Role of localised surface plasmon polaritons coupling in optical transmission through double-layer metal apertures

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In this paper, we investigate the optical properties of the double-layer metal films perforated with single apertures by analysing the coupling of localized surface plasmon polaritons (LSPPs). It is found that the amplitude and the wavelength of transmission peak in such a structure can be adjusted by changing the longitudinal interval D between two films and the lateral displacements d_x and d_y which are parallel and perpendicular to the polarization direction of incident light, respectively. The variation of longitudinal interval D results in the redshift of transmission peak due to the change of coupling strength of LSPPs near the single apertures. The amplitude of transmission peak decreases with the increase of d_y and is less than that in the case of d_x, which originates from the difference in coupling manner between LSPPs and the localized natures of LSPPs.

Keywords: enhanced transmission, localized surface plasmon polaritons, double-layer metal apertures

PACC: 7320M, 7360D, 7865E

1. Introduction

The optical properties of a single aperture have been the subject of interest since an aperture in a screen is probably a key element in optical devices, and also an object of curiosity and technological application.[1] Early in the nineteenth century the Huygens–Fresnel principle and Kirchhoff's theory appeared which could be applied to apertures much larger than the wavelength of light. Up to 1944, Bethe[2] derived an analytical expression for a small hole in a perfectly conducting metal screen of zero thickness. This theory shows that when the diameter of the aperture is smaller than half the light wavelength, the light can no longer propagate through the aperture and the transmission is very weak. However, in 1998, Ebbesen *et al.*[3] discovered that a metallic film perforated with an array of subwavelength holes displayed highly unusual transmission. The intensities of transmission peaks were orders of magnitude greater than those predicted by Bethe's theory. Since then, a large number of theoretical[4−8] and experimental[9−13] studies have been carried out to explain the rich physics behind such an extraordinary optical transmission phenomenon and explore its potential application. Although the physical mechanism behind such a phenomenon remains controversial,[14−17] it is generally accepted that the unusual transmission is attributed to the resonances of surface plasmon polaritons (SPPs) on metal film surface and localized surface plasmon polaritons (LSPPs) around individual holes.[18]

The LSPP resonances correspond to the Fabry–Pérot-like resonances of guide modes in individual apertures (slits).[19] This kind of resonance is also called "shape resonance" since strong influence of aperture shape on extraordinary optical transmission exists.[20,21] For light polarized with the electric field pointing along the short axis of a single rectangle aperture, it has been shown that the normalized-to-area transmittance at resonance is proportional to the ratio between the long and short sides.[22] It has also been found that the LSPPs are excited on the aperture ridges perpendicular to the polarization direction of incident light.[23] Recently, García–Vidal[24] proposed a theory to describe the optical transmission through a rectangular hole and revealed the localized nature of LSPPs resonances by analysing the electric field maps.

In the past a few years, numerous studies[25−30] of transmission through two- or multi-layer metal films performed with periodic hole arrays have been

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reported due to their interesting optical properties. From these studies, we know that coupling between SPPs (LSPPs) on two films is widely believed to have influence on optical properties of two- and multi-layer metal structures. However, in fact, both the LSPP resonance peaks and SPP resonance peaks in double-layer (multi-layer) metallic hole array structures result from the complex interactions between SPPs and LSPPs.[18] The SPPs propagating on metal film surfaces contribute to the LSPP resonance peaks. If there is no contribution of SPPs, how are the LSPP resonance peaks? Motivated by this question, in this paper we consider the cascaded metal films perforated with single subwavelength apertures, whose transmission peak originates only from the LSPP resonance. Our results show that the transmission characteristics of such a structure are different from those in double-layer metallic hole array structures.[25−30] The variation of longitudinal interval D between two metal films results in the redshift of the LSPP peak due to the variation of coupling strength of the LSPPs. The amplitude of the LSPP peak decreasing with the increase of d_y (which is perpendicular to the polarization of incident light) is less than that in the case of d_x (which is parallel to the polarization of incident light), which originates from the difference in coupling manner between the LSPPs and the localized nature of LSPPs.

