Materials Research Express

PAPER

Robust analogue of electromagnetically induced transparency for stable meta-devices

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Keywords: metasurfaces, electromagnetically induced transparency, terahertz, meta-devices

Abstract

Recently, studying metasurface structures for mimicking the quantum phenomena of electromagnetically induced transparency (EIT) has drawn continuous attention, which promotes a new generation of functional electromagnetic devices, including slow-light devices, optical sensors, and so on. In some cases, metasurfaces which can realize stable EIT effect is of critical importance in the real applications. Here, we propose a novel planar terahertz metasurface which exhibits strong EIT behavior owing to the strong coupling between the dark mode and bright mode. The EIT effect is very robust, which is stable to various variations of the geometric parameters, opening up a new avenue to improve the device stability based on metasurfaces.

1. Introduction

Recently, metasurfaces have been extensively studied for their unprecedented abilities in manipulating electromagnetic waves. The arbitrary artificial characteristics of the metasurfaces offer enormous opportunities for realizing promising applications, such as filters, super lenses, invisible cloaks, polarizers, modulators, sensors, and toroidal dipoles \cite{1–11}. In addition, the artificial characteristics can mimic many quantum phenomena in a classical manner that can work in general temperature and pressure working conditions, for example, the electromagnetically induced transparency (EIT) \cite{12–19}. Various metasurface structures in micro and nano sizes have recently been proposed to emulate the EIT-like spectral response, such as split ring resonators, cut wires, waveguide resonators, and multilayer structures \cite{20–25}, revealing many related meta-devices including slow-light devices, optical sensors, and so on. The common method to create an EIT analogue is to form two coupled modes supported by ‘bright and dark’ \cite{26} or ‘superradiant and subradiant’ \cite{23, 27} resonators with distinct quality (Q) factors. Specifically, the dark or subradiant resonance modes usually possess lower Q factors than those of the bright or superradiant resonance modes. The EIT-like resonances are formed via destructive interference between different excitation pathways of the bright or superradiant modes.

In general, the coupling effect between the two modes has strict requirements on the geometric parameters. A lot of studies have employed this characteristic to design tunable EIT analogues. Recently, a tailorable mode interference was successfully realized in EIT metasurfaces by altering the distance between dark mode and bright mode within 10 \textmu m \cite{28}. In addition, the EIT peak was totally shut down when physically varied the distance between the superradiant and the subradiant resonators by 22 \textmu m \cite{29}. However, a stable EIT effect, which does not change much with variation in the geometric parameters, can be useful in some practical applications. Therefore, seeking stable EIT structures is of critical importance.

In this paper, we theoretically propose a robust EIT structure consisted of a meander-line resonator (MLR) and a double-U resonator (DUR) in the terahertz regime, where the former serves as the bright mode, and the later serves as the dark mode. A strong coupling effect is formed when putting the two modes together, such that a strong EIT phenomenon is observed. Through numerical simulations, we systematically studied the spectral
response of the EIT by changing the spatial configuration of the EIT structure. It is observed that the EIT response does not change significantly when we alter the line width, relative positions and angles between the two resonators, showing a robust feature. This endows us great benefit to eliminate the influence on EIT effect from some inevitable errors, i.e. in the manufacturing process. The particular scheme proposed here would also tremendously expand the configuration design of stable and compact terahertz devices.

2. Design and characterization

The unit cell of the proposed EIT metasurface with different geometric parameters is schematically illustrated in figure 1. The characteristic spectral responses of the proposed structures are supported by a full wave numerical simulation using the finite-element time-domain (FDTD) method. The plane wave was used for simulation, and the incident wave was polarized along y direction on the EIT metasurface with a periodic boundary condition. In the simulation, the 640-μm-thick substrate silicon was modeled as a lossless dielectric with permittivity \( \varepsilon = 11.78 \) and the 0.2-μm-thick Al was simulated as a lossy metal with a conductivity of \( \sigma = 3.72 \times 10^7 \text{ S} \cdot \text{m}^{-1} \). It should be noted that the thickness of Al is selected to be about twice of the terahertz penetration depth to ensure a strong resonance, and the thickness of the silicon substrate is mainly selected by considering the overall performance.

