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Narrow and Dual-Band Tunable Absorption of a Composite Structure with a Graphene Metasurface *

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A tunable absorber, composed of a graphene ribbon on two layers of TiO_2-Au between two slabs of dielectric material all on a metal substrate, is designed and numerically investigated. The absorption of the composite structure varies with the geometrical parameters of the structure and the physical parameters of graphene at mid-infrared frequencies. The numerical simulation shows that a near-perfect absorption with single and dual bands can be achieved in a certain frequency range. We also analyze the electric and surface current distributions to study the dual-band absorber. The results show that the absorber can be tuned by the chemical potential and electron–phonon relaxation time of graphene, and electromagnetically induced transparency phenomenon can be obtained. The results of this study may be beneficial in the fields of infrared communication, perfect absorbers, sensors and filters.

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Graphene metasurfaces, as 2D artificial metamaterials, are applied widely in the fields of phase modulation,[1,2] absorbers,[3,4] and cloaking.[5,6] The special electromagnetic properties of graphene metasurfaces have enabled the rapid development of these fields, which have been of growing interest in recent years. Single-layer graphene integrated with Fano-resonant plasmonic metasurfaces can be used to tune their mid-infrared optical response.[7] A theoretical investigation of an electromagnetic metasurface, which consists of periodically patterned graphene, has been performed. The results show that ultrathin surfaces can be used to dynamically control the electromagnetic wave reflection, absorption, or polarization.[8] A tunable metasurface, composed of an array of graphene ribbons on a silver mirror with a SiO_2 gap layer at terahertz (THz) frequencies, was proposed. The graphene ribbons exhibit localized plasmon resonances depending on their Fermi levels to introduce abrupt phase shifts along the metasurface.[9] Li *et al.*[10] proposed and demonstrated graphene metasurfaces with the potential to dynamically control the phase and amplitude of infrared light with very high efficiency. It was shown that the phase of the infrared light reflected from a simple graphene ribbon metasurface can span over almost the entire 2π range by changing the width of the graphene ribbons, while the amplitude of the reflection can be maintained at high values without significant variations.

The most current research shows that the graphene cut-wire arrays, which realize tunable metasurfaces, can enhance the maximum absorption by more than 50%.[11] Wu *et al.*[3] discussed the novel absorption properties of a conventional metasurface-based THz electromagnetic absorber numerically and theoretically. They showed that two absorption modes could be presented in the considered frequency band owing to the increased dielectric thickness, and both modes could achieve near-unity absorptions. Faraji *et al.*[12] proposed a tunable THz absorber, consisting of two patterned graphene layers separated by a layer of Al_2O_3, with an absorbance of more than 90%. Numerical results show that a tunable or switchable absorber could be obtained and four absorption peaks could be tuned by the chemical potential of the top graphene microribbons. He[13] theoretically investigated the tunable resonance properties of graphene-SiO_2/Si structures deposited on flexible polymer substrates in the THz regime. This study showed that the tuning mechanism of the structure is mainly dependent on the dipolar resonance, which is different from the conventional metallic metamaterial (MM) structure that is dependent on the LC resonance. The maximum absorption is not greater than 0.5. A hybrid graphene system, consisting of graphene and silica layers coated on a metal film with groove rings, was proposed to strongly enhance light absorption by the graphene layer. The results indicated that the excited localized plasmon resonance in the groove rings could effectively improve the graphene absorption from 2.3% to 43.1%, and even to a maximum value of 87.0% in five-layer graphene, at telecommunication wavelengths.[14] Deng *et al.*[15] investigated the THz absorption properties of graphene-based heterostructures using the characteristic matrix method based on conductivity. It was demonstrated that the proposed structure could lead to perfect THz absorption because of the strong photon localization in the

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defect layer of the heterostructure. The THz absorption may be tuned continuously from 0 to 100%.

In this study, a composite structure with a graphene metasurface, which is composed of graphene ribbon, a dielectric layer and a metal substrate as a reflector mirror, is investigated. The dielectric layer consists of TiO_2 and gold that are embedded in the dielectric layer. The absorption of the composite structure is investigated by the finite difference time domain method (FDTD). We study the geometrical parameters of the structure and the physical parameters of graphene to obtain narrow and dual-band perfect absorption. We use the equivalent impedance theory to describe the dual-band absorber. The results also show that an absorber can be tuned by the physical parameters of graphene and electromagnetically induced transparency (EIT)[16] of the structure can be observed. The results can be applied to the fields of perfect absorbers, infrared stealth, filters, and communication.

