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Tunable plasmon resonance of a touching gold cylinder arrays

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Abstract. We investigate the plasmon resonance of a touching gold cylinder arrays surrounded with air or dielectric. We show that the plasmon resonance is tunable by modulating the cylinder radius, the cylinder layer and refractive index of the dielectric. It is found resonance peak blue-shifts and splits as the gold cylinder radius reduces, width of the resonance peak gets much smaller as layer increases, and resonant peak red-shifts noticeably as dielectric refractive index increases. Based on electric field distributions at the resonance wavelengths we reveal the mechanism of the transmission enhancement. These phenomena are helpful for the design of potential optics devices.

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Key words: touching gold cylinders, surface plasmon, electric field distributions

1 Introduction

Metallic nano-structures have attracted a great attention as they can provide many intriguing properties for application in fields like near-field microscopy and spectroscopy, nanoscale photonic devices [1], biological applications, and biosensors [2]. Controllable and tunable surface plasmon resonance of metallic nanopaticales [3], nanoshells [4], nanorods [5], and nanocylinders [6] are investigated recently. It is found that the electromagnetic field can be enhanced in the vicinity of the nanostructures [7,8]. Parameters such as size [9], shape [10], and the surrounding dielectric [11,12] of the structure are investigated in order to clarify the optical properties. It is reported there is an extraordinary optical transmission for a metallic slab perforated with hole arrays [13], even for a continuous metallic

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structure with periodically nanostructured on the surface [14]. If a series of nanocylinders are arranged parallelly touching each other periodically, forming a continuous structure, high enhancement transmission is expected.

In this paper, we investigate plasmon resonance of a touching gold cylinder arrays surrounded with air or dielectric. We show that the plasmon resonance is tunable by modulating the cylinder radius, the cylinder layer and refractive index of the dielectric. It is found that resonance peak blue-shifts and splits as the gold cylinder radius reduces, width of the resonance peak gets much smaller as layer increases, and resonant peak red shifts noticeably as dielectric refractive index increases. By analyzing electric field distributions at the resonance wavelengths, we reveal the mechanism of the transmission enhancement. These properties are helpful for the design of potential optics devices.

2 Model and theory

We apply a periodic array of gold cylinders as shown in Fig. 1, in order to demonstrate the optical property. Transmission spectra and electric fields are simulated by using the finite-difference time-domain (FDTD) method [15, 16]. In the entire work, we investigate a lattice of the periodic cylinder structure with 600 nm length in x-direction and 800 nm length in y-direction; cylinder radius is noted as r, and the thickness of the dielectric is noted as h, and the spatial and temporal steps are set at $\Delta x = \Delta y = \ln m$ and $\Delta t = \Delta x/2c$ (c is the velocity of light in vacuum), and we send a Gaussian single pulse of light with a wide frequency profile. Periodic boundary conditions are imposed on the left and right surfaces, and the perfectly matched layers (PML) are used on the top and bottom of the lattice [17]. Since there are no gaps between cylinders in the structure, all effects related to mechanism of light transmission directly through the slits are absent, and the resonant tunneling through a metal film is the only mechanism responsible for the enhanced transmission. In all calculations below, light illuminates on top of the structure at a normal incidence polarizing along x-direction.

When a plane wave is incident normally on the interface between a metal and a dielectric, in order to excite surface plasmon waves, the phase-matching condition as follows should be obeyed by the incident wave vector [13, 18]

$$\vec{k}_{sp} = \vec{k}_0 \sin\theta + i\vec{G}_x, \tag{1}$$

where k_0 is the wave vector of incident light and θ is the incident angle. $\vec{G}_x$ is the Bragg vector and $|\vec{G}_x| = 2\pi/p$, i is an integer, which is the mode indices. $\vec{k}_{sp}$ is the surface plasmon wave vector whose length is

$$|\vec{k}_{sp}| = |\vec{k}_0| \sqrt{\frac{\varepsilon_d \varepsilon_m}{\varepsilon_d + \varepsilon_m}} \tag{2}$$

ε_d and ε_m are permittivities of the dielectric and the metal, respectively.