Figures 2(a) to (c) show the simulated amplitude transmission spectra of the MLR, DUR, and EIT metasurfaces, respectively. Here, the amplitude transmission was defined by \( |T(\omega)| = |E_{\text{EIT}}(\omega)/E_{\text{Ref}}(\omega)| \), where \( E_{\text{EIT}}(\omega) \) and \( E_{\text{Ref}}(\omega) \) were respectively the simulated transmitted amplitude through the EIT structure and the reference, where the reference was a bare silicon substrate with the same thickness. It can be seen in figures 2(a) and (b) that both the MLR metasurface and the DUR metasurface exhibit strong resonance at corresponding frequencies with a small detuning frequency, but they were excited by orthogonally incident electric fields (see the insets of figures 2(a) and (b)). In addition, their \( Q \) factors are significantly different, where the \( Q \) factor of the MLR metasurface is 4.05, while the \( Q \) factor of the DUR metasurface is 12.03, which obeys the general EIT design rule. Here, under \( y \)-polarized incidence, the MLR acts as the bright mode as it can be directly excited by the incident field, while the DUR acts as the dark mode as it cannot be excited by the incident field but can be excited by the local \( x \)-polarized filed generated by the bright mode. As a result, when these two different resonators were put together in a single unit cell, the strong near-field coupling resulted in a typical EIT-like transmission spectrum under the \( y \)-polarized incidence, as shown in figure 2(c), where a sharp transmission peak appears at 0.63 THz between the two resonance dips, showing a remarkably EIT response.

3. Analysis and discussion

In order to acquire further understanding of the EIT phenomenon, the surface current density distributions of the three metasurface structures are extracted from the simulation. The simulated surface current density distributions at the resonance dip frequencies of the MLR and DUR metasurfaces, and the transmission peak frequency of the EIT metasurface are respectively illustrated in figures 2(d) to (f). It is found from the figures 2(d) and (e) that both the MLR and DUR have strong current oscillations under direct excitation of \( y \)-polarized and \( x \)-polarized incident terahertz fields, respectively. However, when the MLR and DUR are assembled in a unit cell, and \( y \)-polarized incident terahertz field is applied, the surface current in the MLR structure is significantly quenched (see figure 2(f)). This effect can be expressed by looking into the directions of the surface current of

![Figure 1. Schematic unit cell of the proposed EIT metasurface with parameters: \( D = 20 \mu m, d = 15.5 \mu m, L = 48.5 \mu m, l = 27 \mu m, w = 6 \mu m, g = 6 \mu m, s = 7 \mu m, \) and a lattice periodicity \( P = 100 \mu m, \) respectively.](image-url)
MLR and DUR. Since the surface current in MLR is oscillating along the \( y \) direction (see figure 2(d)), a magnetic field would generate along the \( z \) direction (see the red marks in figure 2(d)). Meanwhile, the surface currents in the DUR under \( x \)-polarized incidence reveal that the resonance mode of the DUR is LC resonance. When the DUR is incorporated into the MLR structure, namely, to form the EIT metasurface, the excited MLR by the \( y \)-polarized incidence will generate magnetic fields around the two arms along the \( y \)-direction, which would highly excite the DUR according to the Faraday’s law of electromagnetic induction. The excited DUR would strongly react back to the MLR, leading to the suppression of the resonance of the MLR, and thus opening up a transparency window.

To gain more insight on the destructive coupling between the MLR and DUR in the EIT metasurface, a coupled Lorentz model is adopted to describe the EIT behavior. In this model, the aforementioned two modes are analytically described by the following equations:

\[
\begin{align*}
\ddot{x}_1 + \gamma_1 \dot{x}_1 + \omega_1^2 x_1 + \kappa x_3 &= gE, \\
\ddot{x}_2 + \gamma_2 \dot{x}_2 + \omega_2^2 x_2 + \kappa x_1 &= 0,
\end{align*}
\]  