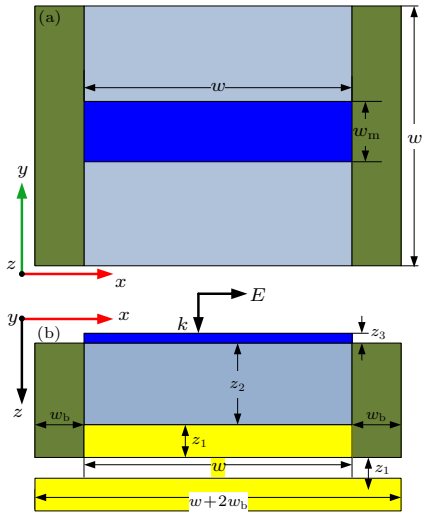

Fig. 1. (a) Front view and (b) side view of unit cell of the composite multilayer metasurface.

For a graphene sheet, the electromagnetic properties are described in terms of the surface conductivity σ, which can take into account interband and intraband transitions using the Kubo model of conductivity.[17,18] The conductivity is derived using

$$\sigma = \frac{ie^2 k_B T}{\pi\hbar^2(\omega + i/\tau)}\left(\frac{\mu}{k_B T} + 2\ln(e^{-\frac{\mu}{k_B T}} + 1)\right) + \frac{ie^2}{4\pi\hbar}\ln\left|\frac{2\mu - \hbar(\omega + i/\tau)}{2\mu + \hbar(\omega + i/\tau)}\right|, \quad (1)$$

where ω is the radian frequency, h is the reduced Planck constant, k_B is the Boltzman constant, e is the charge of an electron, T is the temperature, μ is the chemical potential, and τ is the electron–phonon relaxation time. We assume that the electronic band structure of a graphene sheet is not affected by the neighboring sheets, thus the effective permittivity ε_g of the graphene can be written as[19]

$$\varepsilon_g = 1 + \frac{i\sigma}{\varepsilon_0 \omega z_3}, \quad (2)$$

where z_3 is the thickness of the graphene sheet, and ε_0 is the permittivity in vacuum.

Consider a unit cell of a graphene-based composite structure, consisting of Au-TiO_2-graphene (from bottom to top), between two LiF dielectric layers which are based on Au substrates, as depicted in Fig. 1. We use the finite difference time domain method to determine the normal incident angle of the electromagnetic wave with periodic boundary conditions. The dielectric permittivity of TiO_2 and LiF are provided in the literature.[20] The parameters of the structure for dimensions are $w = 2\,\mu m$, $z_1 = 0.5\,\mu m$, $z_2 = 0.5\,\mu m$, $z_3 = 1\,nm$. Here z_1, z_2, z_3, $z_4 = z_1 + z_2$ are the thicknesses of Au, TiO_2, graphene, and LiF, respectively, and w, w_b, and w_m are the widths of Au, LiF, and graphene, respectively. Assuming electromagnetic wave propagation along the z-direction at TM mode, the electromagnetic waves can be totally reflected by the gold layer at the bottom of the structure. The absorption can be characterized as $A(\omega) = 1R(\omega) - T(\omega)$, $T(\omega) = |S_{21}|^2 = 0$, which is the transmission, and $R(\omega) = |S_{11}|^2$, which is the reflection.

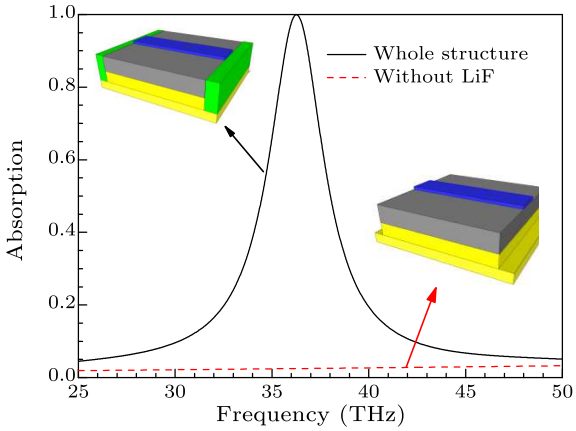

Fig. 2. the compared absorption of different structures.

To study the physical mechanism of graphene metasurface in our structure, the absorption of different structures is shown in Fig. 2. The perfect absorption of our designed structure can be obtained, while the absorption of the structure without LiF layers is nearly zero. We can find that the energy is local by two layers of LiF, which is equivalent to capacitance.[21]

Figure 3 shows the effective permittivity ε and equivalent impedance z of the structure. The imaginary ε is near zero (0.044) and real ε is a large value at the resonant frequency in Fig. 3(a). Hence the absorption resonance is electric resonance.[22] Moreover, the imaginary z of nearly zero means impedance matching at 36.23 THz in Fig. 3(b).

