Research article

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Enhanced THz EIT resonance based on the coupled electric field dropping effect within the undulated meta-surface

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Abstract: In this paper, the enhanced terahertz (THz) electromagnetically induced transparency (EIT) resonance is achieved based on the coupled electric field dropping effect within the undulated meta-surface. It is found that the height difference between the inner ring and the outer split ring could lead to a significant coupled mode with electric field dropping distribution. When the height of the inner ring increases, the electric field of the inner ring gradually cascades to the outer ring just as a waterfall so that the coupling between the two rings in a unit cell and two adjacent units is enhanced. Both the simulation and experimental results show that a nearly 95% transparency window which is twice that of traditional EIT can be observed by applying such coupled electric field dropping effect, which may provide a promising way to develop the high resonance intensity meta-surface in the THz region.

Keywords: terahertz; electromagnetically induced transparency; meta-surface.

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1 Introduction

EIT is the quantum destructive interference in a three-level atomic system, leading to an extremely narrowband transparency window over a wide absorption spectrum [1]. Recent studies have shown that the EIT effect can be mimicked by a series of classical optical systems, such as on-chip plasmonic structures [2], photonic crystals [3–5] and meta-surfaces [6–10]. Apart from its fundamental significance, meta-surface-induced transparency in sub-wavelength structures is the most recent and promising addition to the existing classical EIT schemes [11–13]. Terahertz bandpass devices, such as the THz modulators and sensing devices [14], have been developed by applying the transparency window of the EIT. Recently, in order to achieve more transparent window, many studies have been carried out to optimize the EIT effect by adapting the analysis mode [13], coupling [15–21], absorption [22–27], and active tuning [28–30]. Gu et al. observed the excitation and tuning of EIT by the interference between different excitation pathways of the dark mode in a planar terahertz metamaterial [10]. Xiao et al. realize a complete modulation in the resonance strength of the EIT analog via manipulating the conductivity of graphene [11].

Most of the presented studies show that manipulating the EIT effect could be realized by two common methods: one is to break the symmetry of the unit cell structure or vary the relative distance in a plane between the resonators; the other is to realize the modulation by the active medium. The first approach typically involves the bright mode resonators (low quality factor) and/or the dark mode resonators (high quality factor). In the bright-bright or bright-dark mode system, variation in the relative distance between the resonators could modify the coupling of the bright-dark modes or the bright-bright modes [31, 32]. The second approach is usually to construct hybrid meta-materials through integrating with the active medium, and the resonance strength of the EIT can be modulated

via manipulating the conductivity of the active medium [29, 33–35]. However, very limited attempts have been made to manipulate the EIT effect without either varying the relative distance between the resonators or utilizing the active medium.

In this paper, it is found that the height difference between the inner ring and outer split ring could lead to a significant coupled mode with electric field dropping distribution. The coupling coefficient and the dropping electric field intensity between the two different height resonators undergo a great change with the increase of the height difference, which is defined as the coupled electric field dropping effect in this paper. More importantly, such an interesting effect leads to a remarkable enhancement of the EIT resonant intensity. Both the theoretical and experimental results show that the transmission of the EIT transparency window could be nearly doubled under 20 times height difference. Such a coupled electric field dropping effect may provide a promising way to develop the high resonance intensity meta-surface in the THz region.

2 The mechanism of the coupled electric field dropping effect

As we know, it is a common approach to achieve EIT resonance by applying the dual-resonator system, in which the interaction of the resonators leads to the emergence of a new resonant mode from the splitting of degenerate modes. The ring and split ring resonators are the simplest and common meta-unit structures that have the very intriguing EM response [36]. As shown in the results presented [37, 38], such combined units exhibit rich coupling

effects. Therefore, in this paper, this meta-unit structure is applied to study the coupled electric field dropping effect.

In our structure, the dipolar resonant modes of both the inner ring and outer ring resonators can be directly excited by the incident field and then induces the EIT effect through interaction and coupling. Therefore, the coupling plays a very important role to decide the resonance and transparent resonant intensity of the structure. In the classical EM theory, the conductor is just the electrical wall so that the electric field can be distributed among the conductors to construct a mode. Considering the two conductors with different heights leads to the electric field distribution in the gap between them on a plane, as well as in the direction of falling height. Along with this consideration, the undulated meta-surface could support the 3D electric field distribution which may bring enormous change for the traditional EIT or other resonance in the THz band. Therefore, an undulated meta-surface model based on the split ring and ring meta-atoms is constructed, as shown in Figure 1. In this model, the inner one is the ring resonator (IRR), while the outer one is the split ring resonator (OSRR) whose height (z -direction) is quite different from the former. Moreover, the OSRR is tangentially connected with other units for enhancing the coupling between adjacent units.

