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Modulation of terahertz electromagnetically induced absorption analogue in a hybrid metamaterial/graphene structure

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ABSTRACT
We proposed a two-layer metamaterial structure with graphene that consists of two H-shaped resonators and one I-shaped resonator. The electromagnetically induced absorption (EIA) analog phenomena were observed in absorption spectra, resulting from the near-field coupling of two bright modes. Furthermore, the absorption peak can be tuned by changing the dimension of the I-shaped resonator or changing the Fermi energy of graphene. The theoretical analysis reveals that the EIA analog arises from magnetic resonance using the coupled Lorentz oscillator model. This hybrid-EIA analog structure may provide a possible choice for designing potential devices for dynamic narrow-band filtering and absorber applications.

I. INTRODUCTION
In the past decades, electromagnetically induced transparency (EIT) has been widely studied.\(^1\)-\(^3\) First, this phenomenon is a result of destructive interference between two different excitation pathways in a three-level atomic system.\(^4\) Recently, the EIT analog behavior has been observed in various metamaterial structures, including cut wires, split-ring resonators (SRRs), and asymmetric Fano resonators.\(^5\)-\(^10\) As EIT can be realized much more easily, it attracted significant attention in numerous potential applications, such as optical storage, ultrafast sensing, nonlinear optics, and slow light devices.\(^11\)-\(^15\) The EIT analog effect can be achieved by two approaches: bright-dark mode coupling\(^16\)-\(^20\) and bright-bright mode coupling.\(^21\),\(^22\)

In contrast to the destructive interference of the coupled EIT resonators, a constructive interference will lead to a new fascinating phenomenon, namely, electromagnetically induced absorption (EIA).\(^23\)-\(^26\) Instead of a pronounced transparency window, a sharp absorption resonance is induced in the EIA system. Due to its narrow spectral characteristics, EIA in metamaterials possesses useful potential applications in nonlinear optics, such as narrow-band filtering, absorptive switching, and optical modulators.\(^27\)-\(^30\)

Graphene has attracted considerable attention due to its unique optical, mechanical, and electrical properties.\(^31\)-\(^35\) Instead of redesigning the geometrical dimensions of the structures, the Fermi energy of graphene can be tuned dynamically via electrostatic gating or chemical doping which makes graphene a new material for dynamic tuning of absorption windows. However, few research studies focusing on active modulation of the EIA analog have been reported.

In this paper, we present a structure with two metamaterial layers consisting of two H-shaped resonators (HSRs) and one I-shaped resonator (ISR) with a monolayer graphene sheet, which can exhibit EIA analog effects at the terahertz region. In this system, the numerical simulation and theoretical model fitting results have been shown to demonstrate the EIA analog behavior. In particular, we have discussed the surface current distributions in these resonators to reveal that the EIA analog effect is the result of constructive interference induced magnetic response of the near-field coupled resonators. In addition, EIA analog mechanical
can be represented by the Kubo equation, including the interband and intraband transition contributions: \( \sigma_g = \sigma_{\text{inter}} + \sigma_{\text{intra}} \). In the lower terahertz regime, the interband contributions can be prohibited because of the Pauli exclusion principle. Therefore, we only consider the intraband contributions based on the approximation condition \( E_f \gg k_B T \) at room temperature, and the conductivity of graphene can be simply given by using the Drude-like model as

\[
\sigma_g = \frac{i e^2 E_f}{\pi \hbar (\omega + i\tau^{-1})},
\]

where \( e \) is the charge of an electron, \( E_f \) is the Fermi level of graphene, \( \hbar \) is the reduced Planck’s constant, \( \omega \) is the angular frequency of the incident light, and the relaxation time \( \tau = (\mu e^2/\epsilon_0 \hbar)^{-1} \approx 0.5 \text{ ps} \) for \( E_f = 0.5 \text{ eV} \). In our simulation, we take the carrier mobility as \( \mu = 3000 \text{ cm}^2/\text{V s} \) and the Fermi velocity as \( v_F = 1.1 \times 10^6 \text{ m/s} \), which are referenced from experimental results. Then, the permittivity of graphene can be obtained according to the following equation:

\[
\epsilon_g = 1 + \frac{i \sigma_g}{\epsilon_0 \Delta},
\]

where \( \epsilon_0 \) is the permittivity of vacuum and \( \Delta \) is the thickness of the graphene film. According to the above equations, we can calculate the values of permittivity at different frequencies.

