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Investigation of multiband plasmonic metamaterial perfect absorbers based on graphene ribbons by the phase-coupled method

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We develop an original phase-coupled method to realize multispectral metamaterial near-unity absorbers based on spatially separated graphene ribbon arrays with mid-infrared plasmonic resonances. The results both from the coupled-mode theory and finite-difference time-domain simulations reveal that in addition to the single-band absorption enabled by the bi-layer identical ribbon arrays, the outstanding dual-band perfect absorption is observed with the change in the phase between bi-layer ribbons only by varying the spacer thickness. The spectral positions of absorption peaks are tuned handily by small changes in ribbon widths and chemical potentials of graphene. Moreover, the triple-band absorber is achieved handily by the same principle and such absorbers are robust for nor-normal incident angles. The transfer matrix method is also utilized to uncover further the underlying physics of the phased-coupled-induced multispectral absorbers. Theoretical analysis are in excellent agreement with numerical calculations. The phase-coupled method thus provides new opportunities for obtaining multi-channel metamaterial perfect absorbers.

1. Introduction

Research on two-dimensional layered materials [1–3] and van der Waals heterostructures [4–7] currently has been one of the leading topics in nanophotonics and condensed matter physics. Diverse optical properties including the metallic, semi-conducting and high-index-dielectric behaviors enable atomically thin materials to find important applications in photodetectors [8], light-emitting diodes [9], plasmonic [10] and photovoltaic devices [11] over a very broad spectral range. The ultrathin thickness of the single atomic layer, however, leads to weak light-matter interactions, thereby extremely degrading the performance of two-dimensional layered materials in nanophotonic devices. For instance, the absorption of white light in free-standing graphene with the thickness of 0.34 nm is 2.3% [12], and the light absorption in the monolayer transition metal dichalcogenides (TMDs) with a thickness of 6–7 Å is about 10% [13–16]. Thus, enormous efforts have been focused on enhancing optical absorption of atomically thin materials, especially the graphene, a flat monolayer of carbon atoms packed in a honeycomb lattice [17,18]. Compared to other two-dimensional materials, graphene exhibits fantastic mechanical, electric, magnetic and thermal properties with a multitude of exciting applications. The wonderful properties of graphene allow multiple functions of single emitting, transmitting, modulating, and detection to be achieved in one material. In order to improve the light absorption in unpatterned graphene sheet, the guided-mode resonance in dielectric layers [19], plasmons in metallic nanoparticles [20] and Tamm states in metal-dielectric interfaces [21] have been extensively proposed and investigated. More interestingly, the extraordinary Dirac cones in the electronic band structure [22] of graphene lead to the liner energy-momentum relation for electrons over a wide range of energies, thereby allowing the prominent surface plasmon polaritons (SPPs) [23–25] to be supported by graphene. The existence of SPPs originating from the intraband transitions of electrons improves the interaction time between graphene and light [26] over a broad spectral range extending from the mid-infrared to terahertz regions. Unlike the traditional SPPs in noble metals such as silver and gold, graphene plasmons own advantageous optical properties of extreme field confinement and low losses, so as to confine tightly light at deep subwavelength nanoscales and significantly boost light absorption [27]. In addition, the most outstanding advantage of

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graphene plasmons over conventional metal-based SPPs lies in the dynamical tunability of the chemical potential by using external gate voltages [28–31]. Because the wave vector of graphene plasmons depends directly on the surface conductivity of graphene and the conductivity hinges on the chemical potential, the property of graphene-based plasmonic absorption devices can be tuned dynamically only by using an external gate voltage, instead of re-fabricating a new structure by changing the geometrical parameters [32,33]. In other words, utilizing the external gate voltage, an electrically controlled plasmonic device based on graphene will be realized.

Stimulated by these intriguing characteristics of graphene plasmons, a growing number of nanostructured graphene structures [34–36] have been proposed to boost the absorption of white light in graphene, especially the artificially fabricated metamaterials [37–39] with unit cells much smaller than the wavelength of light. Thus far, based on localized SPP resonances in graphene, the individual graphene strip [40], disk [41], ring [42], cross-shaped structure [43], as well as the electric split ring resonator [44,45], have been designed widely to realize a single-frequency metamaterial perfect absorber in the mid-infrared range. For obtaining broadband or multiband absorption [46–49], two traditional approaches based on the frequency stacking usually have been implemented. One method is to combine multiple nanostructured graphene resonators with different sizes to form a super unit cell [50], such as coplanar multiple graphene disks [51] with different radiuses and multiple graphene ribbons [52] with different widths. The second method consists of stacking multiple layers [53] of nanostructured graphene resonators with small changes in geometrical parameters and separated by dielectric spacers with proper thicknesses. However, graphene-based broadband or multiband metamaterial absorbers based on the aforementioned frequency-stacking method are complicated and require high-precision fabrication techniques. Finding new ways to realize graphene-based broadband or multiband metamaterial perfect absorbers is hence highly desired at present.

