بیست و چهارمین کنفرانس اپتیک و فوتونیک و
دهمین کنفرانس مهندسی و فناوری فوتونیک ایران
۱۰ الی ۱۲ بهمن ۹۶ - دانشگاه شهرکرد
24th Iranian Conference on Optics and Photonics (ICOP 2018) and
9th Iranian Conference on Photonics Engineering and Technology (ICPET 2018)
Jan 30 - Feb 1 , 2018 - Shahrekord University

جذب همدوس کامل توسط متاسطح گرافینی قابل انعطاف و تنظیم‌پذیر در بازه وسیع زاویه تابش در بازه تراهرتز

رویا ابراهیمی میمند، علی سلیمانی، و نصرت‌ا... گرانپایه

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چکیده – در این مقاله، به بررسی جذب کامل همدوس در بازه فرکانسی تراهرتز توسط طرح متاسطح گرافنی به صورت حلقه مربعی پرداخته‌ایم. نتایج شبیه‌سازی برای هر دو مد الکتریکی عرضی و مغناطیسی عرضی نشان‌دهنده این است که مقدار جذب در بازه وسیعی از زاویه تابش همچنان بالای ۹۰٪ است و مقدار جذب همدوس در این ساختار از مقدار ۰٪ تا مقدار ۱۰۰٪ توسط تنظیم فاز نسبی دو پرتو کم توان با جهت انتشار مخالف قابل کنترل است. فرکانس مرکزی جذب متاسطح ارایه شده، توسط تغییر پتانسیل شیمیایی گرافین و همچنین با دستکاری پارامترهای هندسی آن به سادگی قابل کنترل است. ضخامت این جاذب فقط در حدود یک بیستم طول‌موج کاری ساختار متاسطح است. از این جهت جاذب طراحی شده پتانسیل این را دارد که در ادوات نوری مختلفی از جمله مدولاتورها، آشکاسازها و سوییچ‌های الکترومغناطیسی مورد استفاده قرارگیرد. این مقاله راهی بدیع برای جذب کامل در فاصله تراهرتزی ارایه می‌دهد.

کلید واژه- جذب کامل همدوس، گرافین، متاسطح، مدولاسیون، تراهرتز

Highly Flexible and Tunable Coherent Perfect Absorption in Graphene Metasurface at Wide Angle of Incidence in Terahertz Regime

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We exploit graphene square-ring to realize coherent perfect absorption (CPA) in the terahertz (THz) regime. The simulated results show a 90% absorption coefficient over a wide range of angles of incidence for both TE and TM radiations. The coherent absorptivity is tunable from nearly 0% to 100% by adjusting the relative phase of two low power counter-propagating coherent beams. The central frequency of the absorption simply can be tuned by varying the chemical potential of graphene and by changing the geometric parameters of metasurface. Thus, the proposed absorber is very promising for various optical applications as modulators, detectors and electromagnetic switches. This article offers a novel path for perfect absorption in THz gap, it should be noted that the thickness of proposed absorber is only about $\lambda/20$.

Keywords: Coherent perfect absorption, Graphene, Metasurface, Modulation, Terahertz

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1 Introduction

In recent years electromagnetic (EM) wave absorbers in the terahertz (THz) range have attracted great attentions. Conventional EM absorbers were very thick, and their structure were based on metals, which due to restricted flexibility of permittivity and permeability of metals, most of them operate at a specific pre-designed frequency [1]. To achieve high absorbance and simultaneously thin membrane, metals should swap with patterned and doped graphene.

Graphene because of its exceptional optoelectronic and photonics properties is a promising candidate for THz absorption. Its interaction with light is normally weak, there are several methods to enhance the light–matter interaction in graphene. In THz regime, plasmonic response of graphene is very strong [2], patterned and doped graphene can support localized plasmonic resonances which significantly enhance absorption of graphene.

