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A tunable dual-band graphene-based perfect absorber in the optical communication band

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ABSTRACT

In order to remarkably enhance its absorption capability, a tunable dual-band graphene-based perfect absorber is proposed. By using the finite-difference time-domain (FDTD) simulations, dual-band perfect absorption peaks are realized in the optical communication regime based on the critical coupling effect. By changing the lateral displacement of the two different holes, multiple absorption peaks could also be achieved. Furthermore, by manipulating the widths of air trenches, the wavelengths of absorption peaks could be shifted, while the values of absorption peaks are almost unchanged. Moreover, our proposed absorber also demonstrates polarization-dependence.

1. Introduction

Over the past decade, graphene, due to its atomically thin dimension and much stronger binding of surface plasmons (SPs), has attracted extensive attention in nanophotonics and optoelectronics [1–13]. Furthermore, the optical response of graphene, originating from its unique gapless band structure, can be tuned in an ultra-wideband range through electrostatic field, magnetic field, and chemical doping [14–17]. Thus, many graphene plasmonic devices have been motivated extensive studied, such as optical absorbers [18–20], filters [21,22], optical sensors [23–26], modulators [27,28], photodetectors [29,30] and antennas [31,32].

In particular, among these devices, the graphene-based optical absorbers are important and indispensable in highly integrated optical circuits. Based on the unique features of graphene, several graphene-based optical absorbers have been demonstrated in recent research. Moreover, in the infrared and terahertz regions, since graphene with appropriate doping can generate SPs and lead to strong light-graphene interaction [6], most of graphene-based optical absorbers focus on these wavelength ranges. Li et al. [18] proposed a wide-angle plasmonic single-narrowband perfect absorber based on the periodic double-layer graphene ribbon arrays separated from a metallic ground plate by an ultra-thick dielectric layer, and showed that a narrowband perfect absorption peak with the FWHM (full width at half maximums) of 300 nm was achieved. In Ref. [19], Zhang et al. theoretically studied a dual-band metamaterial absorber where the two absorption bands can be independently tuned, and also showed that absorption peaks of greater than 99% were obtained under normal incidence, and high absorbance remained at large incident angles up to 50 degrees for both of the bands under TE and TM polarizations. Thongrattanasiri et al. [20] investigated that perfect light absorption can take place in a single patterned sheet of doped graphene, and furthermore demonstrated that arrays of doped graphene nanodisks displayed full absorption when supported on a substrate under total internal reflection and also when lying on a dielectric layer coating a metal.

In contrast, in the visible and near-infrared ranges, graphene does not support SPs for undoped, unpatterned graphene [33]. Furthermore, in these wavelength regimes, graphene acts as a lossy dielectric material with wavelength-independent absorption, and only absorbs about 2.3% of light at normal incidence due to its conical electronic band structure [3,34]. In order to remarkably enhance absorption in this wavelength range, one can place the graphene inside a resonant Fabry-Perot cavity [27] or place graphene near plasmonic nanoantennas [35]. Cai et al. [36] demonstrated a graphene optical absorber inspired by metal-dielectric-metal metamaterial for perfect absorption of electromagnetic waves. Piper and Fan [37] theoretically studied a perfect absorption scheme by coupling unpatterned monolayer graphene with patterned defect-free photonic crystal slab via critical coupling with guided resonance. Although multiple perfect absorption peaks can be proposed by choosing appropriate parameters, the absorption peaks will tend to decrease greatly when the wavelengths of multiple absorption peaks are simultaneously tuned. Most of graphene-based perfect absorbers are single channel, however, dual-band and even multi-band ones are rarely reported.

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Moreover, a challenge facing the multi-band graphene-based perfect absorber is how to strengthen its adjustability.

In this letter, we propose and investigate a tunable dual-band graphene-based perfect absorber in the optical communication band, where a monolayer graphene is on top of a patterned silicon slab backed by a metal reflector. The patterned silicon slab is composed of period super units structured by two different air holes, and two identical air trenches. By using the finite-difference time-domain (FDTD) simulations, dual-band perfect absorption peaks are realized in the optical communication regime. By changing the lateral displacement of the two different holes, multiple absorption peaks could also be realized in this wavelength range. Furthermore, by manipulating the widths of air trenches, the wavelengths of two perfect absorption peaks could be shifted, while the absorption strength of them are nearly unchanged. Meanwhile, the proposed absorber also demonstrates polarization-dependence. Although this work focuses on numerical investigation, the proposed graphene-based absorber can be relatively easier to realize experimentally compared with the other graphene-based absorbers. Subwavelength all-dielectric metasurfaces based on silicon nanostructures are easy for integration to the current CMOS technology, and chemical vapor deposition (CVD) grown graphene can be transferred over the patterned silicon slab using standard transfer techniques [46]. Thus, our results are very useful for the development of multi-band and frequency-selective photodetectors working at optical communication regime.