First of all, we studied the phenomena in such an undulated meta-surface by the Computer Simulation Technology with the Floquet boundary condition. The meta-surface is deposited on a $140\text{-}\mu\text{m}$ -thick quartz substrate which is treated as a loss-free dielectric with a relative permittivity of 3.75 in the simulation. The IRR and OSRR with the almost same resonant frequency and Q -factor values ($Q_{\text{IRR}}=5.64$ and $Q_{\text{OSRR}}=5.61$) are constructed in the same plane with uniform height ($0.2\text{ }\mu\text{m}$). Undoubtedly, a normal EIT resonance is induced by the

Figure 1: Structure of the enhanced EIT resonance.

(A) Three dimensional schematic diagram of the undulated meta-surface. (B) Geometrical parameters of a unit cell: $P_x=110\text{ }\mu\text{m}$, $P_y=110\text{ }\mu\text{m}$, $R=110\text{ }\mu\text{m}$, $r=70\text{ }\mu\text{m}$, $w=4\text{ }\mu\text{m}$ and $g=4\text{ }\mu\text{m}$.

Figure 2: Simulation results of the undulated meta-surface.

(A) Transmission spectra and current distribution of the sole IRR, the sole OSRR and the combined structure. Simulation results of the transmission spectrum for the various heights of the IRR (B) and OSRR (C), respectively. (D) Linewidth and Q factor with different height differences Δ .

incident electric field E which is oriented along the y axis, as shown in Figure 2A. It is clear that the surface current flows with opposite current directions along inner and outer rings, resulting in the destructive interference that gives rise to the EIT resonance at 0.44 THz.

Next, a significant change of the transparency is caused by the height difference between the IRR (h_1) and OSRR (h_2), as shown in Figure 2B and C. The results showed that as h_1 increases while h_2 is fixed, the resonant intensity of the transparency becomes stronger and stronger. In the case of $h_1 = 4 \mu\text{m}$, which corresponds to the 3.8 μm height difference (the limitation of our manufacture platform), the transmission of the transparency window is nearly doubled compared with the original uniform height. However, under the condition that the IRR maintains a constant height of 0.2 μm , Figure 2C shows that the increase of h_2 leads to the reduction of the resonance intensity from 50% to 34%. Moreover, the evolution of linewidth ($\Delta\omega = \omega_+ - \omega_-$) and Q factor for different height differences between the IRR and OSRR is shown in Figure 2D. When the height difference is positive ($h_1 > h_2$), the linewidth becomes wider as the height difference

increases while the Q factor remains almost the same, but for the case where the height difference is negative ($h_2 > h_1$), the linewidth decreases and Q factor increases with the height difference increasing. In this paper, we will focus on the effect of enhanced EIT in the case of positive height differences.

The slow light is a remarkable characteristic of EIT response which is of significance for optical technology. The group delay representing slow light is calculated by $\tau_g = -d\phi(\omega)/d\omega$, where $\phi(\omega)$ and ω are transmission phase and angular frequency, respectively. The group delay of the EIT meta-surface with various h_1 and h_2 is shown in Figure 3A and B, and a large group delay indicating the lag of the wave packet is observed. As the height difference increases, the group delay of the wave packet near the peak of the transparency window increases from 3.08 to 4.83 ps for various h_1 and from 3.08 to 3.96 ps for various h_2 , both of them enhancing their slow light characteristics.

The distribution of the electric field with different IRR heights is shown in Figure 4, indicating that the dramatic modulation on electromagnetic response is caused by the electric field dropping effect. When the heights of the

Figure 3: Group delay of the EIT meta-surface with the increase in the height of the IRR (A) and OSRR (B) in the range 0.2–4 μm .

resonators are the same, the normal EIT resonance can be induced and the field distribution is shown in Figure 4A. In this case, the field distributions of the two resonators seem to be complementary. The place where the field intensity of the inner resonator is strongest always corresponds to the weakest field distribution of the outer resonator. The cross sections of the field distribution and direction just illustrate the field of the black dashed line in the figure, indicating the complementary field distribution of the IRR and OSRR. Therefore, in such a unit cell,

the coupling between the IRR and OSRR is very weak due to the complementary field distribution.