The numerical calculations are performed by using the commercial software CST. In the simulation, Al was simulated with a conductivity of \( 3.72 \times 10^7 \text{ S m}^{-1} \); the Si substrate and polyimide layer were modeled as dielectrics; the permittivity were taken as 11.7 and 2.96 + 0.27 i, respectively; and the graphene material was set by importing different calculated dispersion values of permittivity at different frequencies.

II. MODEL AND PARAMETERS

The designed metamaterial structure and propagation of the incident terahertz wave are shown in Fig. 1(a). The unit cell consists of one I-shaped resonator at the top layer and two H-shaped resonators at the bottom layer which are symmetric along the x-axis, respectively. The metasurface structure is made from a thick aluminum film, which is fabricated on a 10-μm-thick silicon substrate. Each adjacent metal layer is separated by a dielectric layer of polyimide, with a thickness of 20 μm. Figure 1(b) shows the top view of the unit cell with periodic length \( P_x = P_y = 120 \text{ μm} \). Figure 1(c) illustrates other dimensions of the metallic structure, which are \( a = 106 \text{ μm}, b = 48 \text{ μm}, c = 70 \text{ μm}, d = 28 \text{ μm}, e = 30 \text{ μm}, g = 6 \text{ μm}, \) and \( w = 6 \text{ μm} \). We defined \( x = 0 \text{ μm} \) when the ISR is located at the center of the structure.

The monolayer graphene sheet is placed under the ISR and can be regarded as a sheet material. The surface conductivity of graphene modulation has been observed by changing the dimension of the ISR. More importantly, the proposed structure can actively control the absorption window and achieve on/off switching of the EIA analog via varying the Femi energy of graphene without refabricating the structure. Therefore, this work makes possible the design of tunable absorber and switches.

III. RESULTS AND DISCUSSION

At first, an individual ISR, HSRs, and a composite structure without graphene are simulated to investigate the EIA analog phenomenon. The simulated transmission and absorption spectra of the individual ISR and HSRs are investigated, as shown in Fig. 2. For the single ISR, a broad resonance at 0.58 THz is directly excited by incident terahertz waves when the electric field is polarized along the y-axis and the magnetic field is polarized along the x-axis. Meanwhile, for HSRs, a narrower resonance at 0.49 THz is directly excited by incident terahertz waves with the same polarization direction of the electromagnetic field as in the ISR, as shown in Fig. 2(a). Therefore, the ISR and HSRs both sever as bright modes. Moreover, it
can be seen that a narrow absorption peak with an intensity of 0.30 rises from HSRs at 0.497 THz. By contrast, a broad absorption rises from the ISR at 0.541 THz with an intensity of 0.20, as illustrated in Fig. 2(b).

As expected, when the ISR and HSRs are integrated together to form a hybrid structure, a narrow absorption peak rises at 0.506 THz with an intensity of 0.74, which displays EIA analog behavior. The absorption peak shows a slight blue shift compared with the absorption of individual HSRs. Therefore, we consider that the high and narrow absorption peak is caused by the coupling between the ISR and HSRs. Figure 3 not only displays the absorption spectrum of the structure but also shows the transmission and reflection spectra. In the transmission spectrum, the structure also shows two transmission dips at 0.49 THz and 0.58 THz, respectively. Theoretical fitting results are illustrated in Fig. 3(b), which are consistent with simulation results.

Further to understand the physical mechanism of the EIA analog behavior in such a structure, the simulated surface current distributions at the peak absorption frequency are plotted in Fig. 4. Only concerning the top ISR or the bottom HSRs, respectively, the currents generated in the ISR and HSRs are both directed upwards along the y-axis, as exhibited in Figs. 4(a) and 4(b). It is evident that the direction of surface currents in bottom resonators is reversed after putting them together, as shown in Fig. 4(c). The antiparallel currents form a current circle and then lead to the formation of a magnetic dipole. The magnetic dipole direction parallels to incident magnetic field polarization. Therefore, it traps incident magnetic energy, thus enhancing the surface current density in ISR. As a result, a narrow and strong absorption peak appeared.