2. Structure design

As shown in Fig. 1, the proposed graphene-based perfect absorber consists of a monolayer graphene on top of a patterned silicon slab backed by a metal reflector (600 nm Au coated glass substrate). Here, the patterned silicon slab (the periods in the x and y directions are 900 nm and 1300 nm respectively) is composed of period super units structured by two different air holes, and two identical air trenches. The radii of air holes are $R_1 = 150$ nm and $R_2 = 100$ nm respectively. The width (x direction) between the two air trenches is $D_1 = 360$ nm. Meanwhile, the widths (x direction) and lengths (y direction) of the two air trenches are both $D_2 = 40$ nm and $L = 800$ nm, respectively. In our calculations, the thickness (z direction) of graphene sheet is taken as 0.34 nm. Since the graphene thickness is so small that the anisotropy can in general be ignored, the refractive index of graphene is assumed as $n = 3 + i5.446\lambda/3\ \mu m^{-1}$ [38], where λ is the wavelength of incident light. Simultaneously, the permittivity of silver is described by the Drude formula [39] and the wavelength of incident light is 1400 nm. Moreover, the transmission from the whole structure is very close to zero (T = 0), as the thickness of the metallic ground plate is much larger than the penetration depth of electromagnetic waves. In addition, the thickness of the patterned silicon slab is 90 nm. The lateral displacements of two air holes with respect to the symmetry axis of the air trench are $S_1 = 150$ nm and $S_2 = 200$ nm, respectively.

In our calculations, the 3D finite-difference time-domain (FDTD) method is used for the numerical simulation and the commercial software of Lumerical FDTD Solutions is performed. Periodic boundary conditions are applied along the x and y directions and perfectly matched layers are set for all three dimensions. A plane wave with the electric field parallel to the x axis illuminates normally the periodic structure. The non-uniform mesh is adopted, and the minimum mesh size inside the graphene layer equals 0.1 nm and gradually increases outside the graphene sheet, for saving storage space and computing time.

3. Results and discussions

As mentioned above, in the visible and near-infrared ranges, graphene acts as a lossy dielectric material, and the absorption efficiency of a suspended monolayer graphene is only 2.3%. Thus, for the proposed graphene-based absorber, when the silicon slab is unpatterned, the absorption is as low as shown in Fig. 2 by using the FDTD method. In order to significantly enhance the absorption, we utilized the patterned silicon slab in the graphene-based absorber, as shown in Fig. 1(a). Due to the patterned silicon slab is composed of period super units, when the normally incident light is couple into the structure, the patterned silicon slab can support in-plane guided mode that is strongly confined by the slab without any coupling to external radiations [40]. Meanwhile, for the pat-

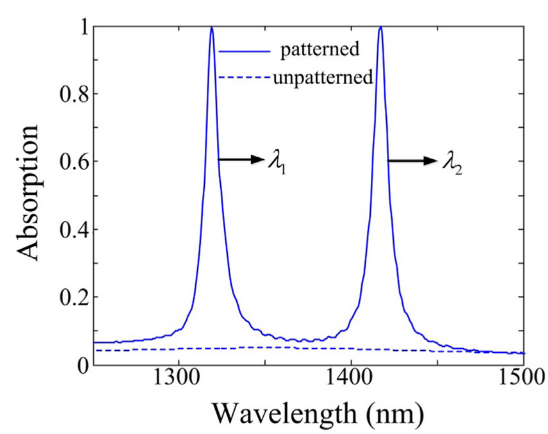

Fig. 2. Absorption of the proposed graphene-based absorber with a patterned or unpatterned silicon slab.

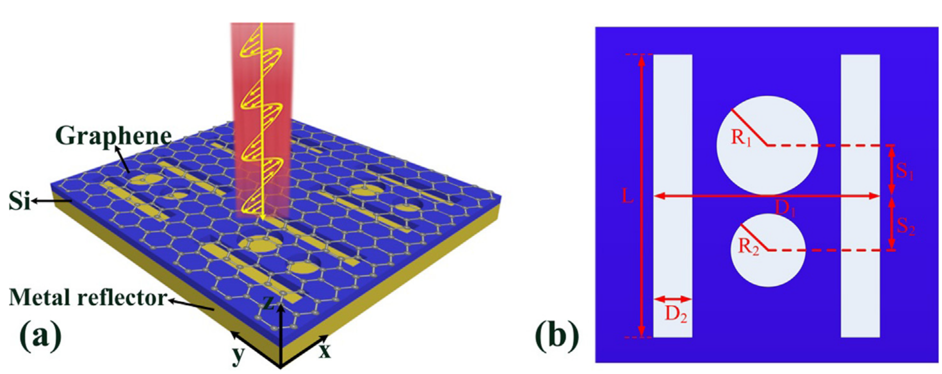

Fig. 1. (a) Schematic diagram of the graphene-based perfect absorber. (b) Top view of a super unit in the silicon slab with dimensions specified.