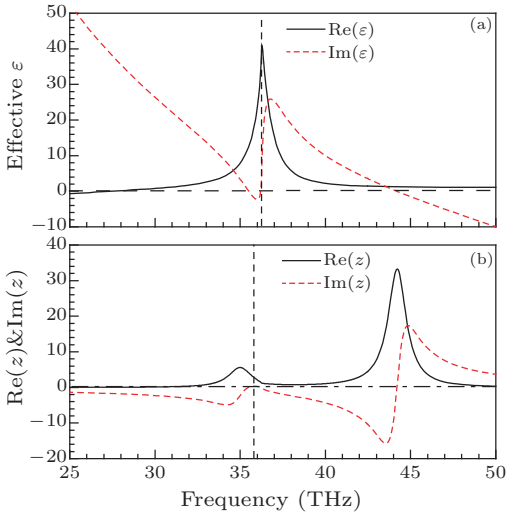

Fig. 3. Effective permittivity and equivalent impedance at $w_m = 0.2\,\mu m$, $w_b = 0.2\,\mu m$, $z_1 = z_2 = 0.5\,\mu m$, $\mu = 0.1\,eV$, and $\tau = 0.01\,ps$.

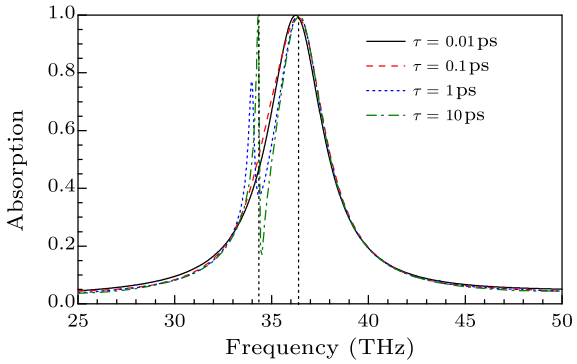

Fig. 4. Variation of absorption with frequency for different τ at $w_m = 0.4\,\mu m$, $w_b = 0.2\,\mu m$, $z_1 = z_2 = 0.5\,\mu m$, and $\mu = 0.1\,eV$.

The permittivity of graphene is influenced by the chemical potential μ and electron–phonon relaxation time τ. Figure 4 shows that the absorption spectra vary with τ. The results show that dual-band absorption can be attained at τ larger than 1 ps. However, the absorption peak at 36.4 THz hardly changes and large fluctuations at 34.3 THz are observed. It is worth noting that, although it is difficult to tune τ using the current technology available, such a study is still meaningful.[23] Meanwhile, it is worth noting that the electromagnetically induced transparency (EIT) phenomenon which is electric resonance can be generated.[24,25]

As shown in Fig. 5 at $\tau = 10\,ps$ and other parameters as the same as Fig. 4, the equivalent impedance z of the composite absorber is calculated using the equivalent medium theory.[26] It is observed that the real z is near 1 (normalization impedance) and the imaginary z is zero at 34.3 and 36.4 THz. This means that impedance are matching at the corresponding frequencies.[27]

To further study the absorption performance of the proposed structure, the electric field and surface current distributions are shown in Fig. 6. Compared with the two absorption peaks at frequencies of 34.3 THz and 36.4 THz, we can find that the electric field distributions concentrate on the surface of the structure at resonant frequencies in Figs. 6(a) and 6(d). It is clearly represented in Figs. 6(b) (front view) and 6(c) (side view) that surface current distribution is 34.3 THz. One can see that the surface current distributions are focused on the layer of LiF and are densest between LiF and graphene ribbon. A similar result is shown in Figs. 6(e) (front view) and 6(f) (side view) of 36.4 THz. In contrast to Fig. 6(d), the maximum density appears on both sides of the LiF layer away from the graphene ribbon.

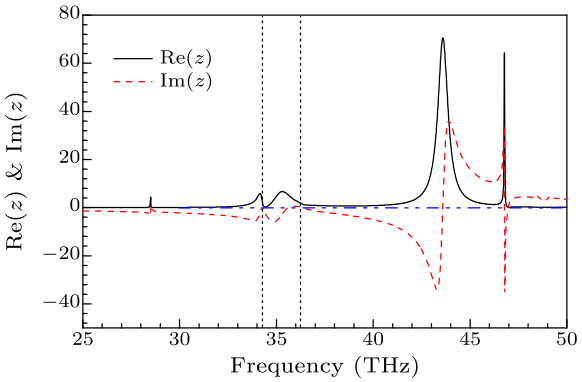

Fig. 5. The effective impedance of $\tau = 10\,ps$ at $w_m = 0.4\,\mu m$, $w_b = 0.2\,\mu m$, $z_1 = z_2 = 0.5\,\mu m$, and $\mu = 0.1\,eV$.

