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Near-unity absorption of graphene monolayer with a triple-layer waveguide coupled grating

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ABSTRACT

In order to achieve the enhancement and manipulation of light absorption in graphene monolayer within the visible (Vis) and near infrared (NIR) regions, a design of absorber inspired by contact coupled gratings with an absentee layer is demonstrated. It is proved that the absorptance of monolayer graphene can be greatly enhanced to near unity through rigorous coupled-wave analysis (RCWA) numerical calculation. The thickness of grating and homogeneous absentee layers can significantly change the linewidth and resonant mode position in absorption spectrum. Furthermore, the lateral shift of the contact coupled gratings changes the magnetic field distributions in the grating cavity and the surface-confined mode at the cover/grating interface, thus facilitating the dynamic control of the spectral bandwidth of the graphene absorber. The proposed devices could be efficiently exploited as tunable and selective absorbers, allowing to realize other two-dimensional (2D) materials-based selective photo-detectors.

1. Introduction

Two-dimensional (2D) materials are dramatically changing the world of electronics and photonics due to their unique and unprecedented properties. Among these, graphene, a 2D carbon sheet with a honeycomb lattice, has attracted particular attention recently because of its unique electronic and optical properties with tunable conductivity from NIR to terahertz (THz) frequencies [1,2]. In the THz region, graphene with appropriate doping can generate surface plasmon polaritions (SPPs) and lead to strong light-graphene interactions [3]. In contrast, the exploitation of atomically thin carbon films for light modulation faces the problem of their relatively weak interaction with light in the visible and NIR ranges. Graphene does not support SPPs and acts as a lossy dielectric material with wavelength-independent absorption [4]. It has been theoretically and experimentally demonstrated that the absorption of a monolayer graphene does not depend on the material parameters but only on the fundamental constants, that is equal to $\pi\alpha$ (defined by the fine structure constant $\alpha = e^2/\hbar c$) which corresponds to about 2.3% over the Vis range [5].

Optical absorption plays an important role in a variety of applications such as photodetectors, saturable absorbers and photovoltaics. The concept of perfect absorbers has initiated a new research area with important applications in optoelectronics [6–8]. Various microstructures and approaches have been proposed to get complete absorption in graphene, including guided resonance [9–11], photon localization [12], attenuated total reflectance (ATR) [13] and other resonant configurations, such as the Fabry-Perot cavity [14,15], multilayer dielectric layers [16–18], 2D photonic crystal cavities [19], and plasmonic nanostructures [20–24]. Quiet recently Guo et al. has demonstrated a total absorption over 99% at a wavelength around 1.5 μm for monolayer graphene which was coupled with subwavelength gratings on top of a gold mirror [25].

In this work, we theoretically investigate a structure with a monolayer graphene embedded on the top of a triple-layer guided-mode resonance grating structure. It consists of two binary identical gratings and a homogeneous layer with refractive index equal

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to that of the gratings, which can produce resonant enhancement in the absorption of un-doped graphene. The excitation of planar waveguide mode, which has strong near field enhancement and increased light interaction length with graphene, plays a vital role in total absorption. The coupling characteristics between the two gratings and the absorption of monolayer graphene were studied with respect to the thickness of gratings and homogenous layer, as well as the lateral alignment shift between gratings. The related results show that the linewidth and the resonant position of the absorption response can be altered by adjusting the grating thickness and lateral alignment. Meanwhile, the tunability of the absorption can be altered with respect to different resonant channels and grating filling factor.

2. Design principles and methods

The triple-layer waveguide grating is sketched in Fig. 1. The refractive indices of the cover, homogeneous layer and substrate layer are called n_c, n_u and n_s, respectively. It is supposed that $n_c = 1$, $n_H = 2.25$, $n_L = 1$, and the wavelength of incident light is 800 nm. The geometric parameters are period Λ, height h, fill factor f, lateral alignment shift s. Graphene is modeled as a thin dielectric layer with permittivity $\varepsilon_G = 1 + i\sigma_G/\omega\varepsilon_0 t$, where $t = 0.34$ nm is the graphene monolayer thickness, ω is the angular frequency, ε_0 is the vacuum permittivity, and σ_G is the graphene surface conductivity. The permittivity is calculated as the sum of the intraband σ_{intra} and interband conductivity σ_{inter} [26]:

$$\sigma_{intra}(\omega) = i\frac{e^2 k_B T}{\pi\hbar^2(\omega + i\Gamma)}\left(\frac{E_F}{k_B T} + 2ln\left(e^{-\frac{E_F}{k_B T}} + 1\right)\right) \tag{1}$$

$$\sigma_{inter}(\omega) = i\frac{e^2}{4\pi\hbar^2}\left(\frac{2E_F - (\omega + i\Gamma)\hbar}{2E_F + (\omega + i\Gamma)\hbar}\right) \tag{2}$$

where e is the elementary charge, $\hbar = h/2\pi$ denotes the reduced Planck's constant, $\Gamma = 10$ meV is the carrier scattering rate, $T = 300$ K is the temperature, k_B is the Boltzmann constant, and E_F means the Fermi energy (chosen as 0.3 eV in this paper). If the photon energy $\hbar\omega > 2E_F$, the interband transitions dominate, giving rise to a universal limit $\sigma_G = e^2/4\hbar$ at room temperature.