2. Model and numerical method

Figure 1 shows the schematic diagram of a double-layer metal aperture structure which is composed of two identical metallic films perforated with single square apertures. The structure is illuminated normally by a linearly polarized plane wave with an electric field vector parallel to the x axis. The width and the depth of the square aperture are $a = 230$ nm and $t = 100$ nm, respectively. The two films are separated by an air gap with an longitudinal interval D; d_x and d_y denote the lateral displacements along the x and y axes, respectively. The metal is chosen to be silver (Ag). For its dielectric function readers may refer to Ref. [31].

In this paper, we employ a three-dimensional finite-difference time-domain (3D-FDTD) approach to simulate the interaction between metal film and the incident wave. The validity of the 3D-FDTD approach has been verified by calculating the transmission spectra of metal films with compound periodic hole arrays in Ref. [32]. In our calculation, the spatial mesh cells are set to be $\triangle x = \triangle y = \triangle z = \triangle s = 10$ nm and the time step is taken to be $\triangle t = \triangle s/2c = 1.6667 \times 10^{-17}$ s. The grids are terminated by a ten-cell-thick convolutional perfectly matched layer (PML).[33]

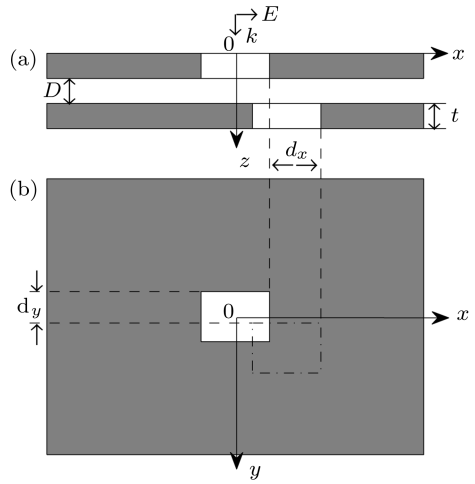


Fig. 1. Scheme of double-layer metallic films perforated with single apertures: (a) side view picture and (b) top view picture.

3. Results and discussion

First, we investigate the effect of longitudinal interval D on the transmission spectrum. The transmission spectra of the cascaded metal films at different values of D, in the case without the lateral displacement ($d_x = d_y = 0$ nm), are displayed in Fig. 2.

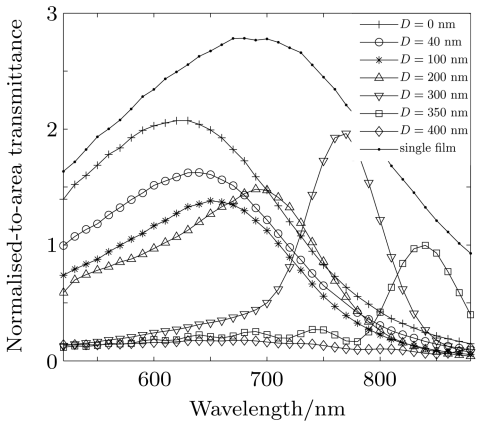


Fig. 2. Transmission spectra of the single metallic structure and the double-layer metallic structures at different values of D, with $d_x = d_y = 0$ nm.

The transmission spectrum of a corresponding single metallic structure is also shown there for comparison. In the special case of $D = 0$ nm, the two single metal layers are in close contacted, the structure is equivalent to one metal layer with thickness $t' = 2t$, and the transmission spectrum has one transmission peak located at 630 nm. Since the transmission peak originates only from the excitation of LSPPs around aperture, in this paper we will refer to this peak as

the LSPP peak for the sake of simplicity. In the corresponding single metallic structure, the wavelength of the LSPP peak (about at 670 nm) is larger than that in the cascaded metallic structure, which is in agreement with results in the previous paper.[34] As D varies, the LSPP peak in the cascaded metallic structure follows several distinct types of behaviour. When D increases from 0 to 100 nm, the transmission intensity of the localized surface plasmon peak falls quickly from 210% to 140%, while when D further increases, the intensity of LSPP peak increases. At $D = 300$ nm, the LSPP peak value rises to 200%. Once D exceeds 300 nm, the LSPP peak intensity begins to decrease again. When D is large enough ($D \geq 400$ nm), almost no transmission peak appears in the spectrum. During the increase of D, it can be also seen that the LSPP peak keeps shifting towards the longer wavelength regime.

