Extraordinary optical transmission induced by electric resonance ring and its dynamic manipulation at far-infrared regime

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Abstract: We present a design for a sub-wavelength hole array (SHA) decorated with an electric resonance ring (ERR) to realize angle-insensitive extraordinary optical transmission (EOT) at 9.7 μm. A net electric resonance in the whole MM plane, induced by the counter-circulating LC loops in each MM unit-cell, is proposed to have the primary responsibility for the EOT. By tuning the carrier density of an added doped-semiconductor that participates in the in-plane LC resonance, dynamic EOT manipulation and an electric-control turn-on/off function is obtained in our MM.

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References and links
limitation was accomplished by Ebbesen and his associates in 1998 [9]. The observed uniformity and only permits very poor optical transmission. The first step to overcome the dimensions are much smaller than the wavelength of light, would diffract light in all directions continuously for centuries. Standard diffraction theory says that an aperture, whose wavelength hole array (SHA) decorated with a traditional electric resonance ring (ERR) [16]. Liu metallic films [12]. In 2009, Aydin et al. has been proved not to be the necessary condition for EOT. For instance, in 2004, Lezec et al. reported EOT phenomenon in periodic square holes perforated with subwavelength hole arrays, [8]. In their design, SRR array and n-doped GaAs substrate are combined together to effectively form a Schottky diode, which enables about an order of magnitude improvement modulation of THz transmission over existing devices.

On the other hand, optical transmission through sub-wavelength aperture has been studied continuously for centuries. Standard diffraction theory says that an aperture, whose dimensions are much smaller than the wavelength of light, would diffract light in all directions uniformly and only permits very poor optical transmission. The first step to overcome the limitation was accomplished by Ebbesen and his associates in 1998 [9]. The observed enhanced transmission is several orders of magnitude more than that of the conventional prediction in periodic arranged sub-wavelength holes [10]. It is generally accepted that Surface Plasmons Polariton (SPP) [9,11], a specific electromagnetic wave trapped on a metal-dielectric interface, plays a crucial role on the enhanced transmission. Different from the mentioned magnetic coupling and ring-resonance-induced dipole emission in previous work [12–15], our

1. Introduction

Meta-materials (MMs) have generated great interest [1,2] due to their ability to exhibit an artificial response not readily available in naturally occurring materials, such as artificial magnetism [3], negative refractive index [4,5], and so on. Recently, a hot field in MMs studies, which is obtaining extensive attention, is to create an active or dynamical response at many technical relevant frequencies [6]. Dynamic modulations in MMs at microwave and THz regime have been realized experimentally. In 2004, Lim et al. introduced the concept of dynamic control into a composite transmission-line structure to realize a leaky-wave antenna with tunable radiation angle and beamwidth at microwave frequencies [6]. Subsequently, this concept was extended to higher frequencies. For instance, Padilla et al. utilized split-ring resonator (SRR) on high resistivity GaAs substrate to realize dynamical electric and magnetic response at terahertz (THz) frequencies [7]. Chen et al. developed an active THz device based on MM element [8]. In their design, SRR array and n-doped GaAs substrate are combined together to effectively form a Schottky diode, which enables about an order of magnitude improvement modulation of THz transmission over existing devices.

In this paper, we report that angle-insensitive EOT phenomenon can exist in a sub-wavelength hole array (SHA) decorated with a traditional electric resonance ring (ERR) [16]. A net electric response, induced by MM unit-cell, is proved to be supported in the whole MM surface, which accounts for the enhanced transmission. Different from the mentioned magnetic coupling and ring-resonance-induced dipole emission in previous work [12–15], our

mechanism provides a possible mean of endowing the angle-insensitive EOT with the characteristic of dynamic control at far-infrared regime when considering the tunable electromagnetic response in MMs [7,8,17].

2. Structure and experimental results

Fig. 1. (a) Schematic drawing of SHA’s unit-cell and (b) its ERR-decorated element. (c) These MM elements are adjoining arranged in square period (making sure all unit-cells are electrical connected), to form the ERR-decorated SHA on n-doped Si substrate. A surrounding metal ring with width of 1 μm is formed in the margin of the substrate, in order to apply a voltage bias between MM and the substrate. The inset shows the arrangement of the incident wave. Different incident directions are realized by tuning the angle (θ).