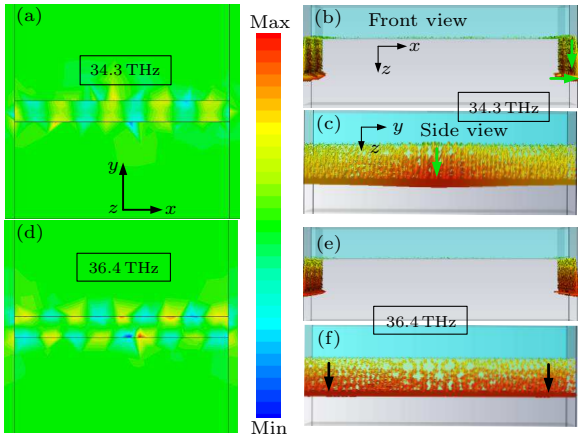

Fig. 6. The electric field ((a), (d)), front view ((b), (e)), and side view ((c), (f)) of surface current distributions for the composite structure with a graphene metasurface at frequencies of 34.3 and 36.4 THz, respectively, at $w_m = 0.4\,\mu m$, $w_b = 0.2\,\mu m$, $z_1 = z_2 = 0.5\,\mu m$, $\mu = 0.1\,eV$, and $\tau = 10\,ps$.

Figure 7 shows the results of the absorption tuned by the chemical potential μ and electron-phonon relaxation time τ of graphene for the composite structure. An increase in μ leads to a decrease in the absorption, while the absorption frequency is hardly changed in Fig. 3(a) at $\tau = 0.01\,ps$. However, when $\tau = 0.01$ and 10 ps, a dual-band absorption can be observed. Additionally, the absorption frequency can be tuned by μ and τ.[28–30]

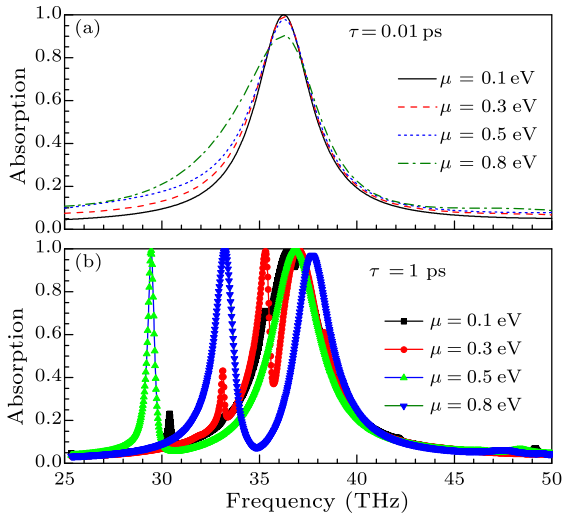

Fig. 7. Variation of absorption with (a) $\tau = 0.01$ ps and (b) $\tau = 1$ ps with different μ at $w_{\rm m} = 0.2\,\mu$m, $w_{\rm b} = 0.2\,\mu$m, and $z_1 = z_2 = 0.5\,\mu$m.

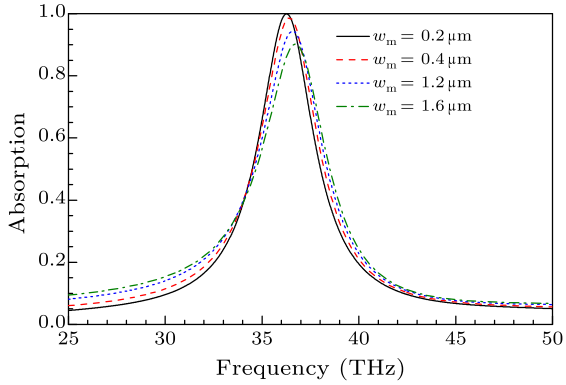

Fig. 8. Variation of absorption with different frequencies $w_{\rm m}$ at $w_{\rm b} = 0.2\,\mu$m, $z_1 = z_2 = 0.5\,\mu$m, $\mu = 0.1$ eV, and $\tau = 0.01$ ps.

To study the absorption of graphene in our structure, we analyze the absorption of the structure at normal incidence, as shown in Fig. 8. Choose $w_{\rm b} = 0.2\,\mu$m, $w_{\rm m}$ from 0.2 to 1.6 μm and other parameters following Fig. 2. It is demonstrated that a perfect absorption can be obtained at nearly 36.23 THz for $w_{\rm m} = 0.2$–$1.6\,\mu$m. Figure 8 also shows that as $w_{\rm m}$ is increased, the influence of the graphene ribbon on the absorption is slight. The graphene ribbon in the designed structure has slight effect on the absorption at $\mu = 0.1$ eV and $\tau = 0.01$ ps.

