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Original research article

Sensitive perfect absorber with monolayer graphene-based multi-layer dielectric grating structure

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ABSTRACT

We propose a simple structure based on monolayer graphene with two layers dielectric grating. The effect of structural parameters on the optical behavior is studied by using the rigorous couple wave analysis method. The situation of changing incident angle for TM polarization is considered without changing the geometrical parameters. The absorption of about 77% and the Q-factor value of about 3390 can be obtained. In order to enhance absorption, we further design perfect absorption based on monolayer graphene with multiple-layer dielectric grating structure. The guide-mode resonances of both the grating and the dielectric layers are excited to achieve perfect multi-peak absorption. The proposed structure uses relatively less layers to achieve the perfect absorption, which can provide a reference for the further development of high sensitive modulators.

Graphene, a two-dimensional material, plays an important role for many optoelectronic applications, such as biosensors, photo-detectors, optical modulators, tunable filters, photovoltaic cells and tunable filters [1–3], since its prominent mechanical, electrical and optical properties with tunable conductivity from near-infrared (NIR) to terahertz (THz) frequencies [4,5]. Graphene can support SPPs and induce strong confinement of fields from the mid-infrared (mid-IR) to terahertz regions, which is beneficial to the optical absorption. The monolayer graphene can only absorb 2.3% of the normal incident light in the visible (VIS) and near-infrared ranges, which brings about a limitation to its optical properties on light absorption and limits the development of further optoelectronic devices. Therefore, the challenge of the absorption enhancement of monolayer graphene in the visible and near-infrared ranges attracts extensive and considerable attention recently, such as one-dimensional photonic crystals [6,7], guided resonance [8–10], multilayer dielectric layers [11,12], photon localization [13], attenuated total reflectance (ATR) [14,15], the Fabry–Perot cavity structures [16,17], two-dimensional photonic crystal cavities [18], and plasmonic nanostructures [19,20].

In this letter, we design a multilayer structure, which is based on monolayer graphene with multiple-layer dielectric grating structures and can achieve a theoretical maximum absorption of about 100%. We initially design a simple structure based on monolayer graphene with two layers dielectric grating. The effects of the geometrical parameters of grating layer and the change of incident angle on the absorption behavior are investigated. The guide-mode resonances of both the grating and the dielectric layers can be excited to achieve 100% multi-peak absorption after optimizing parameters of the proposed multilayer structure. The rigorous coupled wave analysis (RCWA) method is utilized to calculate the light absorption spectrum and the optical magnetic fields.

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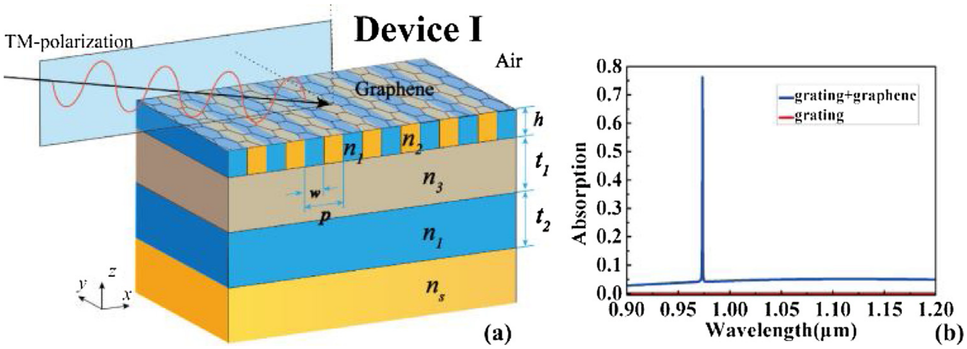

Fig. 1. (a) a structure of monolayer graphene prepared on the top of dielectric grating with two dielectric layers. n_1 and n_2 are the high and low refractive index of the grating; p, w, h are grating period, width and height, respectively; t_1 and t_2 are the thickness of dielectric layers(SiO_2/Si) corresponding to the refractive index n_3 and n_1, respectively. (b) Absorption spectra as a function of the wavelength at normal incidence for TM polarization at two different structure in Device I. The parameters are $n_1 = 3.48$, $n_2 = 1$, $n_3 = 1.48$, $n_s = 1.5$, $h = 71.5$ nm, $p = 0.657$ um, $w = 64.3$ nm, $t_1 = 168.9$ nm, $t_2 = 71.8$ nm.