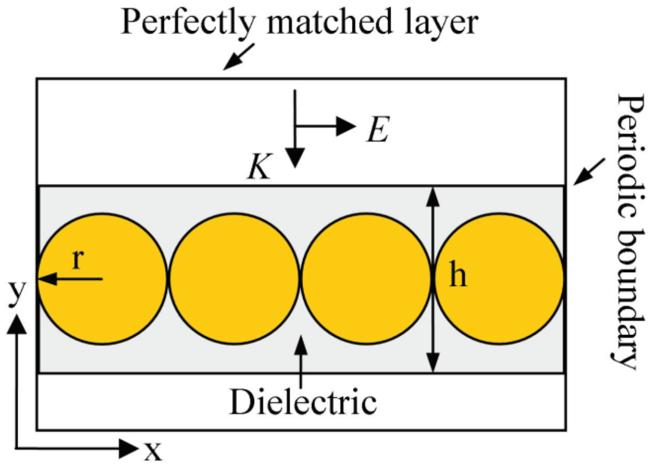

Figure 1: A schematic of the $x-y$ cross section of the investigated lattice of touching gold cylinder array. Light illuminates on top of the structure in a normal incidence and polarizes along x-direction.

The metallic structure is made of gold, and the dielectric constant of gold is described by the Drude model [19]

$$\varepsilon_m(\omega)=1-\frac{\omega_p^2}{\omega^2+i\gamma\omega}, \tag{3}$$

where ω_p is the plasma frequency and γ is the collision frequency, related to energy loss. The parameters used in the Drude model for gold are $\omega_p=1.374\times10^{16}s^{-1}$ and $\gamma=4.08\times10^{13}s^{-1}$, taken from Ref. [20].

3 Results and discussion

Fig. 2 shows the zeroth order transmission, reflection, and absorption spectra as a function of wavelength λ for different cylinder radii of the bare touching gold cylinder structure. The absorption spectra are obtained via $A=1-T-R$, where A, T, and R are the absorbance, transmittance, and reflectance, respectively. It is worth noting that peak value, peak shape and center peak wavelength of the resonance spectra varied noticeably as the radius alters. From Fig. 2 it can be seen that the center wavelengths of the transmission resonance peaks for the structure with cylinder radius $r=150$ nm, $r=75$ nm, and $r=50$ nm are $\lambda=642$ nm, $\lambda=450$ nm, and $\lambda=432$ nm, respectively, here the length of the investigated structure is set as 600 nm invariably. With radius decreasing, transmission is intensified, and the transmission peak splits into two peaks (when the cylinder radius decreases to $r=60$ nm in the lattice, the transmission peak starts splitting) and the split becomes greater as the cylinder number increases.

It is reported that transmission can be enhanced in corrugated metallic films without holes by Bonod *et al.* [21], which is recently demonstrated experimentally [14]. Since

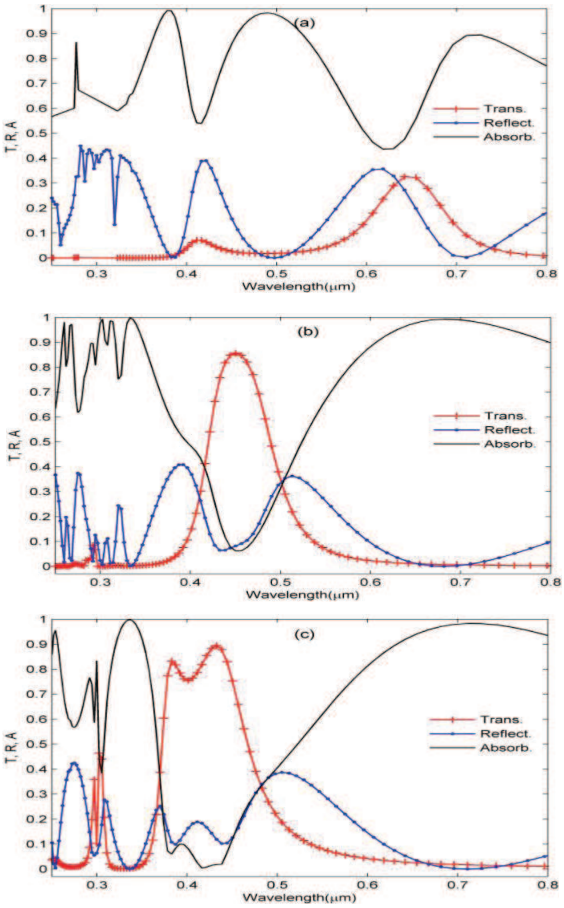

Figure 2: Transmission, reflection, and absorption spectra of the bare touching gold cylinder array for different cylinder radii: (a) $r=150$ nm, (b) $r=75$ nm, and (c) $r=50$ nm.

