Small-Angle Ultra-Narrowband Tunable Mid-Infrared Absorber Composing from Graphene and Dielectric Metamaterials

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Abstract: We report a small-angle ultra-narrowband mid-infrared tunable absorber that uses graphene and dielectric metamaterials. The absorption bandwidth of the absorber at the graphene Fermi level of 0.2 eV is 0.055 nm, and the absorption peaks can be tuned from 5.14803 to 5.1411 µm by changing the graphene Fermi level. Furthermore, the resonance absorption only occurs in the angle range of several degrees. The simulation field distributions show the magnetic resonance and Fabry–Perot resonance at the resonance absorption peak. The one-dimensional photonic crystals (1DPCs) in this absorber act as a Bragg mirror to efficiently reflect the incidence light. The simulation results also show that the bandwidth can be further narrowed by increasing the resonance cavity length. As a tunable mid-infrared thermal source, this absorber can possess both high temporal coherence and near-collimated angle characteristics, thus providing it with potential applications.

Keywords: absorption; graphene; near-collimation; mid-infrared absorber

1. Introduction

Metamaterial, which is an artificial electromagnetic material, has extraordinary physical properties that natural materials do not have. Metamaterial absorbers have been widely studied in recent years because they have such potential applications as photo-detection [1], sensing [2], solar cell [3], and thermal emission source [4]. For photo-detection and solar cell applications, broadband or multiband absorbers are needed [5–17]. However, for sensing and coherent thermal emission source applications, the narrower the absorption bandwidth is, the better performance it will have [18,19]. Thus, to achieve better performance, many schemes have been proposed to narrow the absorption bandwidths for ultra-narrowband absorbers [20–25]. Unlike the conventional metal metamaterials, dielectric metamaterials have almost no absorption loss; therefore, their use provides an extremely efficient way to produce ultra-narrowband absorbers [26–29]. On the other hand, tunable absorbers are generally desirable because they can work at different resonance wavelengths to meet various requirements. By combining active medium and resonant microstructures, several tunable absorbers have been proposed based on vanadium dioxide, Ge2Sb2Te5, etc. [30–33]. Recently, great attention has been paid to graphene because it possesses many unprecedented properties such as high optical transparency, high electron mobility, flexibility, and tunable conductivity [34–40]. In addition, due to the advantage of rapid-response conductivity by applying the bias voltage upon graphene, tunable ultra-narrowband mid-infrared absorbers with graphene are very desirable.

Particularly, manipulation of the incidence angles with perfect absorption is another important topic in the research of metamaterial absorbers. For example, for solar cell and
photo-detection applications, absorbers are expected to operate within a wide-angle range to collect more incident electromagnetic energy [6–8]. On the other hand, similarly to lasers, mid-infrared thermal emission sources based on the metamaterial absorbers are expected to emit near-collimated light, which means that the emissions occur within a small angle range to focus the radiation energy in space [41]. However, to date, no small-angle ultra-narrowband tunable mid-infrared absorber has been reported.

In this paper, a small-angle ultra-narrowband tunable mid-infrared absorber is proposed based on graphene and dielectric metamaterials. The ultra-narrowband resonance absorption in the mid-infrared regime can be tuned by changing the Fermi level of graphene. In this proposed structure, a Bragg mirror consisting of the 1DPCs efficiently reflects the incident light. Furthermore, the resonance absorption only occurs within several degrees. Such an absorber can be used as a tunable near-collimated coherence thermal emission source.

2. Structure of the Proposed Absorber

Figure 1 shows the schematic diagram of the proposed absorber. The top-layer material is graphene, which is placed on the periodic micro-structured Ge material determined by period $p$, height $h$, and width $w$. A ZnS film layer is inserted between the periodic micro-structured Ge material and 1DPCs, which consist of $N = 10$ pairs of CaF$_2$ and Ge film layers. The thickness of ZnS is $t$. The substrate material is calcium fluoride. Compared with graphene, reduced graphene oxide (RGO) has a larger imaginary part of refractive index due to G–O bonding of RGO; therefore RGO is difficult to use in narrowband absorption [42,43]. Although RGO is a material that is commonly available at scale for practical applications, we choose graphene in Figure 1 instead of RGO to obtain ultra-narrowband absorption in our design. We use Ge microstructures because Ge has high refractive indices, which are often used to localize the electromagnetic field in the mid-infrared regime [44]. ZnS is an optical thin film material with middle refractive indices, and it is placed under the Ge microstructures in order to decrease the transmission from the upper layer. A plane electromagnetic wave with the transverse-magnetic (TM) polarization is incident on the proposed structure with angle $\theta$. Rigorous coupled-wave analysis (RCWA), which is a semi-analytical method, is utilized to study the light absorption characteristics [45]. In the simulation process, the reflection $R$ and the transmission $T$ are the sum of reflected Fourier components and the transmitted Fourier components, respectively. The absorption $A$ can be evaluated with $A = 1 - R - T$. The refractive index of air is set as 1. The refractive indices of calcium fluoride, zinc sulfide and Ge are obtained from previously published studies [46,47].