Figure 1(a) shows the unit-cell of a copper SHA with dimensions of $P = 1.3 \mu m$ and $a = 1.3 \mu m$, which are much smaller than the concerned wavelength in the far-infrared regime (near 10 μm). The modification from Fig. 1(a) to Fig. 1(b) shows the specific way to introduce ERR into SHA. The primary SHA is decorated by ERR through integrating the side metal portion of ERR with the unit-cell. ERR has dimensions of $w = 0.4 \mu m$, $d = 0.1 \mu m$ and $l = 0.1 \mu m$. Figure 1(c) shows the integrated structure combined with a semiconductor substrate material, which is a 300-μm-thick intrinsic Si layer with carrier density of $N_o \approx 1.08 \times 10^{10} \text{ cm}^{-3}$ at room temperature [18] and high-frequency dielectric constant about 11.7. At the same time, its dielectric property is described by Drude model as shown by Eq. (1) between 8 and 12 μm:

$$
\varepsilon = \varepsilon_\infty - \frac{\omega_p^2 \tau^2}{1 + \omega^2 \tau^2} + i \frac{\omega_p^2 \tau}{1 + \omega^2 \tau^2} \frac{\tau}{\omega}
$$

(1)

where $\tau \approx 1 \times 10^{-13} \text{ sec}$ is the constant scattering time and $\omega_p^2 = Ne^2/m^*\varepsilon_0$ is the plasma frequency ( $\varepsilon_0$ represents the permittivity of vacuum, $e = 1.6 \times 10^{-19} \text{ C}$ is the free electron charge and $m^* = 0.26m_e$ where $m_e$ is the mass of the free electron) [19].

As a beginning, the electromagnetic responses of SHA and its ERR-decorated structure are simulated using a commercial microwave studio of CST 2006B with appropriate periodic boundary conditions, i.e., unit-cell boundary in x-z and y-z planes. In the z direction, two waveguide ports and respective open (with added space) boundary conditions are used for mimicking the incident wave and collecting transmission and reflectance data. Specially, the receiving port is far away from the MM surface (larger than 100 μm), in order to avoid the near-field effect and obtain stable transmission results. Figure 2 shows the corresponding amplitude spectrum of the SHA described in Fig. 1(a). It demonstrates that the pure SHA has poor optical transmission ability from 8 μm to 12 μm in our case. However, when we introduce ERR into the primary SHA according to the description in Fig. 1(a), and choose the polarization of incident wave to be y-direction (meaning that the electric field runs parallel with the split-wire in ERR), the corresponding simulated spectrum is remarkably changed as depicted by the red curve in Fig. 2. The amplitude bears evident enhancement at about 9.7 μm,
which is almost four times that of the pure SHA. Comparing the two cases, we see that the introduced ERR may play an important role in the enhanced transmission. Additionally, we also observe that although the amplitude is slightly changed, the frequency of EOT peak almost has no shift with angle (TM wave), which demonstrates an angle-insensitive property.

![Fig. 2. Respective transmission amplitude spectra of the pure SHA and ERR-decorated SHA with variable incident angle (TM wave).](image)

3. Discussion

We figure out the role of ERR in our proposed structure through investigating the influence of the main parameters of ERR on the transmission behavior. As shown in Fig. 3(a), we get the dependence of the peak frequency on the width of the gap (w). It can be noticed that the transmission peak has obvious blueshift when the gap’s width decreases from 0.5 μm to 0.2 μm in the case of fixed period and aperture dimensions. Figure 3(b) shows the influence of period (P) upon transmission spectrum, the space (l) of the gap also increases respectively in this case. We can see that the peak point moves to higher frequency (shorter wavelength) with increasing the period and space. In fact, both the gap’s width and space influence the effective capacitance \( C \) according to the formula \( C = \varepsilon_{\text{eff}} \frac{w \times l_{\text{eff}}}{l} \). That is, the bigger width indicates the larger \( C \), and the narrower space means smaller \( C \). Thus, the resonance frequency \( f \) decreases or increases according to the formula \( f = \frac{1}{2\pi} \left( \frac{1}{LC} \right)^{0.5} \) when we increase the gap’s width or space, respectively.

![Fig. 3. Dependence of the peak frequency on the width of split-gap (a) and period (b). In (b), the space of the gap increases from 0.1 to 0.3, respectively.](image)

Further, we investigate the current distribution and the equivalent model at the frequency of the EOT peak to analyze the electromagnetic coupling of our MM with incident wave. As shown in Fig. 4(a), it is evident that in the plane of the composite structure, there are two counter-circulating currents respectively located in the two sub-regions in ERR, which are associated with two in-plane LC resonances as shown in Fig. 4(b) (the split-gap and side metal portion in ERR provide the respective capacitance and inductance). Each in-plane \( LC \) resonance would induce a local magnetic response which is in the normal direction of the MM
Due to the counter-excitation of the currents, the two magnetic responses would counteract each other in a single unit-cell. As a result, a net electric resonance is supported in the whole MM surface. Obviously, it is the mechanism of the EOT in ERR-decorated SHA, which is different from the case of EOT induced by the non-SPP mechanisms mentioned before [12–15]. Also, such an EOT behavior is not the case of SPP where the EOT position can be calculated through the momentum matching condition $k_g = k_n \sin \theta \pm mG$ ($k_n$ is the incident wave vector, $m$ is an integer and $G = 2\pi/\Lambda$ where $\Lambda$ is the specific period). Two apparent pieces of evidence are the blueshift of the peak frequency with increasing period as shown in Fig. 3(b), and the insensitivity of the peak frequency to incident angle as shown in Fig. 2.