the cylinders touch each other in a line, the system can be treated as a continuous film with periodic corrugations on both surfaces. The corrugations play no significant role in the light transmission through the film directly, but only serve as a periodical perturbation to ensure the coupling between the incident wave and the surface plasmons at the two interfaces of the cylinder and air. When compared with grating hole array, high transmission through film requires smaller thickness. This is natural since propagation in gold is attenuated stronger than in the holes. For a structure with larger cylinder radius, the interaction between the surface plasmon polariton modes on the up and bottom interfaces is weaker, most electromagnetic energy is absorbed and reflected at the transmission resonant wavelength, while for a structure with smaller cylinder radius, the interaction between the surface plasmon polariton modes on the opposite interfaces is stronger, so the transmission peak is magnified and splitting, and the surface plasmon resonance would happen in a high energy state, so the transmission peak shifts to shorter wavelength range as the cylinder radius gets smaller, it is obtained from Fig. 2 that continuous the transmission wavelength shifts $\Delta\lambda = 210$ nm to the shorter wavelength region as the cylinder radius is reduced from 150 nm to 50 nm. In addition, there is a low transmission resonance peak at a shorter wavelength region, which exhibits a similar trend of the high transmission peak. We treat it as the high order coupling transmission resonance. It is found that a peak in a transmission curve always corresponds to a minimum in the reflection and absorption curves at the same frequency as shown in Fig. 2, and the reflection and the absorption at the high transmission wavelength are reduced as the transmission strengthened, which means electromagnetic radiation at this wavelength range is mostly transmitted but reflected and absorbed little. As the cylinder radius becomes smaller, the dips of the reflection and absorption get even lower. Furthermore, we can see a clear blue-shift in the resonance dip of the reflectance and absorbance spectra as the cylinder radius is reduced. The reflectance and absorbance spectra clearly indicate the resonant features.

In Fig. 3 we show the field distributions associated with the main transmission resonances of the periodic structure with different cylinder radii reported in Fig. 2. The x/y components of the electric field have completely different distributions at the main resonance. For the E_x component (polarized perpendicular to the wave propagating), the electric field is subject to an enhancement near the contact point of cylinders. Wave nodes of E_x confined near the cylinder junctions with the same charge sign on the top and bottom spacing. When a normal incidence matches the frequency of a standing-wave surface plasmon mode, a surface plasmon mode on the top surface is excited and strong field is built up inside the groove schemed by two adjacent cylinders, which in turn resonantly excites the standing-wave surface plasmon mode on the bottom surface of the cylinder structure, then a strong electric field is built up in the grooves of the bottom surface, which finally emits the radiation downwards into air. As a result, resonant transmission happens at the frequencies of standing-wave surface plasmon polariton modes. This

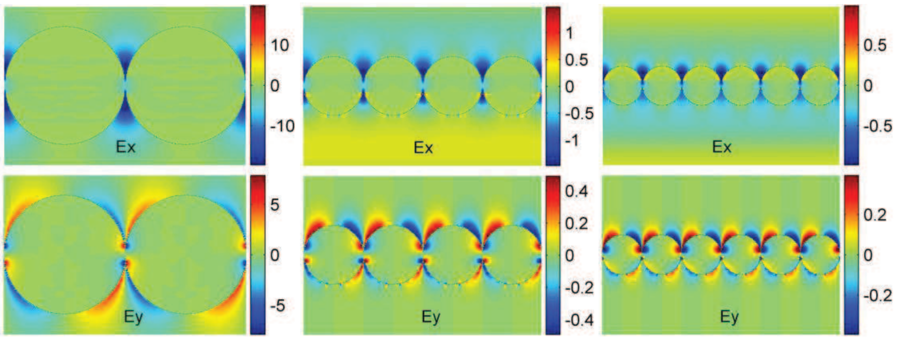

Figure 3: The distribution of the electric field intensity E_x and E_y at transmission wavelengths $\lambda=642$ nm, $\lambda=450$ nm and $\lambda=432$ nm, for the bare touching gold cylinder structure with cylinder radii $r=150$ nm, $r=75$ nm, and $r=50$ nm, respectively, corresponding to Fig. 2(a), 2(b) and 2(c).

