (a) Conventional metal wedge plasmonic waveguide: a thin metal layer covering on a dielectric photonic waveguide for investigating comparatively the propagation characteristics of metals, Ag, Au, Cu and Al; (b) metal wedge plasmonic waveguide similar to (a), however, a thin oxidized metal layer covered on a respective thin metal layer.

Complex refractive indexes and SPP propagation length of metal wedge waveguides covered by a respective 5 nm thin oxide layer calculated at the optical communication wavelength of 1.55 μm.

Table 2. Complex refractive indexes and SPP propagation length calculated at the optical communication wavelength of 1.55 μm of commonly-used metals in plasmonics.

Metals Oxide\ Physical parameters	Refractive index (n)	Extinction coefficient (k)	LSPP (μ)m)	FoM (10^3)
Ag2O	2.8	0.25	160	12.1
CuO	2	0.03	89	3.23
Cu2O	1.6214	8×10^{-5}	73	2.59

III. RESULTS AND DISCUSSION

To protect the metals from oxidation, we choose the SiO_2 layer as a protective oxide layer for depositing on the Ag wedge. The oxide layer SiO_2 is a stable material layer to environment. Furthermore, the SiO_2 layer has low refractive index (1.445) compared to the above-investigated plasmonic metals and its fabrication technology is well established. The proposed waveguide model is shown in Fig. 1 (b).

Firstly, we investigate the modal characteristics of the proposed waveguide. Then, we will compare its performance with the conventional metal wedge plasmonic waveguides having an identical geometry. In the following investigations, we choose Ag and Au, two typical metals having the best wave guiding properties for comparative investigation. Fig. 2a presents the investigated result of the normalized mode area, A_{eff}/A_0, as a function of t_0/t_m. Here, $A_0(=\lambda^2/4)$ is the diffraction-limited mode area in free space, and t_m is the thickness of the Ag metal layer.