\[\text{Figure 2.} \text{ (a)--(c) Simulated transmission amplitudes of the MLR, DUR and the EIT metasurfaces, respectively. The insets show the corresponding unit cells and the incident terahertz polarizations. (d)--(f) Simulated surface current density distributions of the proposed MLR, DUR and EIT metasurfaces, respectively. The black arrows in (d)--(f) illustrate the direction of the surface current, and the red marks in (d) illustrate the direction of the magnetic field derived from the nearby surface current.}\]
Here, $x_1, x_2, \gamma_1, \gamma_2, \omega_1$ and $\omega_2$ represent the amplitudes, damping rates and resonance angular frequencies of the bright (subscript 1) and dark (subscript 2) modes, respectively; $\omega_2 = \omega_1 + \delta$ with $\delta = 6 \times 10^{10}$ rad/s being the detuning of the resonance angular frequency of the dark mode to the bright mode ($\omega_1 = 2\pi f_0, f_0 = 0.59$ THz); $\kappa$ is the coupling coefficients between the two modes; and $g$ is a geometric parameter denoting the coupling strength of the bright mode coupling with the incident electromagnetic field $E$. According to equation (1), the susceptibility $\chi_e$ of the EIT metasurface can be expressed as:

$$\chi_e(\omega) = \frac{\tilde{P}(\omega)}{\varepsilon_0 \tilde{E}(\omega)} \propto x(\omega) / \tilde{E}(\omega),$$

(2)

where $\tilde{P}(\omega)$ is the intensity of polarization, and $\varepsilon_0$ is the vacuum permittivity. $x(\omega) = x_1(\omega)$ is the total resonance amplitude, since in our case only the bright mode contributes to the transmission spectra under y-polarized incidence. Therefore, the polarizability of the EIT metasurface with a thickness $t$ is expressed as $\tilde{\chi} = \chi_e / t$. Furthermore, the amplitude transmissions of the EIT sample $|t(\omega)|$ can be calculated as [20]
where $c$ represents light velocity in vacuum, and $n_{Si}$ is the refractive index of the high-resistance silicon substrate. The dotted blue curve in figure 3(a) illustrates the fitting results using equation (3) with parameters $\gamma_1 = 0.31$, $\gamma_2 = 0.09$ and $\kappa = 0.02$ THz$^2$, which is in good agreement with the simulated results.

Since the slow light capability is of significant importance in the application of the EIT metasurface, the group delay ($\Delta t_g$) of the terahertz wave through the EIT structure is also extracted, as shown in figure 3(b). Here, $\Delta t_g$ is theoretically calculated by taking difference between the absolute group delays of the EIT metasurface (with substrate) and vacuum with the same thickness. In addition, their wave packets shown in figure 3(b) with

\[
|\tilde{t}(\omega)| = \left| \frac{c(1 + n_{Si})}{c(1 + n_{Si}) - i\omega e} \right|
\]  

(3)

Figure 5. Simulated transmission amplitudes at specific values of (a) $\Delta x = -5 \mu m$, (b) $\Delta x = 5 \mu m$, (c) $\Delta d = -15 \mu m$, (d) $\Delta d = 5 \mu m$, (e) $\Delta \theta = -10^\circ$, (f) $\Delta \theta = 10^\circ$, (g) $\Delta w = -3 \mu m$, (h) $\Delta w = 3 \mu m$, respectively.
central frequency of 0.55 THz is both delayed by about 6.21 ps, which is comparable to the high group delay values reported in previous EIT works \cite{20, 30}.

Apart from the high group delay shown above, the proposed EIT is also very stable. In order to show the stable feature of the strong EIT effect in the designed metasurface, we looked at the EIT spectra at all variation levels, including relative vertical and horizontal distances, rotation angles, and line widths. (i) We changed the