![Figure 4](image)

**Fig. 4.** (a) Current distribution at the EOT peak. (b) Equivalent circuit model of the in-plane LC resonance corresponding with (a). (c) Influence of the carrier density on the effective resistance in the split-gap region. The inset shows the Diagram of the n-doped Si substrate and the depletion region near the split-gap, where the grey scale indicates the carrier density.

Although there is counteraction between two neighboring magnetic responses induced by LC current loop, the excited current still exists in the MM unit-cell. Thus, if the substrate is doped-semiconductor with high enough carrier density, it would participate in the LC loop and influence the electromagnetic coupling of our MM when the current passes through the split-gap. It may provide us a clue to realize dynamical EOT through changing the carrier density. Actually, researches on dynamic EOT have been done a lot due to the attractive possible application [20–27]. However, these previous work focused on visible or THz regime, and were based on SPP mechanism which would, without doubt, be sensitive to incident angle. Dynamic and angle-insensitive EOT based on MM resonance has not been reported at far-infrared regime so far. To demonstrate this feature, a numerical experiment is carried out as follows. An additional dielectric layer is added between the composite structure and the Si substrate, which is a n-doped Si layer with thickness of 1 $\mu$m and high free-carrier density, for example, $N_{doped} \approx 7 \times 10^{18}$ cm$^{-3}$ (the density level can be realized by using standard ion implantation doping process). Analogous with the method used in Ref. [8], the carrier density can be tuned by applying a bias-voltage between ERR-decorated SHA and a surrounding square copper strip as shown in Fig. 1(c). A space with distance of 50 $\mu$m is designed to make sure the strip will not influence the existing response. In this way, the nearby doped semiconductor will play as a tunable resistance to influence the in-plane LC resonance of ERR, further, influence the net electric resonance.
We approximately calculate the resistance $R_s$ (for simplify, only the real part will be considered) in the effective region under the split-gap using the simple Eq. (2):

$$R_s = \rho \frac{l}{S} = \frac{l}{w \times t_{off}} \frac{\gamma m^*}{N_{doped} e^2}$$

where $l$ and $S$ represents the length and the cross-section’s area of the effective region respectively. The resistance rate $\rho = \frac{\varepsilon_0 \omega \mu}{\gamma - i\omega}$, where $\gamma = \tau^{-1} = 1 \times 10^{11}$ Hz is the collision frequency. The cross-section’s area is approximately calculated by $w \times t_{off}$ where $w$ is the width of the gap, and the height $t_{off}$ approximately equals the space (l) of gap if we assume that the depletion process is isotropy in semiconductor. The curve in Fig. 4(c) shows that $R_s$ is obviously in inverse proportion to $N_{doped}$, which means that we can utilize the dependence of $R_s$ on $N_{doped}$ to manipulate the LC loop as shown in Fig. 4(b). Figure 5(a) depicts the influence of $N_{doped}$ on transmission of ERR-decorated SHA. It can be seen that the transmission amplitude of ERR-decorated SHA increases gradually with the decrease of $N_{doped}$. Especially, the respective amplitude when $N_{doped}$ reaches $1.7 \times 10^{17}$ cm$^{-3}$ gets almost close to that in the case of intrinsic Si as shown in Fig. 2.

![Fig. 5. (a) Transmission amplitude spectra with increasing carrier density in the split-gap region. (b) Dependence of transmission amplitude on carrier density.](image)

We investigate the function of the tunable resistance when altering the carrier density from $1 \times 10^{15}$ cm$^{-3}$ to $1 \times 10^{17}$ cm$^{-3}$. The results are depicted in Fig. 5(b). Two obvious transmission levels are obtained. One case is the low transmission with high $N_{doped}$, such as $1.8 \times 10^{17}$ cm$^{-3}$. In this case, the carrier density is so high that the split-gap is almost electrically connected. Thus, the capacitance formed by the split-gap will be destroyed, which lead to that the in-plane LC resonance is in a turn-off state. In other words, LC loop will not exist in ERR. As a result, the net electric resonance will not be supplied, and the EOT phenomenon disappears.

Another case is the high transmission with a lower $N_{doped}$, for instance $0.1 \times 10^{17}$ cm$^{-3}$. In this
case, the nearby doped semiconductor only acts as a tunable resistance to influence the resonant property due to that $N_{\text{doped}}$ is not high enough to induce a cut circuit between the split-gap. The function of the capacitance formed by the split-gap still exists, which ensure that the in-plane LC resonance is in a turn-on state.

4. Conclusions

In summary, it is shown that a SHA decorated by ERR has angle-insensitive EOT at about 10 $\mu$m. The net electric resonance existing in the whole MM surface is verified to lead to the EOT in our case. At the same time, dynamic EOT based on electric resonator is investigated through introducing high doped-semiconductor and voltage control into ERR-decorated SHA. The scheme presented in this paper combines optical and electrical technology together at far-infrared regime, and the tunable angle-insensitive EOT may have potential application in integrated electro-optical devices. Additionally, the design can also be adjusted into near-infrared or microwave regime by appropriately scaling dimensions.

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