process is effectively photon tunneling through touching gold cylinders via resonantly exiting surface plasmon modes. Resonant excitation of a surface plasmon mode in the groove between cylinders results in strong field enhancement and reflection and absorption minimum at the frequency of the surface plasmon mode. For the E_y component (polarized parallel to the wave propagating vector), the electric field exhibits an opposite symmetry property of the field modes in x and y directions with +/- charges as a form of quadruple on each cylinder surface, and each cylinder remains neutral.

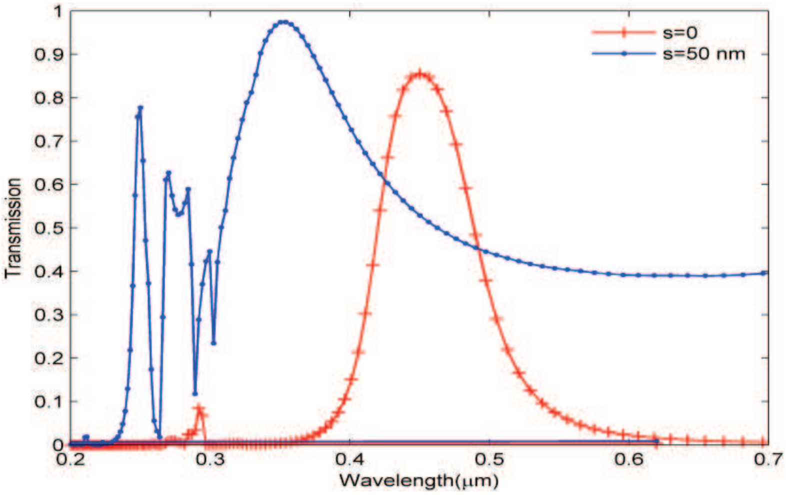

Figure 4: Comparison of transmission spectra of touching and un-touching structure composed of gold cylinders with radius $r=75$ nm. Cylinder separation is marked as $s=0$ and $s=50$ nm.

Touching gold cylinders periodically arranged form a special kind of corrugated gold film. It has the enhanced transmission property, which is the same as a corrugated metallic film. It is found the transmission, reflection and absorption of this touching structure depend on the cylinder radius sensitively. Additionally, it is convenient and practicable to tune the transmission by adjusting cylinder radius in the realization of experiment.

In our study, we focus our attention on the optical transmission of the structure with gold touching nanocylinder array. It is found that the structure with touching cylinders has a good filter property, in other words, there is only one enhanced resonance mode in the transmission spectra. However, for the un-touching one, there are many resonance modes in the transmission spectrum as shown in Fig. 4 and Fig. 5. In Fig. 4, we simulate the comparison of transmission spectra of touching and un-touching structures by varying the separation between cylinders, while keeping cylinder radius unchanged. In Fig. 5, we depict the difference of transmission characteristics for the touching and un-touching cylinder structure by modifying the cylinder radius with central position of each cylinder being immobilized.

It is known that the surface plasmon is very sensitive to the refractive index in the

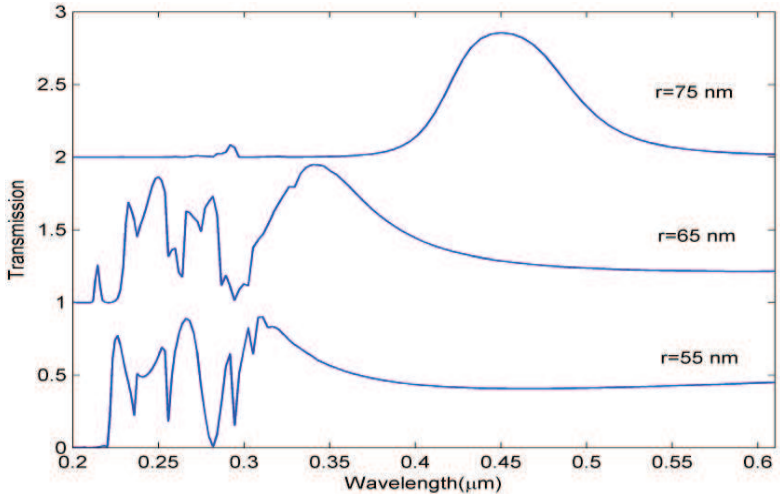

Figure 5: Transmission spectra for the structure changes from a touching one to a un-touching one by decreasing cylinder radius from $r=75$ nm to $r=55$ nm in step of 10 nm with central position of each cylinder being immobilized.

