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Metal plate for guiding terahertz surface plasmon-polaritons and its sensing applications

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ABSTRACT

We report the guiding of THz surface plasmon-polaritons using metal plates. We theoretically study the transmission characteristics of the bare and dielectric coated metal plate and compared the difference between them. We propose coupling the THz SPPs on a bare metal plate using single dielectric film, and the highest theory coupling efficiency we get can be 45.64%. Moreover we study the hybrid plasmonic modes of a dielectric slab above the metal plate, and we find that the THz SPPs on metal plate is strongly affected by the dielectric slab. We further discuss the interesting phenomenon of the transmission spectrum influenced by the variation of air interval between the dielectric slab and metal plate.

1. Introduction

THz waveguides have been widely studied in recent years, such as cylindrical wire waveguides [1], low-index THz pipe waveguides [2] and planar wire waveguides [3]. Since they are first proposed, there are many similar THz waveguides [4–7] have been studied, and many interesting theoretical and experimental conclusions have been given. THz waveguides have been widely used in communications, spectroscopy, imaging, detection and sensing [8–11]. The sensing of the thin dielectric film on the cylindrical metal wires are reported by several articles [10,11]. There are also several articles report the THz surface plasmon-polaritons (THz SPPs) on single metal plate [12–14], and the sensing of dielectric film on single metal plate surface has also been discussed [13,14]. Although similar results have been given on coated or uncoated metal plates waveguide, the theory has not been given exclusively yet. And even though the coupling efficiency is increased much after coating the metal plate, the coupling efficiency to bare metal plate is extremely low [12]. Moreover the hybrid plasmonic modes [15,16] of a dielectric slab above the metal plate is not discussed yet.

In this paper, we report the guiding of THz SPPs using metal plates. We theoretically study the transmission characteristics of the bare and dielectric coated metal plate and compared the difference between them. We propose coupling the THz SPPs on bare metal plate using single dielectric film, and the highest theory coupling efficiency we get can be 45.64%. Then we study the hybrid plasmonic modes of a dielectric slab above the metal plate, and we find that the THz SPPs on metal plate is strongly affected by the dielectric slab. We further discuss the interesting phenomenon of the transmission spectrum influenced by the variation of the air interval between the dielectric slab and metal plate. We believe that these results are very useful for sensing applications of THz SPPs on metal plate.

2. THz SPPs on metal plate

The structure of metal plate is shown in Fig. 1, $x=0$ plane is on the metal interface, and the waveguide width in y direction is infinity. When transverse magnetic (TM) modes propagate in positive z-direction, the field components can be written as [17]:

$$H_y(x) = \begin{cases} Ae^{-h_1 x} & x \geq 0 \\ Ae^{h_m x} & x \leq 0 \end{cases} \quad (1)$$

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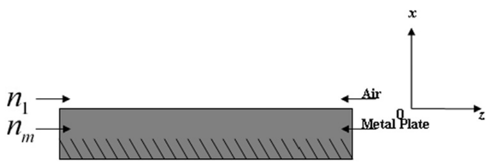

Fig. 1. Metal plate structure and the coordinate system.

where A is a coefficient related with the mode power; $h_1 = (\beta^2 - n_1^2 k_0^2)^{1/2}$, $h_m = (\beta^2 - n_m^2 k_0^2)^{1/2}$; n_1 and n_m are refractive index of air and metal, respectively. $\beta = \beta_1 - j\alpha$ is the propagation constant of the guiding mode, in which the real part β_1 is related to the effective refractive index $n_{eff} = \beta_1 / k_0$ and the imaginary part α is the loss coefficient of the mode. k_0 is the wave vector in vacuum.

The dispersion equation of TM mode can be represented as [7]:

$$\beta = \sqrt{\frac{\varepsilon_m \varepsilon_1}{\varepsilon_1 + \varepsilon_m}} k_0 \tag{2}$$

$\varepsilon_1 = n_1^2$ and $\varepsilon_m = n_m^2$ are the relative permittivity of air and metal plate respectively. Copper is used as the material for metal plate, and the relative permittivity can be obtained according to Drude model:

$$\varepsilon_m = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 - j\omega\omega_\tau} \tag{3}$$

where ω is the angular frequency of the THz wave, ε_∞ is the high frequency permittivity of copper, which is always negligible in the THz region. $\omega_p = 1.1234 \times 10^{16}$ Hz and $\omega_\tau = 1.3798 \times 10^{13}$ Hz are the plasma oscillation frequency and damping frequency of copper [18], respectively.

