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Decay and propagation properties of symmetric surface plasmon polariton mode in metal–insulator–metal waveguide

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ABSTRACT

Decay and propagation properties of symmetric surface plasmon polariton (SPP) mode based on metal–insulator–metal (MIM) waveguide are investigated numerically. SPP mode is excited through a dipole embedded in Al_2O_3 layer of $Au/Al_2O_3/Au$ structure. We demonstrate that the distance between the dipole and Al_2O_3/Au interface is an important tunable parameter to influence the decay properties. The electric/magnetic field intensity horizontal and vertical decay lengths of symmetric SPP mode are 19 nm and 24 nm, respectively. Moreover, the propagation length along Al_2O_3/Au interface of symmetric SPP mode depends on Al_2O_3 layer thickness. The maximal propagation length reaches 0.608 μm with Al_2O_3 layer thickness of 100 nm. These values can provide a theoretical reference for designing a high-performance SPP source using $Au/Al_2O_3/Au$ structure.

1. Introduction

Surface plasmon polaritons (SPPs) are electromagnetic waves coupled to collective oscillations of electron plasma in the metal. They propagate along metal–dielectric interface with the amplitude decaying into both sides exponentially [1]. This surface localization, confining the optical mode to subwavelength scale and minimizing the optical mode size, makes plasmonic waveguide an intriguing alternative to conventional dielectric-based waveguide. Therefore, some novel photonic devices based on SPP are gained with metal–insulator–metal (MIM) waveguide [2,3], such as filters [4–6], couplers [7,8], splitters [9,10], and Bragg reflectors [11,12]. Offering higher confinement factors and closer spacing to adjacent waveguides or structures [13,14], SPP is becoming very promising for compact plasmonic devices of photonic integration.

More recently, one interesting way to excite SPP in MIM waveguide by squeezing the optical energy in nanometric cross section and light-inducing was proposed [4]. An electrical source of SPP using organic diode by Koller [15] and using $Au/Al_2O_3/Au$ (MIM) structure by Walters [16] was demonstrated experimentally. Particularly, Walters and his coworkers theoretically illustrated that under a certain condition of insulator layer thickness ($20-150$ nm) only one propagating subwavelength SPP mode can occur in MIM waveguide.

To the best of my knowledge, some theoretical studies have already gone deep into investigating surface plasmon existence, propagation and confinement in passive MIM structures [17–19,7,20]. However, few literature reports the decay length of excited MIM SPP mode electromagnetic field profile with a dipole in MIM waveguide and the influence of insulator layer thickness on propagation length in detail. It is vital important to explore the effective coupling and propagating of SPP excited between multilayer luminescence centers in MIM waveguide.

In this paper, we investigate the properties of excited SPP mode in the structure of $Au/Al_2O_3/Au$ (MIM) waveguide, in which a dipole is embedded, using the finite-difference time-domain (FDTD) method. Specifically, we introduce an insightful modal discussion for the first time on the influence of the distance between the diploe and Al_2O_3/Au interface (d) to the decay properties and the thickness of insulator layer (w) to the propagation properties of subwavelength symmetric MIM SPP mode. On one hand we study the electromagnetic field intensity decay by tuning the distance d, on the other hand, we discuss the propagation properties of MIM SPP by tuning the thickness w. The presented method in this paper could be valuable for quantitatively studying the efficient SPP

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mode excitation using multilayer luminescence center structures and the valid propagation of SPP mode by tuning the thickness w in Au/Al_2O_3/Au waveguide, thus it may be applied in designing a new SPP source application in CMOS and organic semiconductors.

2. Device model's structure and design

Based on the above literatures' research, especially the theoretical and experimental results of the groups of Koller and Walters, we design deliberately the subwavelength device model's structure and parameters, as shown in Fig. 1(a). The proposed MIM waveguide is composed of two identical Au films (thickness 200 nm) which are separated by an insulator layer Al_2O_3 (thickness 100 nm) (MIM) [21] and its horizontal length is infinite. Here, the reason we choose Nobel metal material of Au is because of its lower imaginary part of the dielectric function and less loss comparing with Cu or Ag, leading to a bigger skin depth. In addition, the coordinates are also given, where x, y and z are the transverse, lateral, and the propagation direction, respectively, as schematically shown in Fig. 1. When the thickness of Al_2O_3 dielectric layer, w, is reduced below the diffraction limit, conventional guiding modes cannot exist. In this case, a transverse electric (TE) 90° polarization incident light (electric dipole) being embedded in the Al_2O_3 dielectric layer is transformed into symmetric MIM SPP mode on the metal surfaces and propagates along the waveguide. The field is confined inside the insulator layer (Al_2O_3). The simulated electric-field intensity distribution of the MIM SPP mode is shown in Fig. 1 (c). The characteristic equation of symmetric MIM SPP mode is given by [20]

$$\frac{\kappa_m}{\varepsilon_m}+\frac{\kappa_d}{\varepsilon_d}\tanh\left(\kappa_d\frac{w}{2}\right)=0, \tag{1}$$

where $\kappa_m=(\beta_{SPP}^2-\varepsilon_m)^{1/2}$ and $\kappa_d=(\beta_{SPP}^2-\varepsilon_d)^{1/2}$ denote the transverse wavenumber of the plasmonic mode in the metal and the dielectric respectively. Gold for the metallic cladding layers is characterized by the Drude model [22]