vicinity of the metal surface of the periodic hole array. Here, we investigate the transmission property of the periodic touching gold cylinders with radius $r=100$ nm embedded in a dielectric with thickness of $h=600$ nm in y direction. Transmission spectra for the structure with single layer touching gold cylinders embedded in the center of the dielectric with refractive index increasing from $n=1$ to $n=2$ in steps of 0.5 are shown in Fig. 6(a). We can see clearly the transmission peak red shifts noticeably with the dielectric

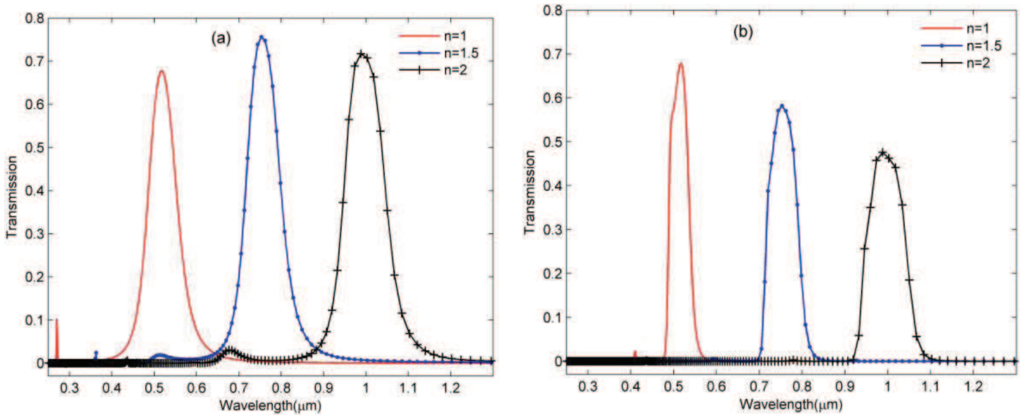

Figure 6: Transmission through the periodic touching gold cylinder array embedded in a material with refractive index varying from $n=1$ to 2 in steps of 0.5: (a) for the single layer structure, and (b) for the double-layer structure.

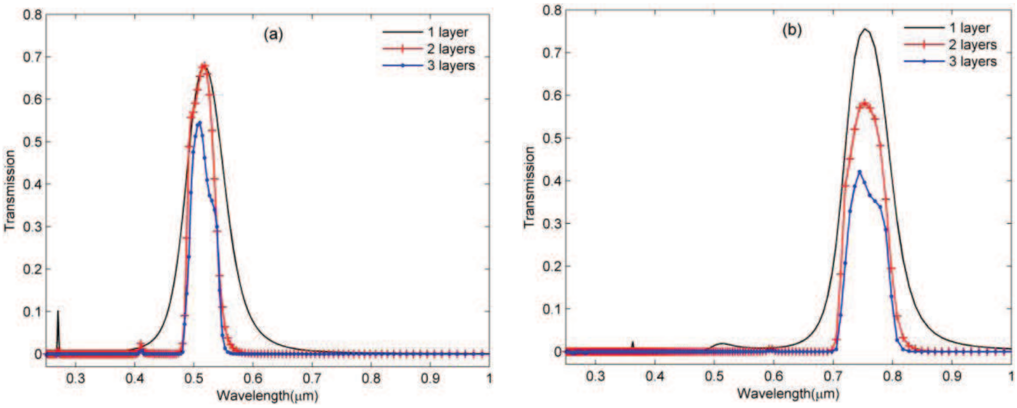

Figure 7: Transmission through 1 to 3 layers of periodic touching gold cylinder arrays: (a) for the structure with bare gold cylinders and (b) for the structure with cylinders embedded in a dielectric with refractive index $n = 1.5$.