Controlling absorption of optical structures is highly desirable for many applications, several ways to achieve the perfect absorption have been reported [1, 3]. Coherent perfect absorption (CPA), a concept of time-reversed lasing [4], has drawn considerable attention in recent years. CPA systems relie on the destructive interference of two counter propagating incident beams. The transmitted waves from one direction cancel the reflected waves of the other direction and vice versa. Absorption can be controlled by manipulating relative phase of two counter-propagating beams.

In this paper, we demonstrate that CPA can be realized in a novel ultrathin THz absorber that achieves greater than 90% absorption over a wide range of angles of incidence. The frequency response can be dynamically tuned by varying the graphene gate voltage and geometric parameters. Hence, the proposed absorber is very promising for tunable THz detections and signal modulations.

The remaining of the paper is organized as follows: In Section 2, the theory and simulation method is introduced. In Section 3, tunability of the structure is discussed. The paper is concluded in Section 4.

2 Theory and Simulation Method

The geometric parameters of the graphene metasurface and corresponding excitation configuration with two counter-propagating beams (I_+ and I_-) is shown in Figs. 1(a) and 1(b). We perform finite-difference time-domain (FDTD) simulations of the metasurface with normally incident plane waves on both sides, The square rings are periodically arranged in *x*-*y* plane, and are illuminated by s- and p-polarized (electric and magnetic vectors **E** and **H** are parallel to the y axis, respectively) optical waves, perfect matched layers (PML) are applied in the z direction. The graphene layer is considered as a sheet modelled by surface impedance. Based on the random-phase-approximation (RPA) [5], the complex conductivity of graphene especially in a heavily doped region and low frequencies (far below Fermi energy) can be described by the Drude model as [6]:

$$\sigma_g = \frac{ie^2\mu_c}{\pi\hbar^2\left(\omega + i\tau^{-1}\right)} \qquad (1)$$

where μ_c depends on the concentration of charged doping and $\tau = \mu\mu_c / e\upsilon_f^2$, where υ_f is the Fermi velocity and ω, μ, $\hbar$ and e are respectively the electromagnetic wave angular frequency, the dc mobility, reduced Planck's constant, and the electron charge.

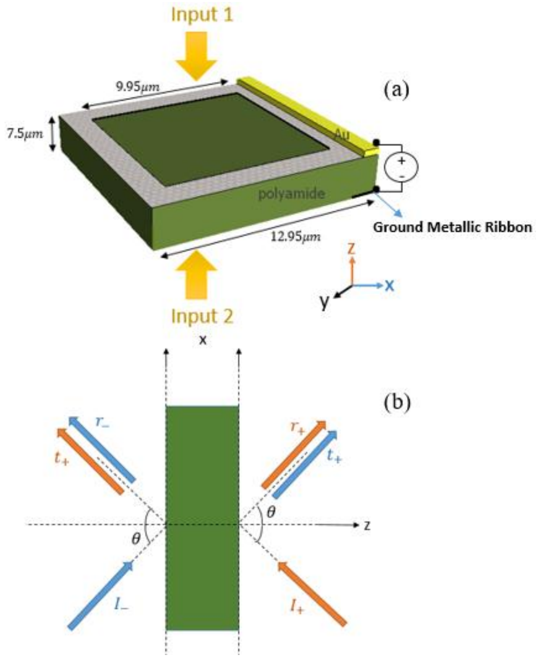

Fig. 1: (a) The schematic view of one cell of the proposed absorber. (b) Coherent interaction of two counter-propagating beams.

The chemical potential $\mu_C = 0.3\,\text{eV}$ and relaxation time τ=0.5 ps are initially considered. We consider the patterned graphene on a flexible polyamide substrate with a dielectric constant of $\varepsilon_r = 2.5$ and thickness of that is set to be $7.5\mu m$ and the thickness of graphene is assumed to be 0.5 nm. The working frequency of the proposed absorber can be manipulated by varying the gate-controlled Fermi energy of the graphene. Our proposed structure has simple design and ability to adapt to other structures. We used this structure for simulation the same as the structure proposed in [7].