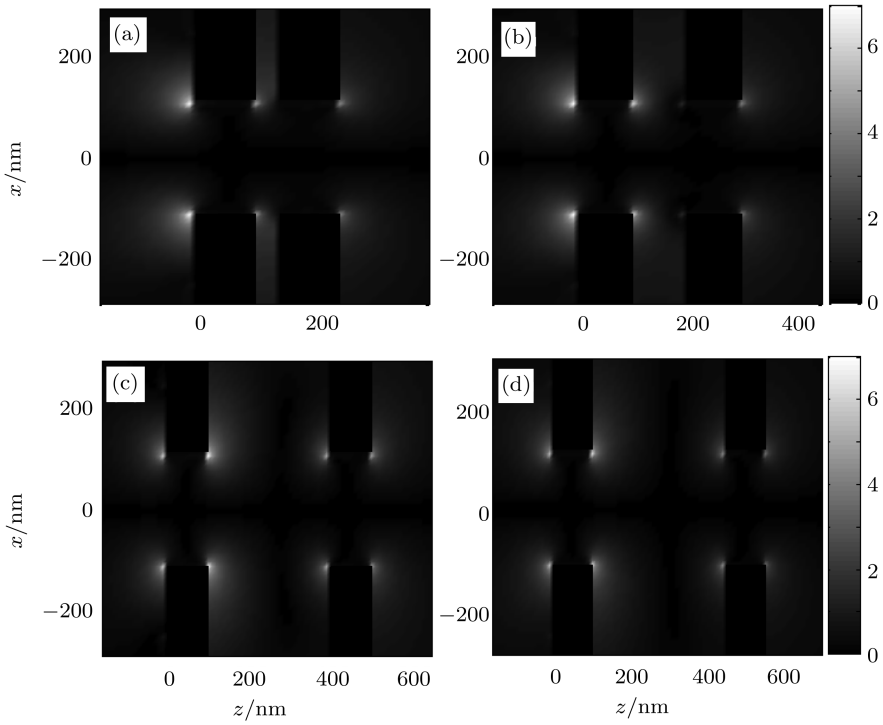


Fig. 3. Calculated time-averaged density distribution of electric field $|E_z|$ along the cross section $y = 0$. Panels (a)–(d) correspond to the transmission peaks at $\lambda_p = 640$ ($D = 40$ nm), 650 ($D = 100$ nm), 770 ($D = 300$ nm) and 840 nm ($D = 350$ nm) in Fig. 2, respectively. In all cases, the incident plane wave with a unitary electric field is incident normally from the left, and the dark areas denote metal.

In order to understand the above behaviour of the LSPP peak, we calculate the time-averaged density distribution of the electric field $|E_z|$ of the LSPPs as shown in Fig. 3. Figures 3(a)–3(d) correspond to the transmission peaks in Fig. 2 for $D = 40$, 100, 300 and 350 nm, respectively. The electric field concentrates around apertures and decays exponentially with the increase of separation from the metal surface, implying that the LSPPs are excited.[25] For the cases of $D = 40$ and 100 nm, although the LSPPs on the edges of the output surface of the second film (unillustrated film) cannot be excited effectively, the LSPPs excited on the output surface of the first film (illustrated film) and the input surface of the second film couple with each other. We also calculate the absorbance spectra in a range of $0 \leq D \leq 400$ nm (not shown here) and find that the Ohmic loss is highest when D is equal to 100 nm. It indicates that the coupling of LSPPs between two films are most intense at $D \simeq 100$ nm. In addition, the energy propagating along the xy plane in the spacing between two metallic films increases with the increase of D. Owing to the above two factors, the transmission peak value for $D = 100$ nm is smaller than that for $D = 40$ nm. At $D = 300$ nm (Fig. 3(c)), the coupling of LSPPs between two films is weak in comparison with that at $D = 100$ nm, which