Herein, inspired by the spectral splitting of the classical phase-coupled electromagnetically induced transparency (EIT) scheme [54–56] which occurs at three-level atomic systems and enables a sharp transparency window within a broadband absorption spectrum, the novel phase-coupled method is proposed first to obtain a dual-band metamaterial perfect absorber based on the bi-layer identical graphene ribbon arrays embedded separately in a silica layer on top of a silver substrate. Avoiding dexterously the tradeoff between the near- and far-field coupling, the far-field coupling between graphene ribbon resonators is considered solely to enable the spectral splitting. Without the frequency detuning in bi-layer graphene ribbon arrays with same resonant properties, the dual-band perfect absorption is still realized by the coupling system. This characteristic behavior is theoretically predicted by the coupled-mode theory (CMT) and subsequently is numerically confirmed by the finite-difference time-domain (FDTD) method. To further provide better insights into the coupling system, the versatile transfer matrix method (TMM) is introduced. The excellent matching between theoretical calculations and numerical simulations suggests that the change in the thickness of the dielectric spacer between graphene arrays directly affect the phase of the far-field coupling between ribbon resonators, thereby leading to the spectral splitting and the eventually observed the dual-band absorption. At the same time, in addition to changing the ribbon width, the spectral positions of absorption peaks are tuned dynamically by changing the chemical potential in graphene. In particular, the triple-band absorber is achieved handily by the same principle of the phase modulation. Such phase-coupled-induced multispectral graphene-based plasmonic absorber exhibits a wide-angle absorption stability and a novel slow-light effect. Consequently, our findings will benefit plasmonic nanophotonic devices for optical filtering and storage in the mid-infrared range. The investigated phase-coupled method would offer a new way to realize multi-channel metamaterial absorbers.

2. Structural description and CMT analysis

The schematic view of the investigated structure consisting of bi-layer graphene ribbons arrays embedded separately in a silica layer on top of a silver substrate is shown in the inset in Fig. 1. The refractive index of silica is $n = 1.45$. The relative permittivity of silver is characterized by the Drude model [57] $\varepsilon_m(\omega) = \varepsilon_\infty - \omega_p^2/(\omega^2 + i\omega\gamma)$, where the dielectric constant at infinite angular frequency is $\varepsilon_\infty = 3.7$, the bulk plasma frequency is $\omega_p = 9.1$ eV, and the damping frequency of the oscillations is $\gamma = 0.018$ eV. The geometric parameters are demonstrated on the cross-section of the structure, as shown in the configuration of Fig. 1. The widths of graphene ribbons in the upper and lower arrays are W_1 and W_2, respectively. The period is P. The vertical distance between graphene ribbon arrays is H_1, and the spacer thickness between the lower ribbon array and the substrate is H_2. The thickness of the silver substrate is $D = 2000$ nm, which is much larger than the skin depth of electromagnetic waves so as to block all transmission. Once the transmission channel is closed, the structure can be treated as a single-port system. When the plane wave with frequency ω is normally launched into the port, the well-known localized SPP resonance will be excited directly on graphene ribbons due to the satisfied wave-vector matching condition. As shown in the inset (a) of Fig. 2, the electric dipole resonance is supported by the single graphene ribbon. With the help of plasmonic resonances in graphene ribbons, the proposed structure hence behaves as such configuration of the single-port system coupled with two resonators simultaneously. The typical CMT

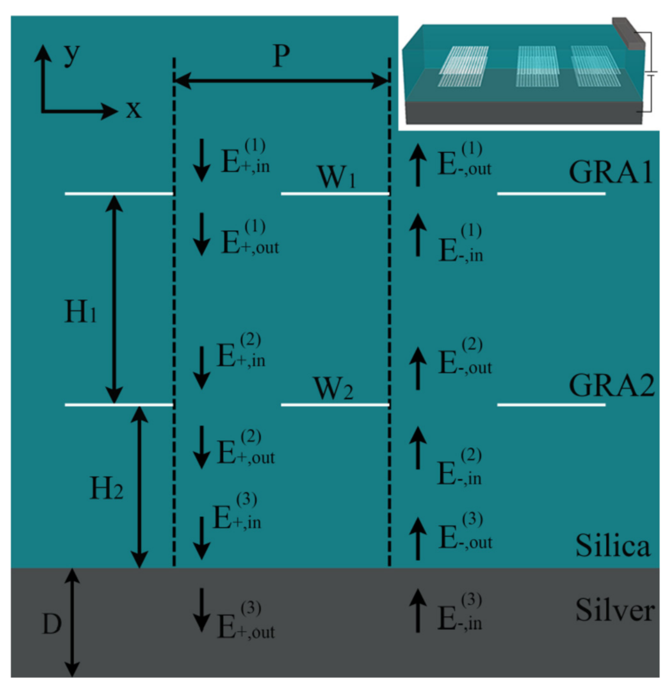

Fig. 1. The schematic of the TMM and the geometry under investigation: the bi-layer graphene ribbon arrays are encapsulated in the silica layer on top of a silver substrate. The inset shows the sketch of the graphene-based dual-band perfect absorber. (A colour version of this figure can be viewed online.)