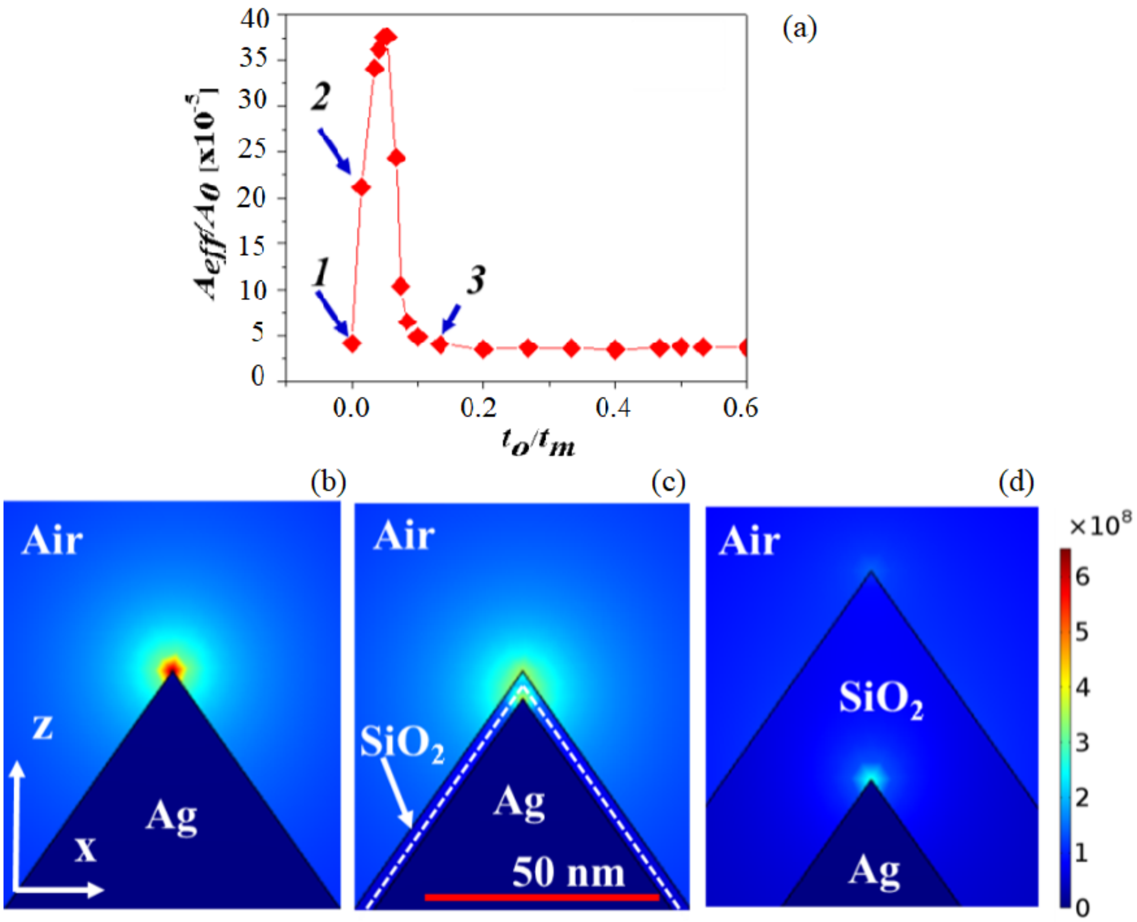

Fig. 2. Normalized mode area and electromagnetic distributions of the wedge plasmonic waveguides with the height of the SiO_2 support to be 1 μm and $t_m + t_0 = 150$ nm: (a) A_{eff}/A_0 as a function of t_0/t_m, (b)-(d) electromagnetic distribution images of Ag wedge embedded in Air and Ag wedge covered by 2 nm and 15 nm SiO_2 layers respectively, which correspond to the data points 1, 2, and 3 in (a). Here, the electromagnetic distribution images are taken from the apex of the waveguide in Fig. 1b including the parts of Ag, SiO_2 and air medium marked in the rectangular.

Figs. 2b, 2c, and 2d show the normalized electric field distributions of the wedge SPP mode for the Ag wedge waveguide embedded in air and the Ag wedge waveguide covered by SiO_2 layers with the thickness of $t_0 = 2$ nm and 15 nm, respectively. When $t_0/t_m \leq 0.05$, the mode area increases with t_0/t_m which is due to the extension of electromagnetic field to the two interfaces, the air/SiO_2 interface and the SiO_2/Ag interface, Fig. 2c. When $0.05 < t_0/t_m < 0.1$, the SPP mode is gradually squeezed into the oxide layer with the increment of t_0/t_m. At values $t_0/t_m > 0.1$, the SPP mode is absolutely squeezed into the oxide layer (Fig. 2d, $t_0 = 15$ nm). When $t_0/t_m > 0.1$, the mode area of the Ag and SiO_2/Ag wedge waveguides is almost constant ($A_{eff} = \lambda^2/10^5$), Fig. 2a. In this investigation, we have fixed the sum $t_m + t_0$ at 150 nm. In addition, the normalized mode area strongly depends on the total height the plasmonic waveguide [4]. In practice, tm should be chosen at a definite value (normally, tm is in the range 100 - 250 nm) to ensure the plasmon wave guiding while it does not need too thick due to time-consuming metal film depositing process and high cost in fabricating devices. Therefore, we have chosen $t_m + t_0 = 150$ nm. In this case, tm has a wide tolerance for application while t_0 can be appropriately varied to squeeze the guiding mode into the oxide layer.

Now, we investigate the propagation length of SPP mode of the SiO_2/Ag waveguide (L_{SPP}) depending on the thickness ratio between the SiO_2 layer and the Ag metal layer, t_0/t_m. Fig. 3 shows L_{SPP} investigated as a function of t_0/t_m for three different Ag thicknesses, $t_m = 75$ nm, 100 nm, and 125 nm. At first, when $t_0/t_m \leq 0.05$, L_{SPP} increases with t_0/t_m due to the extension of the mode area as analysed above. Then, when increasing the thickness of the SiO_2 layer the propagation length of the waveguide is strongly decreased. When t_0/t_m increases from 0.05 to 1, LSPP decreases more than 9 times (from 740 μm to 82 μm for the case $t_m = 125$ nm, Fig. 3).

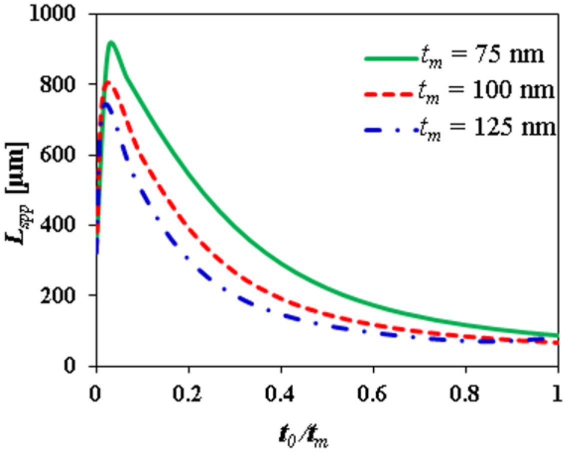

Fig. 3. Propagation length of thin SiO_2 layer/Ag wedge waveguide investigated as a function of thickness ratio between the SiO_2 layer and Ag layer, t_0/t_m, with three different values of Ag layer thickness $t_m = 75$ nm, 100 nm, and 125 nm.