![Figure 1. Schematic diagram of the proposed absorber.](image-url)
The surface conductivity $\sigma_s$ of graphene can be expressed by using the Kubo formula with

$$\sigma_s = \frac{2e^2 k_B T}{\pi \hbar^2} \frac{i}{i \tau - \omega} \ln \left[ 2 \cosh \left( \frac{E_i}{2 k_B T} \right) \right] + \frac{i e^2}{4 \pi \hbar} \ln \left[ \frac{2 E_f + h(\omega - i \tau^{-1})}{2 E_f - h(\omega - i \tau^{-1})} \right]$$

(1)

where $k_B$ is Boltzmann’s constant, $\tau$ is the relaxation time, $T$ is the temperature, $e$ is the electron charge, $\hbar = h/2\pi$ is the reduced Planck’s constant and $E_f$ is the Fermi energy [48]. Thus, the refractive index of graphene can be expressed as $n_g = \sqrt{1 - i \sigma_s/(\omega \epsilon_0 \mu_g)}$ with the approximate graphene thickness $t_g = 0.34$ nm and vacuum permittivity $\epsilon_0$. In addition, $T$ and $\tau$ are 300 K and 1 ps, respectively.

3. Results and Discussion

To provide efficient reflection with 1DPCs, the optical thickness of each film layer in 1DPCs should be equal to one quarter of the interested wavelength [49]. In addition, to obtain higher reflection with less film layer pairs, the refractive index ratio of two dielectrics in 1DPCs should be large. CaF$_2$ and Ge have little absorption loss in the mid-infrared regime. Furthermore, CaF$_2$ has low refractive indices. Therefore, to achieve high reflection in the mid-infrared regime, we choose CaF$_2$ and Ge as the two primitive dielectrics of 1DPCs, and the thicknesses of the CaF$_2$ and Ge layers are set as $t_C = 0.55$ $\mu$m and $t_G = 0.31$ $\mu$m respectively. Other parameters are optimized with $p = 2.0$ $\mu$m, $N = 10$, $\omega = 1.0$ $\mu$m, $h = 1.0$ $\mu$m, $\theta = 0^\circ$ and $l = 1.027$ $\mu$m. Figure 2a shows that, at $E_f = 0.2$ eV, there is an absorption peak at the wavelength of 5.14803 $\mu$m with a full width half maximum (FWHM) of 0.055 nm, which is much less than those with metallic metamaterials [21–25]. The parameters used in the next parts are the same as those in Figure 2a if they are not specified. Figure 2b shows that the absorption peak can shift from 5.14803 to 5.1411 $\mu$m by changing $E_f$ from 0.2 to 0.6 eV.

![Figure 2](https://via.placeholder.com/150)

Figure 2. (a) Absorption spectrum with $E_f = 0.2$ eV; (b) absorption spectra with $E_f = 0.2$ eV and $E_f = 0.6$ eV.

To investigate the influence of the incidence angle on absorption, we plot the absorption spectra with different incidence angles in Figure 3a. As seen in Figure 3a, we can find that the ultra-narrowband resonance absorption exists in two angle regions. One is from $0^\circ$ to $4^\circ$, and the other is from $5^\circ$ to $8^\circ$. To further show the angle-dependent absorption characteristics, we plot the absorption spectra with small angle ranges in Figure 3b,c. From Figure 3b, we can see that the absorption peak shift in the angle range from $0^\circ$ to $2^\circ$ is smaller than 0.2 nm, and the absorption rate is still larger than 0.95 for angles up to $2^\circ$. Furthermore, the absorption rate decreases drastically in the angle range from $2^\circ$ to $4^\circ$. Figure 3c shows that the absorption peaks will shift to the shorter wavelengths as the
incidence angles increase in the angle range from $5^\circ$ to $8^\circ$. In addition, we can see that, in the angle range from $5^\circ$ to $8^\circ$, the resonance absorption rate decreases when the incidence angle deviates from $6^\circ$. From the above discussion, we can conclude that the resonance absorption only occurs in a small angle range, which means that our absorber can be used as a mid-infrared thermal source with a near-collimated light beam.

To reveal the physical mechanism of the perfect absorption, we calculate the electromagnetic field distributions of $|H_y|$ and $|E_z|$ within one-unit cell at the resonance absorption peak of $5.14803 \, \mu m$ in Figure 4. From Figure 4a, we can find that the magnetic field is mainly localized in the Ge microstructure layer, which causes strong magnetic resonance to occur. In addition, the magnetic field distribution in the ZnS film layer exhibits Fabry–Pérot resonance [50] at the absorption peak. Furthermore, the intensity in the 1DPCs from top to bottom decrease to zero; thus, the 1DPCs with 10 pairs of CaF$_2$ and Ge film layer act as a perfect Bragg mirror to totally reflect the incidence light. Figure 4b shows that the electric field is mainly localized at the top-surface of the microstructures where graphene is located. Therefore, due to the electromagnetic resonance in the Ge microstructures and Fabry–Pérot resonance inside the ZnS film layer, near-perfect absorption can be realized.