The resonant part above the substrate layer consists of two identical grating layers and a homogeneous layer between the gratings. The effective permittivity of the grating layer for the TM polarization is given by the effective medium theory (EMT) of the subwavelength grating [27,28], i.e,

$$\varepsilon_{eff,TM} = \varepsilon_{0,TM} + \frac{\pi^2}{3}f^2(1-f)^2\left(\frac{1}{\varepsilon_H} - \frac{1}{\varepsilon_L}\right)^2(\varepsilon_{0,TM})^3\varepsilon_{0,TM}^{(0)}\left(\frac{\Lambda}{\lambda_0}\right)^2 \tag{3}$$

where f is the grating filling factor, and ε_H and ε_L represent the high and low permittivity of the grating materials, respectively. Λ and λ_0 denote the grating period and the central resonant wavelength. The zero-order permittivity ε_0 in Eq. (3) is given by

$$\varepsilon_{0,TE} = f\varepsilon_H + (1-f)\varepsilon_L$$

$$\varepsilon_{0,TM} = \varepsilon_H\varepsilon_L/[f\varepsilon_L + (1-f)\varepsilon_H] \tag{4}$$

for TE- and TM-polarization components [29,30]. For a high-spatial frequency waveguide grating ($\Lambda/\lambda_0 \to 0$), the second term of the polynomial expression on right side of Eq. (3) is negligible and the expression of the effective index of the grating under TM-polarization can be approximately written as

$$n_{eff,TM} = \{\varepsilon_H\varepsilon_L/[f\varepsilon_L + (1-f)\varepsilon_H]\}^{1/2} \tag{5}$$

For a fixed filling factor, the triple-layer resonant grating can be obtained through appropriate choice of the homogeneous layer's refractive index, which should be equal to the effective refractive indices of gratings calculated by Eq. (5) [31]. For a given design wavelength at a particular angle, the required grating thickness and period can be approximately estimated by using the slab waveguide

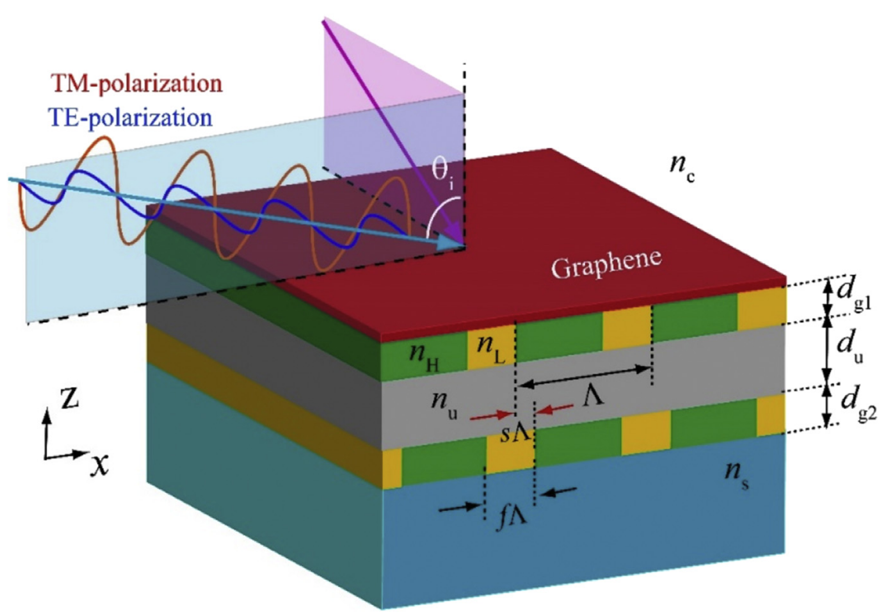

Fig. 1. Schematic diagram of the triple-layer guided-mode resonance grating. The low and high refractive indices of the gratings are $n_L = 1.0$ and $n_H = 2.25$, respectively. The filling factor of the grating, defined as the ratio between the width of the low refractive index region and the grating period, is set to $f = 0.5$. The refractive indices of the cover, substrate and homogeneous layers are set to $n_c = 1.0$, $n_s = 1.46$ and $n_u = 1.99$, respectively. The thickness of the grating layer and homogeneous layer are set to $d_{g1} = 50$ nm, $d_{g2} = 80$ nm, $d_u = 78$ nm, respectively. The lateral alignment shift is denoted by $s\Lambda$. The period of the identical gratings is set to $\Lambda = 400$ nm.