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Transmission of light through slits array in a metal–insulator–metal structure

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ABSTRACT

Light transmission through slits array in a thin dielectric core layer sandwiched between two metallic cladding (MIM) is investigated using the finite-difference time-domain (FDTD) method. The dispersion relation of surface plasmon polariton (SPP) in the MIM structure is analyzed. The results show that SPP modes on the core layer act as a resonator-coupler, which helps to couple the resonance energy in the upper slit arrays to that in the lower slit arrays, and there is an enhanced transmission peak under appropriate resonance conditions. Coupling process is verified by the field profiles of the SPP modes calculated by FDTD method. Different MIM structures are designed to control the light transmission.

1. Introduction

How light interacts with an obstacle encountered in propagation is an 'old' problem that has been studied since the age of Isaac Newton. The significant progress of nanotechnology at the end of the last century makes it possible to design various nano-structure obstacles, that has opened a new chapter in the investigation of the 'old' problem. The discovery of the extraordinary optical transmission (EOT) through a thin metal film perforated with sub-wavelength hole arrays by Ebbesen et al. has been one of the fantastic phenomena in the last years [1]. Based on the fact that the period of the array determines the position of the transmission peak, Ebbesen et al. immediately related EOT phenomenon to surface plasmon polaritons (SPPs) that were excited when their momentum matched the momentum of the incident photon and the period of the arrays. However, the transmission peaks predicted by the dispersion relation of the SPPs do not match with the experiments values, which have been attributed to experimental error (10%) by the authors. The subsequent series of related articles affirmed that Bloch-like SPP modes excited by a periodic sub-wavelength structure are responsible for the EOT phenomena [2–7]. However, analysis results by Cao and Lalanne, using a rigorous coupled wave analysis (RCWA), showed that the SPP modes played a negative role. Transmission minimum appeared at wavelength equal to an integer multiple of the SPP wavelength [8]. Later, the microscopic theory proposed by Liu and Lalanne argued that two very different near-field modes, SPP modes and creeping wave (CW) modes, contributed to light transmission, depending on the frequency range and the actual geometry of the sub-wavelength structure [9]. The above controversies show that although SPP modes play a critical role in EOT phenomena, it is still not clear how exactly they play this role [10].

When a plane wave is normal incident on a slit array having period p in thin metal film, SPP is excited on the incident and exit surfaces, if its momentum is equal to an integral multiple of $2\pi/p$. The coupling between the Fabry–Perot cavity mode in the slit and the SPP mode on the surface leads to EOT phenomena for some specific wavelength [2,5]. Exciting and coupling of the SPP modes are two key prerequisites for the EOT phenomena. For slit array in a thin dielectric core layer sandwiched between two metallic cladding (MIM) (Fig. 1), we also need to consider the impact of SPP modes on the top and bottom surfaces of the dielectric core layer. Previous studies show that SPP modes on the dielectric core strongly influence the transmission behavior in the MIM structures [11–13]. It is well known that MIM structures support a negative group velocity SPP (NGV-SPP) mode for frequencies above the surface plasmon resonance frequency, but below the bulk plasmon frequency of the metal [14]. The negative group velocity means that the energy and phase fronts of the SPP mode propagate in opposite directions, and its propagation length and skin

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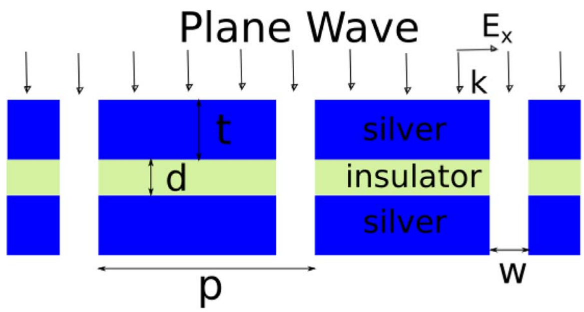

Fig. 1. Slit array having period *p* and aperture width *w*, punching in two silver film of thickness *t* separated by an insulator with *d* thickness.

depth are different from those of the normal SPP mode [15]. Those differences mean NGV-SPP has different effects on the transmission behavior in the MIM structures compared to normal SPP. However, previous studies are less concerned about this difference [11–13]. In this work, we first study the dispersion relation of the NGV-SPP mode and the normal SPP mode. Then we study their influence on the transmission behavior in the MIM structures. Comparing our work with previous research, we show that the transmission property of a MIM structure could be controlled by using the different features of the NGV-SPP mode and the normal SPP mode. This study may help us to understand the action of those different SPP modes.

2. Simulation structures and methods

In this paper, we use the finite-difference-time-domain (FDTD) method [16] to investigate the optical transmission through a periodic array of slits in MIM structure, as shown in Fig. 1. For the transmission calculations, we use a three-dimensional FDTD implementation [17]. The dielectric core layer thickness is d. Slit array has period p and aperture width w. Two cladding silver layers have the same thickness of 150 nm. Slit aperture width w is 50 nm. The optical properties of the silver are characterized by the Drude model:

$$\epsilon_m(\omega) = \epsilon_f - \frac{\epsilon_f \omega_p^2}{\omega^2 + 2i\omega\delta} \tag{1}$$

where the bulk plasma frequency ω_p and the damping constant δ are 5.8×10^{15} rad/s (3.8 eV) and 3.0×10^{13} rad/s (0.02 eV) respectively. The fitting permittivity ϵ_f is 6.8 [18].

