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Visible light transmission properties of double metal thin gold films with sub-wavelength hole arrays

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ABSTRACT

The transmission spectrum of linearly polarized visible light through double metal thin films perforated with nano-hole arrays is investigated and simulated by using the three dimensional finite-difference time-domain method. The results show that the transmission spectra can be controlled by changing the longitudinal interval G between films and, their lateral displacements L_x and L_y, which are parallel and perpendicular to the polarization direction of the incident light, respectively. We have two important peaks (due to guided mode and SP mode) in these spectrums. The variation in longitudinal distance results a wavelength shift in guided mode peak of transmission spectrum while the wavelength of SP mode peak remains fixed. The lateral displacement L_x leads to the higher transmission of the guided mode peak, while the lateral displacement L_y suppresses the transmission of this peak. Here we try to discuss the physical explanations of these spectral behaviours by surface plasmon waves on the metal films and by using the concepts of surface plasma (SP) and guided modes in our double metal structure.

1. Introduction

The optical properties of light transmission through apertures have been the subject of interest since an aperture in a screen is an important element in optical devices and has technological applications. Since the first time where Ebbesen et al. [1] reported extraordinary electromagnetic transmission through a metallic film with two-dimensional periodic subwavelength cylindrical holes, this phenomenon has became a hot subject, with rich physics and fruitful applications such as subwavelength photolithography [2], near-field microscope [3], optical modulator [4], flat-panel display [5], subwavelength photonics, data storage, biosensors and biophotonics [6–9]. Sharp transmission peaks were observed at wavelengths much larger than the diameter of the holes, where the transmittance could be several orders greater than that predicted by standard aperture theory [1]. This phenomenon is called the extraordinary EM transmission. This phenomenon has been investigated in various subwavelength metallic nanostructures, such as two-dimensional periodic arrays of cylindrical [1,10] and rectangular (square) holes [11,12], one dimensional periodic arrays of slits [13], annular apertures [14], and in a single aperture (hole or slit) surrounded by periodic grooves [15–17].

However, most of the investigations on the extraordinary EM transmission phenomena are done in the single-metallic grating structure. Recently EM transmission through dual-metallic gratings has been investigated [18–20]. Meanwhile Ye and co-workers [21,22] reported experimental results on enhanced light transmission through two periodically perforated metal films separated by a layer of dielectric in the middle-infrared region. They found that enhancement transmission is further increased when two metal films are cascaded, and the maximum transmission of the cascaded metallic structure is sensitive to the distance between two metal films. Afterwards Tang et al. [23] demonstrated that the enhancement in optical transmission originates not only from SPPs but also from the coupling of SPPs in the metal/dielectric multilayers with subwavelength hole arrays. Meng-Dong et al. [24] investigated the transmission characteristics of the cascaded metal films perforated with periodic hole arrays by using the 3D-FDTD method. More recently Ortuno and co-workers [25] related two peaks of transmission to the internal and external surface plasmon and showed that the resonant frequency strongly depends on the dielectric layer parameters where the spatial distribution of the electromagnetic field plays an important role in determining the transmission resonances. Then Marcet et al. measured the transmission of IR radiation through double-layer aluminium films for arrays of subwavelength holes with period of 1 μm. Bilayer hole arrays have been shown to exhibit negative refraction index at specific wavelengths [26]. The effect of lateral shift on negative refraction index is an interesting topic that warrants further investigations [26,27,29].

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In this paper we investigate the effects of lateral (L) and longitudinal (G) displacements between two gold metal films (with perforated nano-holes) on the light transmission spectrum for the visible region. We also interpret physically the behaviour of the peaks amplitudes in the transmission spectrum with respect to these displacements. In Section 2 of this article we briefly explain the set-up of the structure which is used in our simulations. Section 3 entails the main results of our numerical study as well as the discussion of the relevant physical effects. The explanation of our results in transmission peaks for different displacement situations by SP and guided modes concepts in these double metal films is presented in Section 4. Finally, we summarize our main results in Section 5.

2. Simulation set up

Here, we investigate the light transmission spectrum characteristics of the double metal films for different values of G (longitudinal displacement between two films) and L_x and L_y (the lateral displacements between the two layers along the x and y axes, respectively) in the visible region by using the three-dimensional finite difference time-domain (3D-FDTD) method. Fig. 1 depicts a 3D schematic of cascaded metallic structure composed of two identical metallic films with nano-hole arrays surrounded by the air. The first film of structure is illuminated normally by a linearly polarized Gaussian modulated continuous plane wave with electric field vector parallel to the x axis. The circular holes with diameters d = 100 nm and depth h = 120 nm are arranged in each metal film with period p = 650 nm. The metal chosen to be gold (Au) with the dielectric function obeying the Drude model plus two-pole Lorentz model. The observation plane for detection of the transmitted field is considered 1 μm away from the second film of the structure.