By varying the length $b$ of the ISR without the monolayer graphene sheet, mechanical modulation of absorption spectra is observed, as shown in Fig. 5. The absorption declines and the full width at half-maximum (FWHM) becomes wider when the length
b of ISR decreases from 48 to 28 \( \mu m \). These behaviors can be interpreted through that as \( b \) becomes shorter, the resonance frequency of the ISR changes from 0.58 THz to 0.7 THz, and the frequency shift results in reduction of coupling strength between two bright modes. The corresponding frequency modulation depth is introduced as MDA = \( \Delta A/A0 \) x 100\%, where \( A0 \) is the absorption peak without the monolayer graphene sheet when \( b = 48 \mu m \) and \( \Delta A \) refers to the change compared with \( A0 \). As \( b \) decreases from 38 to 28 \( \mu m \), an absorption dip gradually appears, the EIA analog behavior is no longer pronounced. When \( b = 28 \mu m \), the absorption peak reaches 0.44 with the modulation depth MDA = 41\%. As the length \( b \) decreases, the absorption peak shows a slight blue shift from 0.506 to 0.512 THz, because the coupling strength of ISR to the external field reduced.

In order to achieve active modulation of absorption rather than reconstructing the geometric dimensions of the structure, a monolayer graphene sheet is placed under the ISR with \( b = 48 \mu m \) as shown in Fig. 1(a). As shown in Fig. 6, the absorption displays a significant decline and a slight blue shift when the Femi energy increases from 0.05 eV to 0.2 eV. When the Femi energy is at 0.05 eV, the absorption window still maintains a high value and the modulation depth is MDA = 6.8\%. As the Femi energy continues to increase, the absorption will reduce and broaden; meanwhile, transmission dips will vanish. The MDA goes up to 49.8\% when the Femi energy is at 0.2 eV; simultaneously, the EIA analog effect almost disappeared. This can be contributed to the decreasing coupling strength between the ISR and HSRs and the increasing damping rate of HSRs. The increasing Femi energy of the monolayer graphene sheet enhances the losses in the ISR and HSRs, thus weakening the ability of trapping the incident magnetic energy.

### IV. THEORETICAL CALCULATIONS

To explore the underlying physical mechanism of the EIA analog behavior, the coupling behavior between two bright modes can be analytically described by the following model:\(^{19}\)

\[
\dot{x}_0 + \gamma_0 \dot{x}_0 + \omega_0^2 x_0 + \kappa_0 x_0 = g_0 H,  \\
\dot{x}_b + \gamma_b \dot{x}_b + \omega_b^2 x_b + \kappa_b x_b = g_b H,  \\
\]

where \( x_0, x_b \) and \( \gamma_0, \gamma_b \) are the amplitudes and damping rates of the resonance modes of the ISR and HSRs, respectively. \( \omega_0 = 2\pi \times 0.58 \) THz and \( \omega_b = 2\pi \times 0.49 \) THz are the resonance frequencies of the ISR and HSRs, respectively. \( \kappa \) represents the coupling coefficients between the two resonators, \( g_0, g_b \) are the geometric parameters indicating the strength of the two bright modes with the incident electromagnetic field \( H = H_0 e^{i\omega t} \). The amplitudes of the bright modes \( t \) and \( b \) can be solved through the above coupled equations (3) and expressed as

\[
x_t(\omega) = \frac{(-\omega^2 - i\gamma_t \omega + \omega_0^2)g_0 H(\omega) - g_b \kappa H(\omega)}{(-\omega^2 - i\gamma_b \omega + \omega_b^2)(\omega^2 - i\gamma_0 \omega + \omega_0^2) - \kappa^2},  \\
x_b(\omega) = \frac{(-\omega^2 - i\gamma_b \omega + \omega_b^2)g_0 H(\omega) - g_b \kappa H(\omega)}{(-\omega^2 - i\gamma_0 \omega + \omega_0^2)(\omega^2 - i\gamma_b \omega + \omega_b^2) - \kappa^2}.  \\
\]

The electromagnetic polarizability of the samples is expressed as

\[
\chi_0(\omega) = P(\omega)/\varepsilon_0 H(\omega) \propto x(\omega)/H(\omega),  \\
\]

![FIG. 6](image-url) Simulated absorption spectra of the EIA analog structure with the increasing the Femi energy of graphene when \( b = 48 \mu m \).