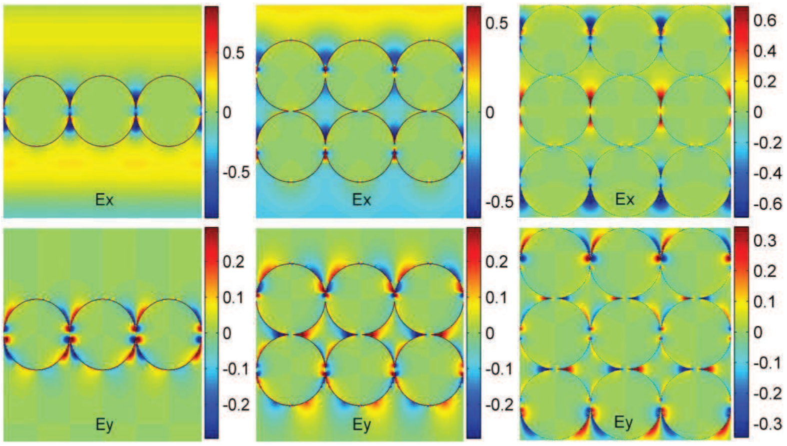

Figure 8: The distribution of the electric field intensity E_x and E_y for the bare structure with one, two, and three layers of touching gold cylinders at transmission wavelengths λ=518 nm, λ=518 nm and λ=510 nm, respectively, corresponding to spectra in Fig. 7(a).

refractive index increasing. In other words, the surface plasmon resonant modes depend on the refractive index of the dielectric covered on the cylinder surface sensitively, so that the surface plasmon resonance can be used to design a potential device such as a sensor.

Maybe the detected peak is quite broad as shown in Fig. 6(a), to optimize the sensitivity of the potential sensor, it is necessary to narrow the peak width. On the purpose, we investigate the transmission spectra for the structure composed of two layers of touching gold cylinders close to each other embedded in a dielectric with refractive index from $n = 1$ to $n = 2$ as shown in Fig. 6(b). With the increase of the refractive index, the resonance peak redshifts gradually with a decrease of the peak value. It is found that full width at half maximum of the resonance peak is narrowed significantly for the structure with two layers compared to that with a single layer, which meets our expectation well. So structure with double-layer cylinders embedded in a dielectric has a better sensitivity.

We have calculated the transmission spectra of the bare structure with different layers of touching gold cylinders as shown in Fig. 7(a) and the structure with different layers of touching gold cylinders embedded in a dielectric with refractive index $n=1.5$ as shown in Fig. 7(b). It can be seen clearly from both figures that transmission resonance peak shifts little for both structures as cylinder layer increases, however, the resonance occurs at a much longer wavelength region for the structure embedded in a dielectric than that for the bare structure. In addition, with the layer increasing, the full width at half maximum of the resonance peak decreases for both the bare and embedded structures. Particularly, for the bare structure, the resonant maximum of the structure with double-layer cylinders is almost the same as that with a single layer as shown in Fig. 7(a). Such a structure is able to provide a sharp filtering. Peak value of the embedded structure is reduced as the layer of cylinders increases as shown in Fig. 7(b).

In Fig. 8 we show the cross sections of the field distribution as a function of the cylinder layer at the transmission resonance wavelength $\lambda=518$ nm, $\lambda=518$ nm and $\lambda=510$ nm for a normal illumination corresponding to the spectra in Fig. 7(a). The field distribution of E_x is homogeneous for structures with different layers, and the field amplitude changes insignificantly, which according well to the resonance transmission property as shown in Fig. 7(a). E_y distribution has both plus and minus charges on each cylinder, which is associated with strongly confined charges of opposite signs as a form of quadruple on each cylinder surface.

4 Conclusions

In conclusion, light tunneling via surface plasmon modes through a periodic touching gold cylinder array has been investigated by using FDTD method. A significant enhancement of the light transmission is provided by the cylinder structure, and the enhancement can be modulated by the cylinder radius, cylinder layer, and refractive index of the dielectric around cylinders. Resonance peak blue shifts and splits as the gold cylinder radius reduces, width of the resonance peak gets much smaller as layer increases, and resonant peak red shifts noticeably as dielectric refractive index increases. The electric field distributions are calculated to explicate the transmission mechanism. These results are helpful to design a good filter device.

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