From another point of view, the dipole model is used to illustrate the physical process. As shown in Figure 4B, the dipolar resonance results in the induced charge distribution in the IRR where the positive charges appear in the upper part and the negative charges are concentrated at the lower part, so the dipole mode can be equal to this charge distribution. Owing to the weak coupling, the field distribution of the adjacent units corresponds to the two pairs of the dipole model shown in Figure 4B, where the IRR plays a major role in coupling compared with the OSRR and the coupling of adjacent IRRs can be seen as a pair of equal heterogeneous charges represented by the orange line.

As the height of the IRR increases, the quantity of induced charges improves, which leads to the enhancement of field around the IRR, causing the opposite charges to be gradually induced at the OSRR, as shown in Figure 4C. From the field contour map demonstrated in Figure 5, the electric field of the IRR gradually cascades down to the OSRR just as a waterfall so that the corresponding place has its own field distribution. When h_1 reaches up to 4 μm , the electrical field dropping effect leads to an equilibrium state that the electric field intensity of the IRR and OSRR is nearly the same. In this case, the electric distribution of the IRR and OSRR is no longer complementary and the coupling between two adjacent units is enhanced, while the induced charge distribution is shown in Figure 4D. Therefore, two pairs of dipole model can be used to illustrate the interaction shown in Figure 4E.

Under this condition, the coupling becomes largest. More importantly, in the dipole model, the IRR and OSRR are regarded as a pair of unequal heterogeneous charges, and the coupling effect in this case includes the interaction between the IRR and OSRR in a separate unit cell represented by black lines, as well as the interaction between

Figure 4: (A, C, D) Electric field distribution and cross-sectional field distribution along the Y direction at 0.44 THz with $h_1 = 0.2 \mu\text{m}$, $h_1 = 2 \mu\text{m}$ and $h_1 = 4 \mu\text{m}$, respectively. (B, E) The dipole model at $h_1 = 0.2 \mu\text{m}$ and $h_1 = 4 \mu\text{m}$, respectively.

Figure 5: The process of coupled electric field dropping within the undulated meta-surface.

two adjacent units, represented by the red line and orange line. As a result, such a significant coupled mode with the electric field dropping distribution leads to a remarkable enhancement of the EIT resonant intensity.

3 Theory and numerical calculation of the coupling EIT resonance

In order to further understand the enhanced EIT resonance, the coupling EM theoretical study and the numerical calculation have been carried out. According to the coupled Lorentz model, the resonant field amplitude of both IRR and OSRR can be described as the linearly coupled Lorentzian oscillators [13, 29, 39–41]:

$$\begin{aligned} \ddot{s}_1 + \gamma_1 \dot{s}_1 + \omega_0^2 s_1 + \kappa s_2 &= \frac{q_1}{m_1} E, \\ \ddot{s}_2 + \gamma_2 \dot{s}_2 + \omega_0^2 s_2 + \kappa s_1 &= \frac{q_2}{m_2} E \end{aligned} \quad (1)$$

where s and γ are the amplitude and the damping rate, and subscripts 1 and 2 represent the IRR and OSRR, respectively. q , m and ω_0 are the effective charge, effective mass and resonance angular frequency ($\omega_0 = 2\pi f_0$, $f_0 = 0.44$ THz), respectively. In this equation, κ denotes the coupling coefficient.

By solving Eq. (1), we can obtain the expressions for s_1 and s_2 as

$$\begin{aligned} s_1 &= \frac{q_1/m_1 B + q_2/m_2 \kappa}{\kappa^2 - AB} E \\ s_2 &= \frac{q_2/m_2 A + q_1/m_1 \kappa}{\kappa^2 - AB} E \end{aligned} \quad (2)$$

with

$$\begin{aligned} A &= -\omega^2 + i\gamma_1 \omega + \omega_0^2 \\ B &= -\omega^2 + i\gamma_2 \omega + \omega_0^2 \end{aligned}$$

Thus, the susceptibility χ_e , which relates the polarization of the particle to the strength of incoming electric field (E), is expressed as

$$\begin{aligned} \chi_e &= \frac{q_1 s_1 + q_2 s_2}{\varepsilon_0 E} \\ \chi_e &= C \left(\frac{\frac{q_1}{m_1} (-\omega^2 + i\gamma_2 \omega + \omega_0^2) - \frac{q_2}{m_2} \kappa + \frac{q_2}{m_2} (-\omega^2 + i\gamma_1 \omega + \omega_0^2) - \frac{q_1}{m_1} \kappa}{-\kappa^2 + (-\omega^2 + i\gamma_1 \omega + \omega_0^2)(-\omega^2 + i\gamma_2 \omega + \omega_0^2)} \right) \end{aligned} \quad (3)$$