In Fig. 1(a), we firstly present a simple structure which consists of monolayer graphene prepared on the top of dielectric grating and placed in contact with two dielectric layers (Device I). The waveguide grating is periodic in the x-direction and extended infinitely in the y-direction. Its period, thickness and width are p, h and w, respectively. The rigorous couple-wave analysis (RCWA) method is used to calculate the one-dimensional grating. Two dielectric layers are SiO_2 and Si, of which the refractive index are assumed to be 1.48 and 3.48, respectively. Graphene is modeled as a thin dielectric layer with the permittivity $\varepsilon_G = 1 + i\sigma_g/\omega\varepsilon_0 t_0$, where $t_0 = 0.34$ nm is the graphene thickness, ω is the angular frequency, ε_0 is the vacuum permittivity, and σ_G is the graphene surface conductivity. The permittivity of graphene can be expressed as a sum of the intraband σ_{intra} and interband conductivity σ_{inter} [21]:

$$\sigma_{intra} = i\frac{e^2 k_B T}{\pi^2\hbar^2(\omega + i\tau^{-1})}[\frac{\mu_c}{k_B T} + 2\ln(\exp(-\frac{\mu_c}{k_B T}) + 1)] \quad (1)$$

$$\sigma_{inter} = i\frac{e^2}{4\pi\hbar}\ln[\frac{2\left|\mu_c\right| - \hbar(\omega + i\tau^{-1})}{2\left|\mu_c\right| + \hbar(\omega + i\tau^{-1})}] \quad (2)$$

where e and μ_c are the electron charge and chemical potential (equal to the Fermi level shift), respectively. k_B and ħ indicate the Boltzmann and reduced Planck constants, respectively, and T is the temperature, while τ stands for the momentum relaxation time due to charge carrier scattering. The physical parameters of the graphene are set as $\mu_c = 0.15$ eV, $T = 300$ K, and $\tau = 0.5$ ps [22].

Fig. 1(b) describes the absorption spectrum of Device I for normal incidence under TM polarization using RCWA method. We need modify the conventional RCWA program to calculate the absorption of the graphene-based structures and field distributions, because the RCWA based on the Floquet's theorem [23,24] could not be used in the structures with graphene sheet. The expression of absorption can be calculated as $A_b = 1\text{-}T\text{-}R$, where T and R are the total transmission and reflection diffraction efficiencies, respectively. We choose the height of grating $h = 71.5$ nm, period $p = 657$ nm, width $w = 64.3$ nm. The thickness of dielectric layers are $t_1 = 168.9$ nm and $t_2 = 71.8$ nm, respectively. These parameters can be regarded as variable and used to optimize the designed structure behavior. As shown in the Fig. 1(b), when the structure does not contain monolayer graphene, the absorption is nearly 0. After monolayer graphene is placed on the grating, the strong light absorption with about 77% is achieved at normal incidence, which is attributed to the light absorption property of graphene. The Q-factor ($Q = \lambda_0/\Delta\lambda$) is a standard of reflecting the strength of sensitivity. Here λ_0 is the central wavelength of the resonant peak, and $\Delta\lambda$ is the full width at half-maximum (FWHM). In Fig. 1(b), the Q-factor is calculated to be about 3390.

Fig. 2 demonstrates the effects of changes in the incident angle α and in the grating width w and period p on the absorption spectrum while other geometric parameters are fixed (e.g., $h = 71.5$ nm, $t_1 = 168.9$ nm, $t_2 = 71.8$ nm) in Device I. The simulated absorption under TM polarization monochromatic plane wave is plotted as a function of the incident wavelength and w, p, α, respectively. As can be seen from Fig. 2(a), with the increasing of the grating width w, the full width at half maximum (FWHM) of the absorption illustration increases. Fig. 2(b) shows that the absorption peak has a red shift with the increasing of p for the normal incidence. The inset graph of Fig. 2(b) shows the grating period p as a function of the Q-factor. The increasing of p gives rise to the higher Q-factor, which shows a strong sensitivity and can achieve a tunable sensitivity by changing the value of p. Fig. 2(c), 2(d) illustrate the relation between wavelength and the angle of incidence, where the incident angle α is varied in the range 0°–20°. It is obvious that the absorbing peak at normal incidence splits into two peaks, and those two absorbing peaks become closer with the decrease of angle ($\alpha < 8°$) as shown in Fig. 2(c). Under larger α conditions ($\alpha > 8°$), the single absorption peak shifts to a longer wavelength as shown in Fig. 2(d).

In order to further enhance light absorption, we explore the possibility to achieve perfect absorption based on monolayer graphene with multiple-layer dielectric grating structure (Device II) as shown in Fig. 3(a). Dielectric layers are composed