In CPA system, the forward and backward scattering fields ($O_\pm$) can be obtained from the two input fields ($I_\pm$) through a scattering matrix, S_g [8]:

$$\begin{pmatrix} O_+ \\ O_- \end{pmatrix} = S_g \begin{pmatrix} I_+ \\ I_- \end{pmatrix} = \begin{pmatrix} t_+ & r_- \\ r_+ & t_- \end{pmatrix} \begin{pmatrix} Ie^{i\varphi_+} \\ Ie^{i\varphi_-} \end{pmatrix} \qquad (2)$$

where $t_\pm$ and $r_\pm$ are the transmission and reflection coefficients in forward and backward directions, respectively. Since the proposed structure is a reciprocal metamaterial with spatial symmetry, (the two input beams ($I_\pm$) are set to be of equal amplitude) the scattering matrix can be simplified with $r_\pm = r$ and $t_\pm = t$. So the scattering coefficients would be:

$$|O_+| = |O_-| = \left| tIe^{i\varphi_+} + rIe^{i\varphi_-} \right| \qquad (3)$$

When the phase difference $\varphi_+ - \varphi_- = 2n\pi$ (n is an arbitrary integer), the CPA occurs. Coherent modulation of the input beams performance is required to suppress the scattering fields, that is $tIe^{i\varphi_+} = -rIe^{i\varphi_-}$, from which we can get the necessary condition for CPA performance: $|r| = |t|$. The reflectance can be achieved as a function of incidence angle, θ, for TE and TM polarizations [9]:

$$r = e^{i\varphi} \frac{1 - 188.68\sigma(\cos\theta)^{\pm 1}(1 + e^{-i\varphi})}{1 + 188.68\sigma(\cos\theta)^{\pm 1}(1 + e^{i\varphi})} \qquad (4)$$

where $e^{i\varphi}$ is the complex reflection coefficient of substrate, σ is the optical graphene conductivity, which can be calculated by Kubo formula. The + and - signs are for TE and TM modes, respectively. Figure 2 illustrates the structure absorbance, $A = 1 - |r|^2$, versus wave incidence angle.

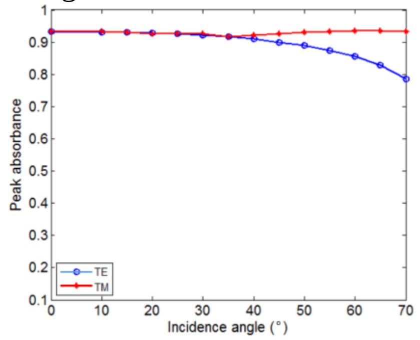

Fig. 2: The maximum coherent absorbance vs. oblique incidence angle, θ, for TE and TM modes at 4.1THz.

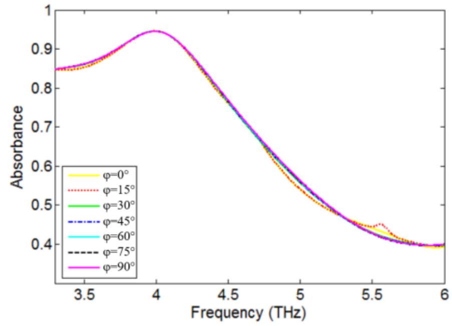

Fig. 3: Absorbance spectra at different azimuthal angle φ.

The magnetic field component parallel to the surface decreases with increased θ, hence, the incident magnetic field can no longer efficiently support the electromagnetic resonance in the metamaterial. For TM polarization, the coherent absorptivity remains higher than 91.70% for all incidence angles from 0° to 70°. It could be noted that the proposed absorber exhibits good absorption performance for both TE and TM modes when θ changes from 0° to 70°. This effect can be beneficial for broadband angular tunability.