results in the decrease of Ohmic loss. As D increases from 100 nm to 300 nm, the decreasing amplitude of Ohmic loss is higher than the increasing amplitude of the energy propagating in the interval between two metallic films, therefore the transmission peak for $D = 300$ nm is higher than that for $D = 100$ nm. With the further increase of D (Fig. 3(d)), the coupling strength of LSPPs between two films becomes very weak, the variation of Ohmic loss is very small. The fall of transmission peak mainly results from the increasing energy propagating between two films. For the redshift of the LSPPs peak in Fig. 2, it is also attributed to the coupling of LSPPs between two metal layers. The coupling of LSPPs leads to new LSPPs whose resonant frequencies are different from those of the corresponding LSPPs in single metallic structures. The coupling interaction strongly depends on the separation between two metal films, thereby the LSPPs peak displays a shift as the value of D varies. From the above discussion, it is found that the behaviour of the LSPP peak is closely related to the coupling of LSPPs excited on two films. Here, it should be noted that the behaviour of transmission peak in this paper is different from that in the previous work.[25,26,29] We think that the main reason for such a difference is that the transmission peaks in the previous work originated from the resonances of LSPPs and SPPs, while the LSPPs peak here only benefits from the resonance of LSPPs. Furthermore, in the cascaded structure of periodic hole arrays, the energy through the illuminated apertures can propagate only along the z axis due to the periodicity of structure, while here the energy can also propagate along the xy plane in the spacing between two metallic films, which influences the LSPPs-activation efficiency and the coupling strength of LSPPs.

Next, we study the effect of lateral displacements d_x and d_y on the transmission spectrum. The calculated transmission spectra at different values of d_x with $d_y = 0$, and d_y with $d_x = 0$ are shown in Fig. 4 separately. In both cases, D is taken to be 200 nm. As d_x increases from 0 to 100 nm (with $d_y = 0$), the transmission intensity of LSPP peak rapidly drops from 150% to 85%, while the peak wavelength remains approximately constant. As d_x further increases, the transmission peak continues dropping and exhibits a slight blueshift. At $d_x = 250$ nm, there is no direct line of sight through the cascaded metallic structure, the transmission peak reduces to 30%. For the case of d_y (with $d_x = 0$), the LSPP peak exhibits a similar behaviour, the LSPP peak also decreases monotonically with the increase of d_y. But the difference is that the amplitude of transmission peak decreasing with the increase of d_y is less than that in the case of d_x.

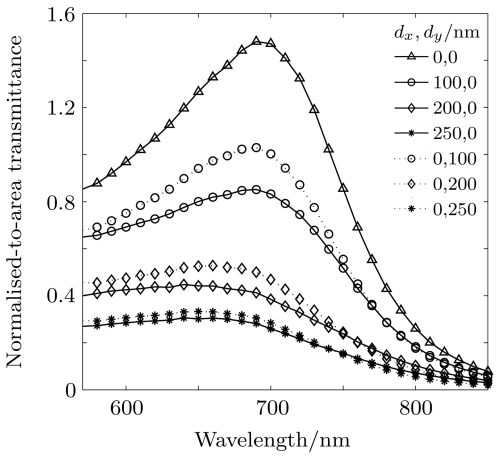


Fig. 4. Transmission spectra of cascaded metallic structures at different values of d_x with $d_y = 0$ nm, and d_y with $d_x = 0$ nm. In both cases, $D = 200$ nm.