To further understand the physical mechanism of the absorption, the absorption as a function of the frequency of the proposed structure is shown in Fig. 9(a). We can observe that the absorption can be tuned by the width of the LiF slabs $w_{\rm b}$. A perfect absorber is generated at 36.23 THz when $w_{\rm b}$ is 0.2 μm. It is shown that the width of LiF layers can tune the resonant frequency. Moreover, a larger $w_{\rm b}$ leads to a red-shifting and a smaller $w_{\rm b}$ leads to a blue shift. Figures 9(b) and 9(c) show that the real and imaginary parts of effective permittivity ε have a red shift with increasing $w_{\rm b}$.

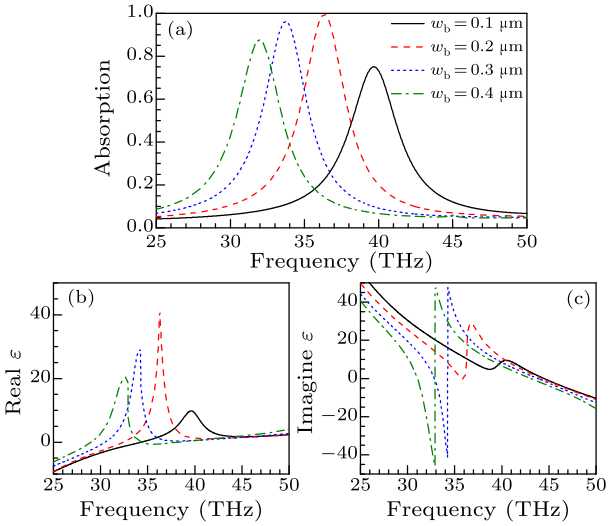

Fig. 9. Variation of absorption (a), real ε (b) and imaginary ε (c) with frequency of different $w_{\rm b}$ at $w_{\rm m} = 0.2\,\mu$m, $z_1 = z_2 = 0.5\,\mu$m, $\mu = 0.1$ eV, and $\tau = 0.01$ ps.

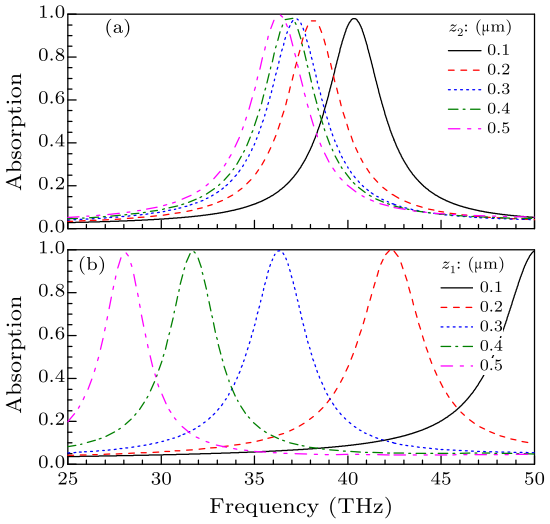

Fig. 10. Variation of absorption with frequency of different z_2 (a) at $z_1 = 0.5\,\mu$m and z_1 (b) at $z_2 = 0.5\,\mu$m with $w_{\rm b} = 0.2\,\mu$m, $w_{\rm m} = 0.2\,\mu$m, $\mu = 0.1$ eV, and $\tau = 0.01$ ps.

Further change parameters of z_1 and z_2 and plot absorption curves are shown in Fig. 10. It is observed that by increasing z_1 and z_2, the absorption frequency exhibits a red shift. Moreover, the range of this shift is large when changing z_1 and is slightly changed with z_2.

In summary, by designing a three-dimensional graphene metasurface composite structure on a metal substrate, narrow and dual band perfect absorption have been successfully obtained and analyzed theoretically at mid-infrared frequencies. The proposed graphene metasurface is composed of a graphene ribbon on two layers of TiO_2-Au between two slabs of dielectric LiF with a metal substrate. The effective permittivity and equivalent impedance of the structure have been analyzed by numerical simulation. The ab-

sorption of the composite structure can be tuned by varying the chemical potential and electron-phonon relaxation time of graphene and width of LiF and TiO_2. Moreover, the EIT effect can be observed in the designed structure. The results are valuable for applications in fields such as the perfect absorber, filters and optical communications.

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