We notice that the optical path in the ZnS layer is approximately equal to the half-resonance wavelength. To further demonstrate the Fabry–Pérot resonance effect, we optimize the ZnS film thicknesses of $t = 2.15 \, \mu m$ and $t = 3.286 \, \mu m$ with different high-order resonance modes. Figure 5a,b show the absorption spectra with $t = 2.15 \, \mu m$ and $t = 3.286 \, \mu m$, respectively. As seen in Figure 5a,b, the absorption bandwidths are narrower than that in Figure 2a. In addition, the bandwidth in Figure 5b is narrower than that in Figure 5a. The magnetic field distributions with $t = 2.15 \, \mu m$ and $t = 3.286 \, \mu m$ are presented in Figure 5c,d, respectively. The magnetic field distributions in the ZnS film layer indicate the first-order mode and second-order mode in Figure 5c,d, respectively. The results in Figure 5 indicate that the bandwidths can be further narrowed by increasing the thickness of the ZnS film layer, and the related mechanism can be interpreted based on the Fabry–
Pérot resonance effect [20]. Based on the Fabry–Pérot resonance theory, the FWHM at the resonance absorption wavelength can be expressed as [30]

\[
\Delta \lambda = \frac{\lambda_0^2}{2\pi n t_{ZnS}} \frac{1 - \mathcal{R}}{2\sqrt{\mathcal{R}}}
\]

(2)

where \(\lambda_0\) is the resonance wavelength, \(\mathcal{R} = \sqrt{R_1R_2}\), and \(R_1\) and \(R_2\) are the reflections of the top layer of the ZnS film layer and the 1DPCs, respectively. Equation (2) shows that the FWHM is inversely proportional to the ZnS layer thickness. Thus, an absorber with narrower bandwidth can be realized by adding the thickness of the ZnS film layer.

Figure 4. Field distributions at the resonance absorption wavelength of 5.14803 \(\mu m\): (a) magnetic field; (b) electric field.

Figure 5. Absorption spectra with different silica layer thickness: (a) \(t = 2.15 \mu m\) and (b) \(t = 3.286 \mu m\). Magnetic field distributions: (c) \(t = 2.15 \mu m\) and (d) \(t = 3.286 \mu m\).

To investigate the influence of the pair layers \((N)\) on the transmission and absorption, we have calculated the spectra of transmission and absorption with different values of \(N\) in Figure 6. As seen in Figure 6a, the transmission decreases to zero as \(N\) increases from 6 to
10. In addition, the absorption rate increases to 100% as $N$ increases to 10 in Figure 6b, and it maintains a constant value of 100% when $N$ is larger than 10. To reduce computation costs, we set $N$ as 10, which indicates that the 1DPCs can act as a perfect Bragg mirror to provide efficient reflection.

Figure 6. (a) Transmission spectra with different $N$; (b) absorption spectra with different $N$.

Next, we calculate the absorption spectra with the different geometric parameters of $w$, $h$ and $t$ in Figure 7. As seen in Figure 7a, the absorption rate of the absorber will decrease as $w$ deviates from 1 μm, and it remains above 0.85 as $w$ ranges from 0.994 to 1.006 μm. The absorption spectra with different values of $h$ are shown in Figure 7b. From Figure 7b, we can see that the absorption peaks shift to longer wavelengths as the grating heights increase, and the absorption rate is still larger than 0.8 in the grating height range from 0.98 and 1.02 μm. Figure 7c gives the absorption spectra with different $t$. As seen in Figure 7c, the resonance absorption peaks shift to the longer wavelengths as the $t$ increases. This phenomenon can be explained by increasing of the optical path $g$. The above discussion indicates that our proposed structure still has good absorption characteristics if the related parameters only slightly deviate from the optimized values.

Figure 7. (a) Absorption spectra with different $w$; (b) absorption spectra with different $h$; (c) absorption spectra with different $t$. 
4. Conclusions

A small-angle ultra-narrowband mid-infrared tunable absorber that uses graphene and dielectric metamaterials has been reported. The absorption bandwidth of the absorber at the graphene Fermi level of 0.2 eV is 0.055 nm, and the absorption peaks can be tuned by changing the graphene Fermi level. Furthermore, the resonance absorption only occurs in the angle range of several degrees. The simulation results also show that the bandwidth can be further narrowed by increasing the resonance cavity length. This absorber has potential applications as a tunable near-collimated coherent thermal source.

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