Having investigated the modal characteristics of the SiO_2/Ag wedge plasmonic waveguide, we now compare its performance with other metal wedge waveguides. Firstly, we consider the propagation length. From the above investigations, two protective thin SiO_2 layers are chosen for depositing on the Ag wedge to be 2 nm and 5 nm. These thickness values are feasible to the current thin film depositing technologies. The Au wedge waveguide is used for study because it is stable to the operating medium and also has quite good SPP wave guiding property. It is clear from Fig. 4a that the Ag wedge covered by a thin SiO_2 layer has much better SPP wave guiding property than the Au wedge embedded in air. Even though the Ag wedge is embedded in the SiO_2 medium (the thickness of the SiO_2 layer is considered to be infinite), its LSPP is also larger than 1.7 times compared to that of the Au wedge embedded in air (Fig. 4a). This is due to the fact that for a metal wedge embedded in a dielectric medium, the propagation length and propagation mode area decrease with the increment of the refractive index of operation medium [16]. For a 2 nm thin SiO_2 layer, LSPP of the proposed waveguide can be enhanced by a factor of 7.5 compared to that of the Au wedge embedded in air for the case $t_m = 250$ nm (543 μm compared to 72 μm), Fig. 4a. Thus, using the SiO_2 layer as a protective layer, we have enhanced LSPP by a factor of 3.75 larger than that using the protective layer made of Au (the propagation length enhances a factor of 7.5 in the current work compared to 2.5 in Ref. [4]).

Secondly, we compare the quality of the proposed waveguide with the conventional waveguides. We use the figure of merit FoM as a trade–off between the propagation attenuation and the mode confinement as presented in section 2. The investigated FoM values for the two types of

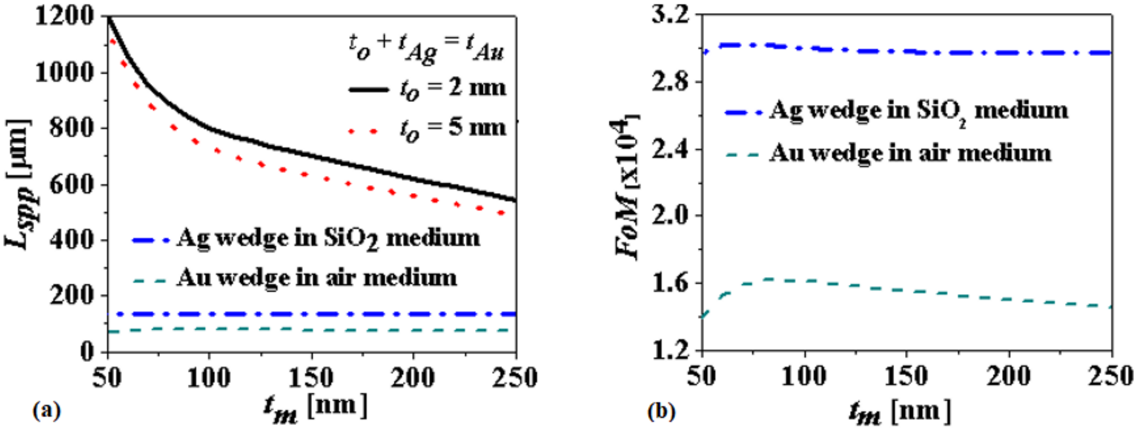

Fig. 4. Comparative characteristics of the proposed plasmonic waveguide and the conventional Au wedge waveguide: (a) propagation length depending on t_m of the Ag metal wedge covered by SiO_2 layers with the thickness of 2 nm (continuous line) and 5 nm (dot line), embedded in the SiO_2 medium (dashed dot line), and the Au wedge embedded in air medium (dashed line), (b) the figure of merit of the Ag wedge waveguide embedded in SiO_2 medium and the Au wedge waveguide embedded in air medium.

waveguide are shown in Fig. 4b. As discussed above about the propagation length, although the Ag wedge is embedded in the SiO_2 medium, its LSPP is much larger than that of the Au wedge embedded in air (Fig. 4a). When comparing the two critical cases shown by the low curves in Fig. 4a, the FoM value of the Ag wedge embedded in the SiO_2 medium is also larger than a factor of 1.7 compared to that of the Au wedge embedded in air (Fig. 4b). Thus, we can use the Ag metal for plasmonic waveguide based devices due to its excellent lightwave guiding ability compared to other metals. This can be carried out by depositing a protective thin oxide layer on the Ag metal layer.

IV. CONCLUSION

We have proposed a dielectric/metal interface for improving the propagation length of plasmonic waveguides. The interface is formed from a metal which has a good plasmon wave guiding property however it is unstable to the operating medium covered by a thin protective oxide layer. Using the Ag wedge covered by a thin protective SiO_2 layer, we can increase the propagation length by a factor larger than 7.5 compared to that using the Au wedge embedded in air.

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