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{simulated_transmission_amplitudes.png}
\caption{Simulated transmission amplitudes at critical values of (a) $\Delta x = -6 \mu m$, (b) $\Delta x = 6 \mu m$, (c) $\Delta d = -20 \mu m$, (d) $\Delta d = 10 \mu m$, (e) $\Delta \theta = -12^\circ$, (f) $\Delta \theta = 12^\circ$, (g) $\Delta w = -5 \mu m$, (h) $\Delta w = 5 \mu m$, respectively.}
\end{figure}
relative position of the two modes by horizontally shifting the DUR along the x-axis by a relative variation of $\Delta x$, as illustrated in the inset of figure 4(a). In this case, the symmetry of the whole structure along the y-axis is broken. Contrary to previous research, it is interesting to find that the amplitude of the EIT transmission spectrum changed little as the $\Delta x$ is changed from $-5$ to $5 \mu m$, as depicted in the area surrounded by the black dotted line in figure 4(a). (ii) We next changed the relative position of the two modes by vertically shifting the DUR along the y-axis by a relative variation of $\Delta d$. As illustrated in figure 4(b), when $\Delta d$ varies from $-15$ to $5 \mu m$, we note that the transmissions are almost unchanged. (iii) We next changed the relative rotation angle of the DUR $\Delta \theta$, as shown in figure 4(c). Again, virtually no variation is observed when $\Delta \theta$ is changed from $-10^\circ$ to $10^\circ$. (iv) At last, we changed the line width $\Delta w$, which often happened in the sample fabrication processes, as shown in figure 4(d). Although the EIT spectra undergo a slight blue shift when $\Delta w$ is changed from $3$ to $3 \mu m$, the overall EIT effect is still very strong. All the corresponding transmission spectra at the black dotted lines in figure 4 are presented in figure 5. It can be intuitively seen all the spectra are very similar to that in figure 2.

When we further expand the variation range of each parameter, specifically $\Delta x$ is expanded to $-6$ to $6 \mu m$, $\Delta d$ is expanded to $-20$ to $10 \mu m$, $\Delta \theta$ is expanded to $-12^\circ$ and $12^\circ$, $\Delta w$ is expanded to $-5$ to $5 \mu m$, the EIT effect is still very strong, as shown in figures 4 and 6. It is very interesting that even though some parts of the bright and dark mode structure connected together (see the insets of figure 6), there could still see a strong EIT effect. The allowable large variations of relative vertical distance, horizontal distance, rotation angle, and the linewidth, reveal that this EIT metasurface is quite robust.

In order to deeply understand the robust EIT phenomenon, an effective circuit model was established for the EIT unit cell, as shown in figure 7. According to the current density distribution illustrated in figure 2, it can be found that there are two symmetrical electrical dipoles in the bright mode, so each arm of the MLR acts as the inductance $L_1 (L_2)$ [31]. Similarly, each arm of the DUR structure works as inductance $L_3 (L_4, L_5, L_6)$. The ends of the surface current in the structure imply large carrier aggregation and usually form a capacitance effect. Therefore, the capacitance $C_1, C_2, C_3, C_4$ and $C_5$ could be set accordingly. Here we can ignore any resistances for the bars because the metal can be seen as perfect electric conductors in the terahertz regime. This effective circuit also reveals that the magnetic coupling between the bright mode and dark mode dominates the conformation of the EIT effect. The magnetic coupling cannot be altered on a large scale when the relative distances, rotation angles, and line widths are changed, so a strong EIT effect is maintained throughout the changing.

4. Conclusion

In conclusion, a robust EIT metasurface consisting of MLR and DUR was theoretically proposed in the terahertz regime. Analyses based on numerical simulation and coupled Lorentz model show the EIT effect is derived from the interference between different excitation pathways of the bright mode. In addition, the pronounced EIT spectra do not display any significant variations when we change the relative distances, rotation angles, and line widths of the two modes. An effective circuit model was also established to explain the EIT phenomenon. As the structure here is designed according to the reliability in measurements, we believe our EIT device can be experimentally validated. In addition, the proposed structure design can be applicable to all radiation domains by scaling the size of the overall structure. This new metasurface design enables excitation of the classical EIT effect, which would eventually contribute to the development of stable EIT meta-devices.
Acknowledgments

This work was supported by the National Natural Science Foundation of China (61705167), the project for the young innovative talents in colleges and universities of Guangdong (2019GQKNCX136), the Scientific Research Project of Tianjin Municipal Education Commission (2020KJ125), the research foundation of Tianjin University of Technology and Education (KJ1920, KYQD1907), the Training plan for young and middle-aged backbone talents of Tianjin. We also thank for the support from Tianjin Key Laboratory of Imaging and Sensing Microelectronic Technology.

Declaration of interests

The authors declare no conflict of interests.

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