Using the above Drude model, we now consider the SPPs mode in the MIM structure. In such a system, each single interface between insulator and metal can sustain bound SPPs, and interactions between those SPPs give rise to coupled modes if the separation between interfaces is comparable to or smaller than the decay length of the SPPs mode. In general, MIM structure supports transverse magnetic (TM) mode and transverse electric (TE) mode. The TE mode is resembled to a conventional dielectric waveguide mode, which cannot exist when the insulator thickness is reduced [15]. In this work the thickness of the core insulator is less than 35 nm, that is why we consider the TM mode only. The TM mode can be divided into two types: odd and even mode. The dispersion relation of the odd and even mode are defined by the following two equations [19]:.

$$\tanh\left(k_1\frac{d}{2}\right) = -\frac{k_2\epsilon_1}{k_1\epsilon_2}\tanh\left(k_2\frac{d}{2}\right) = -\frac{k_1\epsilon_2}{k_2\epsilon_1} \tag{2}$$

with k_i defined by momentum conservation:

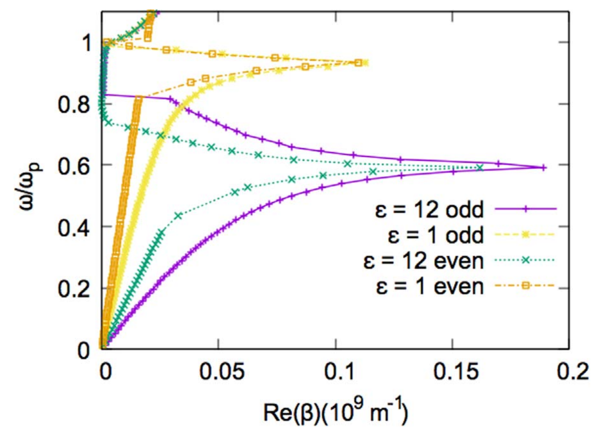

Fig. 2. Eigen frequency normalized by ω_p vs. real part of the propagation constant for the odd and even modes for MIM structure with an insulator core of $\epsilon_1 = 1$ and $\epsilon_1 = 12$. Insulator cores thickness is 25 nm.

$$k_i^2 = \beta^2 - \left(\frac{\omega}{c}\right)^2 \epsilon_i \quad (i = 1, 2) \tag{3}$$

where β is the propagation constant of the SPP, ω is the angular frequency of the incident light, and c is the speed of light in vacuum. The ϵ_1 and ϵ_2 are the complex dielectric constants for the core insulator and cladding material respectively.

The dispersion relations (2) have complicated manner. They link eigen frequency with the propagation constant in implicit form. Eigen frequency as a function of β can be found from the dispersion relations numerically. Fig. 2 shows the results of numerical solving the dispersion relations (2) for SPPs; two different insulators with $\epsilon_1 = 1$ and $\epsilon_1 = 12$ are considered. When the angular frequency is between $0.6\omega_p$ and $0.8\omega_p$, the normal SPP mode for the MIM structure with insulator $\epsilon_1 = 1$ has a wavevector less than 0.03 nm^{-1}, but the dispersion curve for MIM structure with insulator $\epsilon_1 = 12$ exhibits a negative slope with larger wavevector. If these SPP modes take part in the light transmission in the MIM structures, we can expect that those two MIM structures have different transmissions within the frequency range of $0.6\omega_p$–$0.8\omega_p$, because of the differences in the wavevector and the group velocity between the normal SPP mode and the NGV-SPP mode.

Here we take a relatively small array period with 200 nm, which makes the least propagation constant of the SPP is about $2\pi/p = 0.03$ nm^{-1}. This value is larger than the β for MIM structure with air core, when the angular frequency is between $0.6\omega_p$ and $0.8\omega_p$. Within this frequency range, we can expect that EOT phenomena do not appear in this MIM structure because of the mismatch between the wavevector of the SPP mode in the MIM structure and the period of the slit array.

3. Simulation results and analysis

Normal incidence transmission spectrum for different MIM structures obtained with FDTD calculations is shown in Fig. 3, along with the solution to the dispersion relation. We only show the odd mode dispersion, which does not exhibit a cut-off for vanishing core layer thickness [19]. For comparison, the transmission of a 300 nm thickness silver film perforated with a slit array with 200 nm period is shown that demonstrates high-transmission peaks around 460 nm and 890 nm. MIM structure having a 25 nm thickness dielectric core with $\epsilon_1 = 12$ also shows high-transmission peaks around 460 nm and 800 nm. Those two structures have similar transmission spectrum. In order to accurately describe the light transmission through MIM structure,