The transmission of normally incident light through arrays of sub-wavelength holes is enhanced at the wavelengths that satisfy the surface Plasmon resonance conditions given by [28].

$$\lambda_{SP} = \frac{P}{\sqrt{i^2 + j^2}} \sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}} \qquad (1)$$

where P is the periodicity of the array, i and j are integers, ε_m is the dielectric constant of metal (gold) and ε_d is the dielectric constant of dielectric environment (here is air). If we calculate the wavelength of surface plasmon resonance for our structure with (i, j) = (1, 0) we obtain 728 nm. This value is in the range of our study and apply in the next section where we investigate the light transmission spectrum through the structure.

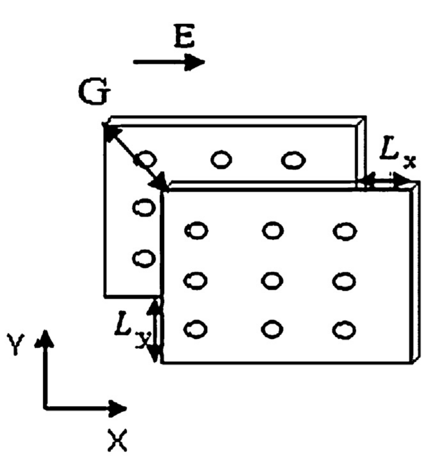

Fig. 1. Top view picture of the schematic configuration of the double thin metallic films structure with longitudinal shift (G) and lateral displacements (L_y and L_x) between its films. The polarization of incident light (E), which is normal to the surface of the films, is along the x axis.

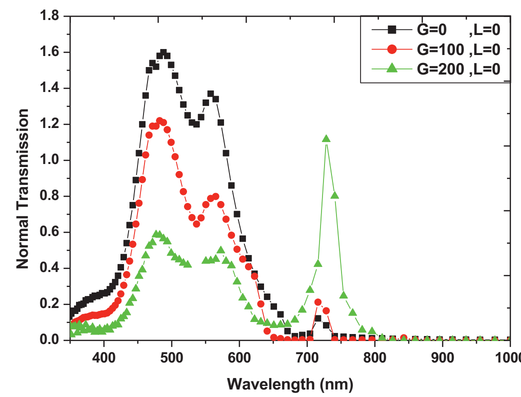

Fig. 2. Visible light transmission spectrums of the double metal layers for different longitudinal displacements. There is no lateral displacement and only two longitudinal intervals, G = 100 nm and G = 200 nm, compared with G = 0.

3. Light transmission spectrums for different values of *L* and *G*

First of all we study the effect of longitudinal interval G on the transmission spectrum of the cascaded metallic structure. The visible light transmission spectrum through double metallic structures for different G values, with $L_x = L_y$ = 0 nm has three peaks, see Fig. 2. When G = 0 nm (i.e., the two single metal layers are closely contacted) the structure is equivalent to one metal layer with thickness $h' = 2h$. Fig. 3 displays wavelength variation of three peaks in this situation. The first peak at 480 nm belongs to the peak which is exist in the spectrum of the gold skin depth (not presented here) because we can see it in the bare gold layer (without any holes), too. Two other peaks follow two distinct types of behaviour as G is varied. The second peak exhibits a red shift (Fig. 3) and its intensity decreased when G is increases from 0 to 300 nm. Fig. 4 displays intensity variation of three peaks of double layer structure at different values of G, with $L_x = L_y$ = 0 nm. According to this figure, the maximum values of the third peak occur where the minimum of the other two peaks values happen. The wavelength of third peak is nearly constant, see Fig. 3, and is approximately equal to 716 nm, that is near the value of 728 nm calculated before by Eq. (1) for the wavelength of the fundamental surface plasmon mode for a single thin gold grating structure. According to this figure the wavelength of the second peak show a red shift as the G is increased.

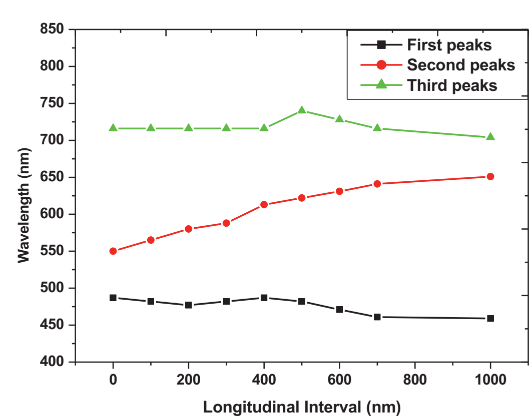

Fig. 3. Variations of the wavelengths belong to the transmission peaks with respect to various longitudinal intervals between two gold films.