Figure 3 gives the simulation results for different polarizations of normal incident EM waves. Because of the symmetry of the structure the absorption is insensitive to the polarization states of the incident waves.

3 Electrical and Geometrical Tunability

The frequency tunability of absorber is a significant important characteristic in practical applications. The central frequency of the total absorption can be tuned by varying, μ_c. By increasing the driven voltage applied to graphene, as shown in Fig. 4, a blue shift of the quasi-CPA frequency occurs. Graphene will have a higher Drude weight by increasing the charge carrier concentration, and shifting the quasi-CPA point to higher frequencies [7]. As depicted in Fig. 4, the quasi-CPA frequency can be tuned from 2.6361 to 5.3527 THz when the doping level varies from 0.1 to 0.6 eV.

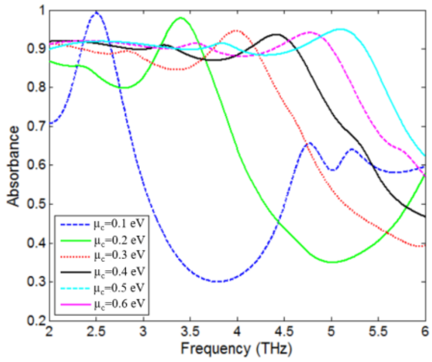

Fig. 4: Absorbance spectra at various chemical potential.

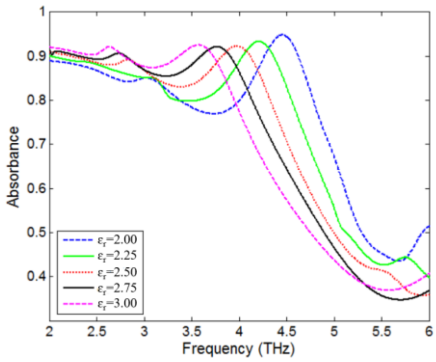

Fig. 5: The effect of substrate dielectric constant on the absorbance spectra of THz metasurface.

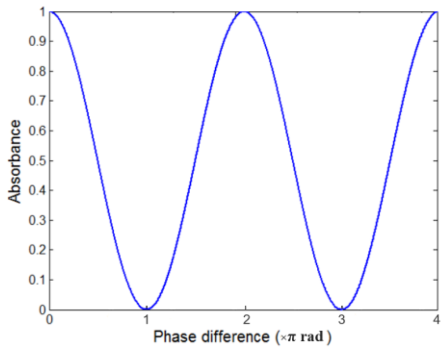

Fig. 6: Absorbance versus relative phase difference between two coherent beams.

In Fig. 5, we show the coherent absorptivity spectra of the metasurface with different dielectric constant. When the dielectric constant increases, the absorptivity remains higher than 90% in all cases.

The coherent absorption varies continuously from 99.92% to less than 0.06% as the phase difference changes from 0 to π at 2.6 THz and $E_F = 0.1\text{eV}$, the absorption becomes maximum if phase difference equal to $2n\pi$ (*n* is an integer). As illustrated in Fig. 6 proper phase modulation leads to perfect absorption and perfect transmission.

4 Conclusion

We have demonstrated an ultrathin terahertz coherent perfect absorber (CPA) based on two low intensity counter-propagating coherent beams illuminating the graphene. The absorption performance under different angles of incidence was studied. The graphene-based coherent perfect absorption is found to be appropriate for broad angular selectivity. The proposed absorber can operate well even in the case of oblique incidence. Furthermore, the CPA can be tuned in an ultra-wide frequency range via electrostatic doping instead of changing its geometric parameters, which greatly enhance the flexibility and controllability of proposed absorber. The structure may provide an opportunity to select the desirable absorption frequency band in the THz regime. The output intensities can be modulated by adjusting phase difference of the two low intensity counter-propagating coherent beams. These results are promising for potential applications in optical modulators, electromagnetic switches, and detectors.

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