![FIG. 7](image-url) The theoretical absorption spectra of the EIA analog structure. (a) Difference lengths \( b \) of the ISR without the monolayer graphene sheet. (b) With the increase in the Femi energy of graphene when \( b = 48 \mu m \).
where \( P(\omega) \) is the effective polarization of metamaterial. \( \varepsilon_0 \) is the permittivity of vacuum. By substituting Eqs. (3) and (4) into Eq. (5), the susceptibility \( \chi_{\text{er}} \) and \( \chi_{\text{eb}} \) of the bright modes ISR and HSRs with adjacent layers can be expressed using the resonance and mutual coupling coefficients \( \gamma_1, \gamma_b, \omega_b, \omega_0, g_1, g_b, \) and \( \kappa \), respectively. Thus, we obtain the susceptibilities \( \chi_t \) and \( \chi_b \) of the two metamaterial layers by considering the thickness of the metal (taken as \( d \)) as \( \chi_i = \chi_{\text{er}}/d \) \( (i = t, b) \). In our simulation, \( d \) takes as 100 nm which is much smaller than the wavelength of the incident terahertz wave. Therefore, the transmission and reflection coefficients of the two bright resonators between adjacent media by taking the limits \( d \to 0 \) are as follows:

\[
\begin{align*}
    t_{1 \to 2} &= \frac{2cn_1}{c(n_1 + n_2) - i\omega \chi_t}, \\
    r_{1 \to 2} &= \frac{c(n_1 - n_2) + i\omega \chi_t}{c(n_1 + n_2) - i\omega \chi_t}, \quad i \in \{t, b\},
\end{align*}
\]

where \( c \) is the light velocity in vacuum and \( \omega \) represents the angular frequency. With these obtained coefficients, the overall transmission and reflection coefficients of the EIA analog system are calculated as

\[
\begin{align*}
    t &= \frac{t_{a \to t}t_{p \to b}t_{b \to a}}{1 - r_{p \to b}r_{b \to a}e^{2i\omega d_p/c}}, \\
    r &= \frac{r_{a \to t}r_{p \to b}r_{b \to a}}{1 - r_{p \to b}r_{b \to a}e^{2i\omega d_p/c}},
\end{align*}
\]

where \( t_{b,a} \) is the transmission at the first silicon–air interface of the reference sample, which can be directly obtained from the Fresnel coefficients. The subscripts \( \{a, t, b, p, s\} \) denote the air, top resonator, bottom resonator, polyimide spacer, and silicon substrate, respectively; \( n \) and \( d \) represent the refractive index and thickness.

The absorption is calculated as

\[
\delta = \frac{1}{\alpha} \ln \left( \frac{1}{t_{b,a}} \right)
\]

where \( \alpha \) is the absorption coefficient. The analytical fitting results of the above equations for the simulated amplitude absorption spectra are shown in Fig. 7. It can be seen that the theoretical results are in agreement with the numerical simulation results. The corresponding fitting parameters are plotted in Fig. 8. From Fig. 8(a), it is observed that \( \gamma_t, \gamma_b \) almost remain constant with a decrease in the length of the ISR, while \( \delta \) displays an obvious increase from 0.09 THz to 0.21 THz, which is primarily dominant for the decreasing coupling coefficient \( \kappa \). Thus, it can be concluded that the mechanical modulation arises from the frequency shift of the ISR. In the active modulation process, \( \delta \) stays roughly constant while \( \gamma_t \) grows up gently with the increasing Fermi energy; simultaneously, \( \gamma_b \) increases markedly from 0.16 THz to 0.4 THz, which induced reduction in the coupling coefficient \( \kappa \). As shown in Fig. 8(b), therefore, it indicates that the active modulation is attributable to the change in the damping rate of the HSRs.

V. CONCLUSION

In conclusion, we explored the physical mechanism of the EIA analog phenomenon in a two-layer system. It has been found that an intensely reducing, broadening absorption peak can be achieved through shortening the length \( b \) of the ISR. In addition, dynamic modulation is achieved by integrating a monolayer graphene sheet into the metamaterial structure and significant decreasing absorption peaks are obtained by increasing the Fermi energy of graphene. These behaviors are confirmed by the simulation and theoretical results. The near field coupling mechanism illustrates the EIA analog behavior. The proposed EIA analog system may provide an opportunity for fabricating applications such as the filter, absorber, and optical modulator.

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