Combined with Eq. (3), the transmission can be presented as

$$t = \left| \frac{4\sqrt{\chi_e + 1}}{\left(\sqrt{\chi_e + 1} + 1\right)^2 e^{j(2\pi d/\lambda)\sqrt{\chi_e + 1}} - \left(\sqrt{\chi_e + 1} - 1\right)^2 e^{-j(2\pi d/\lambda)\sqrt{\chi_e + 1}}} \right| \quad (4)$$

where d is the thickness of the substrate. Considering a lossless model, the influence of the coupling strength κ on the spectral width of the transparency window is given by $\omega_- = \sqrt{\omega_0^2 - \kappa^2}$ or $\omega_+ = \sqrt{\omega_0^2 + \kappa^2}$. Then, the width of the transparency window is simply written as

$$\Delta\omega = \omega_+ - \omega_- \approx \frac{\kappa^2}{\omega_0}$$

Figure 6: Fitting results.

(A) The transmission spectrum with various heights of the IRR and OSRR. (B) The coupling coefficient κ and linewidth with various height differences Δ .

As pioneering researchers did recently [13, 40, 41], the fitting results of different samples can be obtained by substituting the transmission values into (3) and (4), as shown in Figure 6A. The overall qualitative agreement between the simulated and calculated results is quite consistent. In order to better observe the tendency, we have calculated more coupling coefficient κ and linewidth $\Delta\omega$ in different heights of the IRR and OSRR. Both κ and $\Delta\omega$ increase with the increase of the height difference Δ , and then reach saturation of height difference $\Delta = 3.8 \mu\text{m}$. It indicates specifically that the coupling intensity between the two resonators is essentially enhanced with

increasing positive height difference, which is an important factor accounting for the enhanced EIT effect.

4 Experimental design and measurement

Based on the simulation and theoretical study, we purposely fabricate a series of terahertz meta-surfaces following standard photolithography procedures with different inner ring heights ($h_1 = 0.2 \mu\text{m}$, $1 \mu\text{m}$, $2 \mu\text{m}$, $3 \mu\text{m}$, $4 \mu\text{m}$).

Figure 7: Manufactured sample.

(A) Electron microscopy images of the sample ($h_1 = 4 \mu\text{m}$). (B) Original time domain data of TDS with various heights of inner rings. (C) Measured transmission amplitude with various heights of inner rings.

In all these samples (all exhibiting a total size of $1 \times 1 \text{ cm}^2$), the 200-nm-thick gold outer split rings are fabricated on a 140- μm -thick quartz substrate by conventional optical lithography. Meanwhile, the metallic structures of inner rings need to be deposited multiple times depending on the height. Electron microscopy images of the fabricated meta-surface ($h_1 = 4 \text{ }\mu\text{m}$) are shown in Figure 7A, where the light region is the meta layers and the dark area is the quartz substrate.

The meta-surface samples are characterized by using broadband terahertz time-domain spectroscopy (THz-TDS). All measured transmittance signals are normalized against a reference signal, obtained under the exactly same excitation configuration, only with the sample replaced by a quartz substrate of the same height. The multiple scatterings of terahertz wave inside the substrate are purposely excluded in our measurements through a standard time-domain cutoff procedure. The original time domain signals for h_1 values of 0.2 μm , 1 μm , 2 μm , 3 μm , and 4 μm are shown in Figure 7B; similar to the simulation results, the transparency window of the EIT resonance is enhanced with increasing height of the inner ring. It is clear that with increasing positive height difference, the EIT transparency window becomes higher. At the 4- μm -depth case, the transparency window can reach up to 95% transmission which is a very attractive and large value. The experimental results agree with the simulation very well, as shown in Figure 7C.

More important, the errors between the theoretical study and experimental results are below 3%, which verifies the feasibility and possibility of this coupled enhanced EIT resonance.

5 Experimental design and measurement

In summary, the enhanced THz EIT resonance is achieved based on the coupled electric field dropping effect within the undulated meta-surface. It is found that the height difference between the inner ring and outer split ring could lead to a significant coupled mode with the electric field dropping distribution. With increasing height difference, the EIT resonant intensity greatly enhanced due to the larger dropping electric field intensity and stronger coupling. Both the simulation and experimental results show that the amplitude modulation of the transparency peak is achieved by varying the height difference and nearly 95% transparency window which is twice that of traditional EIT can be observed. This coupled electric field dropping effect with

undulated meta-surface design that enables the tuning of the classical EIT effect would eventually lead to the development of high-performance terahertz bandpass devices.

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