$$\varepsilon_m=1-\frac{\omega_p^2}{\omega(\omega+i\gamma)}, \tag{2}$$

where $\omega_p=1.2\times10^{16}$ Hz and $\gamma=1.2\times10^{14}$ Hz are the bulk plasma and damping frequencies, respectively, and refractive index of Al_2O_3 $n_d=1.7$. The Au/Al_2O_3/Au waveguide two-dimensional (2D) structure is designed and modeled by a commercial FDTD package that supports ununiform meshing and eigenmode calculation. The 2D FDTD method with the perfectly matched layer (PML) as the boundary condition is used in this work. The dipole is located in Al_2O_3 dielectric layer at distances of 10, 15, 20, 25, 30, 35, 40, 45 and 50 nm (d) from interface 1 (between nether Au layer and Al_2O_3 layer), when the thickness of Al_2O_3 is fixed at 100 nm. The fundamental TM mode (E_x, E_y, H_z) is excited. The power monitor (PD), vertically placed at interface 1 about 1 μm from the dipole source, is set to detect the incident power flow information.

3. Results and discussion

The simulated electric field intensity in x direction horizontal profiles ($i_{E_x}^x$) at interface 1 with different d for the free space wavelength of dipole from 0.6 to 1.5 μm is shown in Fig. 2(a). The other simulated electric field intensity in y direction horizontal profiles ($i_{E_y}^x$) and magnetic field intensity in z direction horizontal profiles ($i_{H_z}^x$) are not shown because their change trend is similar with $i_{E_x}^x$. When d is varied from 10 to 50 nm in a step of 5 nm, $i_{E_x}^x$ decreases due to the different coupling strengths between the dipole and *Au*/*Al*$_2$*O*$_3$/*Au* waveguide [16]. Therefore, d is critical to the SPP coupling strength. As d gets larger, the SPP coupling strength becomes weaker, leading to the decrease of $i_{E_x}^x$. The MIM SPP resonance mode (peak), which results from Fabry–Perot interference of SPP, clearly appears. Thus, we plot two curves based on the data from peak of $i_{E_x}^x$. The electric field peak intensity in x direction ($i_{E_x(\text{peak})}^x$) and peak wavelength (λ_{SPP}) as a function of d are shown in the inset of Fig. 2(a). λ_{SPP} red shifts consistently and $i_{E_x(\text{peak})}^x$ exponentially decays. The exponential relationship between $i_{E_x(\text{peak})}^x$ and d becomes obvious. $i_{E_x(\text{peak})}^x$ can be fitted using an exponential function to determine the horizontal decay properties of MIM SPP mode. The equation of fitting curve is $i_{E_x(\text{peak})}^x=3\exp(-d/19)+5$. So, the horizontal decay length is 19 nm. It arises from the fact that the increase of d by 19 nm results in $i_{E_x(\text{peak})}^x$ being diminished by $1/e$. This is very useful for designing an SPP source with a desirable distance (~19 nm) between luminescence centers, to make best SPP coupling between top and bottom Au films in Au/Al_2O_3/Au waveguide, thus to efficiently generate SPP. This also provides a theoretical basis for experimentally obtaining a high-performance SPP source, with the distance of 20 nm between luminescence centers using Au/Al_2O_3/Au structure [16]. The reason of the redshift of λ_{SPP} with the augment of d is that the symmetric coupling role of SPP becomes strong when the location of the dipole is close to the middle position. In addition, $i_{E_y}^x$ and $i_{H_z}^x$ at interface 1 are also calculated. It is found that the change trend of $i_{E_y}^x$ and $i_{H_z}^x$ is similar with $i_{E_x}^x$. The

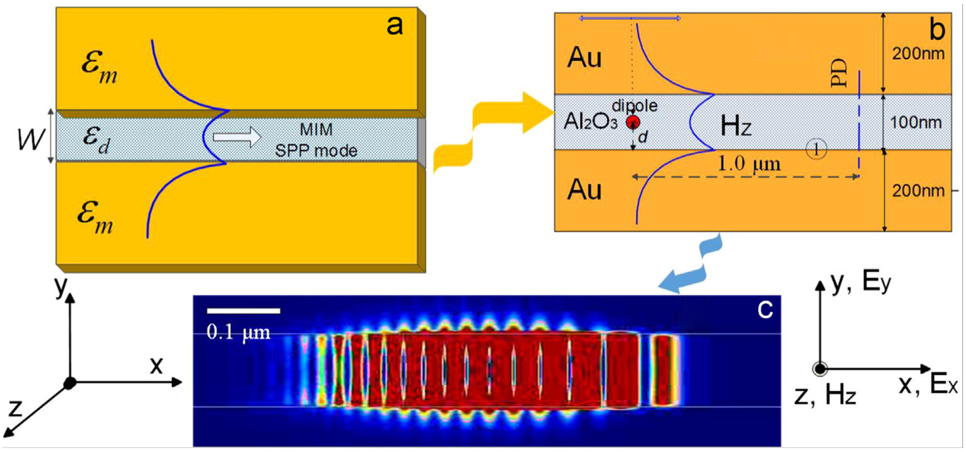

Fig. 1. (a) The schematic of Au/Al_2O_3/Au waveguide and a dipole being embedded in Al_2O_3 layer to excite MIM SPP mode for forward propagating. (b) The front view of device model's structure and design parameters for MIM waveguide. (c) The simulated electric-field intensity distribution of the MIM SPP mode.

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