By Eq.(2), we calculate the dependence of the loss on THz frequency and present the corresponding effective refractive index as shown in Fig. 2:

Fig. 2 illustrates that the loss increases with the increase of frequency, and it is very low. For the regime of less than 1 THz, the loss is lower than 0.008 m^{-1} which is two orders of magnitude lower than the loss of cylindrical wire THz SPPs. However, the effective refractive index is closer to 1 than that of cylindrical wire, and $n_{eff} - 1$ is in the magnitude of 10^{-9}, which means the dispersion is much lower and the mode field radius is much larger.

By Eq. (1), we get the mode field distribution of the metal plate at 1 THz, as shown in Fig. 3:

Fig. 3 illustrates that the field amplitude of metal plate mode is still very strong at 200 mm in the air. However, the THz wave transmits through 0.2 μm in metal only.

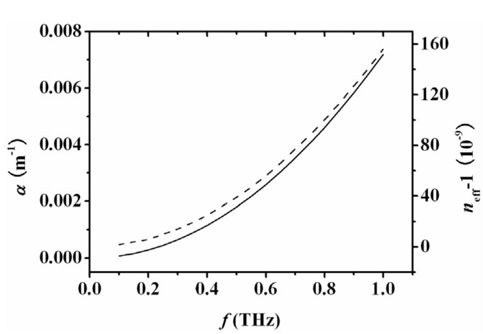

Fig. 2. Loss (solid line) and effective refractive index (dashed line) of metal plate THz SPPs as a function of THz frequency.

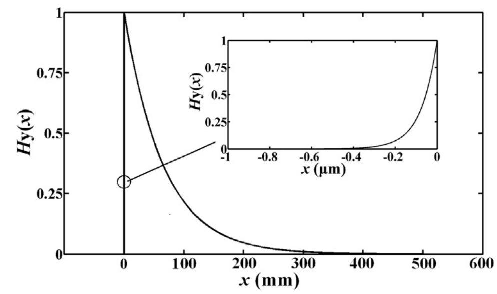

Fig. 3. Mode field distribution of metal plate THz SPPs at 1 THz. Inset shows the mode field distribution in the metal.

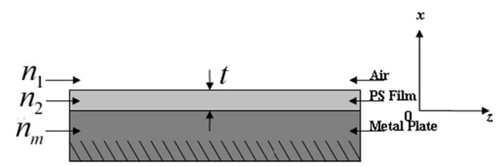

Fig. 4. Dielectric cladding metal plate structure and coordinate system.

3. Sensing applications of metal plate

3.1. The sensing of dielectric film on metal plate

The dielectric cladding metal plate structure is shown in Fig. 4. According to Fig. 4, the waveguide structure has three layers, where $x=0$ plane is still on the metal interface, and a dielectric film of thickness t is placed on the metal plate. When TM modes propagate in the positive z-direction, the mode field distribution equations can be written as [17]:

$$H_y(x) = \begin{cases} A\left(\cos h_2 t + \dfrac{h_m \varepsilon_2}{h_2 \varepsilon_m} \sin h_2 t\right) e^{-h_1 (x-t)} & x \geq t \\ A\left(\cos h_2 x + \dfrac{h_m \varepsilon_2}{h_2 \varepsilon_m} \sin h_2 x\right) & 0 \leq x \leq t \\ A e^{h_m x} & x \leq 0 \end{cases} \tag{4}$$

The dispersion equation of TM mode is [17]:

$$\tan h_2 t = \frac{h_2 \varepsilon_m h_1 \varepsilon_2 + h_m \varepsilon_1 h_2 \varepsilon_2}{h_2 \varepsilon_m h_2 \varepsilon_1 - h_m \varepsilon_2 h_1 \varepsilon_2} \tag{5}$$

where $h_1 = (\beta^2 - n_1^2 k^2)^{1/2}$, $h_2 = (n_2^2 k^2 - \beta^2)^{1/2}$, $h_m = (\beta^2 - n_m^2 k^2)^{1/2}$. Polystyrene (PS) is used as the material of the dielectric film with a parameter of $n_2 = \sqrt{\varepsilon_2} = 1.58 - j0.0036$ [19].

By Eq.(5), we calculate the dependence of loss with respect to film thickness at $f=1$ THz and present the corresponding effective refractive index, as shown in Fig. 5:

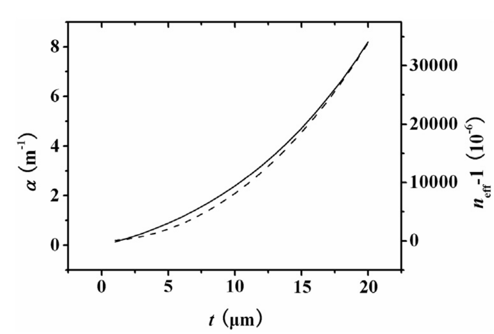

Fig. 5. Variation of loss (solid line) and effective refractive index (dashed line) of coated metal plate as a function of dielectric film thickness at 1 THz.