To obtain more details about the above phenomena, we calculate the time-averaged density distribution of the electric field $|E_z|$ of the LSPPs. Figures 5(a) and 5(b) correspond to transmission peaks in Fig. 4 for $d_x = 0$ and 100 nm with $d_y = 0$ nm, respectively. From Fig. 5(a), it is clearly seen that the LSPPs in the second film are excited effectively at the resonance wavelength. Interestingly, the LSPPs on the upper (lower) ridge of the aperture in the first film are not straightly coupled with those on the upper (lower) ridge of the aperture in the second film, and they are coupled with those near the aperture in the second film. When two metal layers are displaced laterally along the x axis (see Fig. 5(b)), the electric field on the ridges of aperture in the second film is less intense than that in Fig. 5(a). It indicates that LSPPs-activation efficiency for $d_x = 100$ nm is low in comparison with that for $d_x = 0$ nm. More importantly, it is found that the coupling manner of LSPPs between two metal films is changed. The LSPPs on the upper ridge of the aperture in the first film interact with those on the lower ridge of the aperture in the second film. In the cascaded structures of periodic hole arrays,[25,29] the variation in coupling manner of LSPPs leads to the splitting of transmission peak. However, here there exists only one kind of coupling manner of the LSPPs, hence the d_x does not cause the splitting of the LSPP peak. Figure 5(c) corresponds to the transmission peak in Fig. 4 for $d_y = 100$ nm with $d_x = 0$ nm. In this case, the LSPPs on the aperture on the second film can also be excited effectively and the coupling manner of LSPPs is the same as that

in Fig. 5(a). While, the electric field on the ridges of aperture in the second film is slightly more intense than that in Fig. 5(b). Such a difference is caused by two factors. One is the change of the coupling manner of LSPPs near two apertures. The coupling manner of LSPPs in Fig. 5(c) is different from that in Fig. 5(b). The other is the local characteristics of the LSPPs. The LSPPs are excited on the ridges of the apertures along the y axis instead of on the ridges along the x axis.[23] The displacements along different directions d_x and d_y bring different activation efficiencies of the LSPPs on the second film.

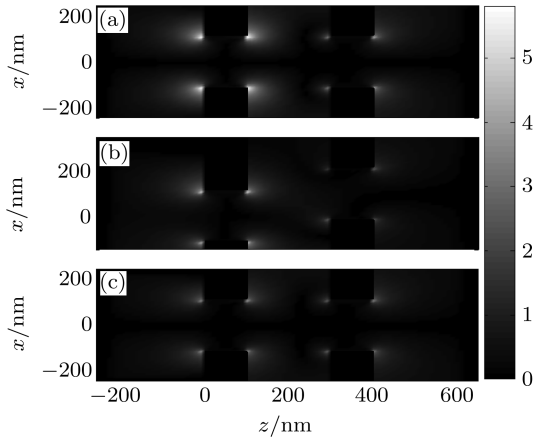


Fig. 5. Calculated time-averaged density distribution of electric field $|E_z|$. Panel (a) corresponds to the cross section $y = 0$, $d_x = d_y = 0$ nm and the peak wavelength $\lambda_p = 690$ nm in Fig. 4. Panel (b) corresponds to the cross section $y = 0$, $d_x = 100$ nm, $d_y = 0$ nm and $\lambda_p = 690$ nm in Fig. 4. Panel (c) corresponds to the cross section $y = 100$ nm, $d_x = 0$ nm, $d_y = 100$ nm and $\lambda_p = 690$ nm in Fig. 4. In all cases, the incident plane wave with a unitary electric field is incident normally from the left. Three plots are shown in the same intensity scaling for comparison, and the dark areas denote metal.

4. Conclusion

We investigated the effect of localized surface plasmon polaritons coupling on the optical properties of double-layer metal apertures by using the 3D-FDTD method. The transmission peaks of such structures are related only to the coupling of the LSPPs around apertures, hence the transmission characteristics of such structures are different from those in double-layer metallic hole array structures.[25,26,29] Our results show that the variation of longitudinal interval D results in the redshift of the LSPP transmission peak due to the change of the coupling of LSPPs near two apertures. The amplitude of the transmission peak decreasing with the increase of d_y is less than that in the case of d_x, which originates from the difference in coupling manner between LSPPs and the localized natures of LSPPs. We expect our findings to be useful for designing optical devices such as sensor and spectroscopy in the future.

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