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ARTICLES

Broadband absorption of graphene from magnetic dipole resonances in hybrid nanostructure

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Abstract: As emerging new material, graphene has inspired great research interest. However, most of the studies focused on how to improve the absorption efficiency of graphene, but payed little attention on broadening absorption bandwidth while ensuring high absorption efficiency. In this work, we proposed a hybrid nanostructure, which not only can improve absorption efficiency but also can increase absorption bandwidth. The proposed hybrid nanostructure consists of a monolayer graphene sandwiched between three Ag gratings with different widths and a SiO_2 spacer on a Ag substrate, these three gratings and substrate can excite three independent magnetic dipole resonances. In our calculations, we numerically demonstrate the proposed hybrid structure can achieve graphene absorption bandwidth of 0.311 μm in near-infrared region with absorption exceeding 30% . We also studied absorption peaks dependence on gratings widths and SiO_2 spacer thickness, and explained the results using physical mechanism. Our research can provide a theoretical guidance for future device preparation.

Key words: graphene; absorption bandwidth; magnetic dipole; grating

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1. Introduction

Graphene is a two-dimensional (2D) carbon sheet with a honeycomb lattice[1], because of its outstanding optical, mechanical and electronic characteristics[2–4], it has aroused the interest of scientific researchers. The absorption efficiency of monolayer graphene is 2.3% within visible and near-infrared regions[5, 6], even though the absorption efficiency is considered to be large to a thin film[7], but still can't meet the requirements of practical applications, such as solar cells or photodetectors[8, 9].

In order to improve monolayer graphene absorption efficiency, several physical mechanisms have been proposed including one-dimensional photonic crystals[10], surface plasmon[11], dielectric multilayer[12], magnetic dipole[13] and so on. However, these methods only improve the absorption efficiency of graphene in the narrowband spectral ranges, which restrict their potential applications[14]. For broaden bandwidth of graphene absorption, attenuated total reflection[7, 15], multi-resonator approach[13, 14, 16], periodical arrays of dielectric bricks[17] and so on are applied. However, most of the studies are concentrated in THz band[16–18], there are few studies in the visible and near-infrared regions, Ref. [16] achievs enhanced absorption of graphene in visible band, but the bandwidth only 0.1 μm, Ref. [14] achieves enhanced optical absorptionofgrapheneinthewavelengthrangefrom0.45to0.8,butitsstructure is more complicated to manufacture.

In this letter, we propose a novel hybrid nanostructure and numerically demonstrate the graphene absorption efficiency over 30% and absorption bandwidth more than 0.3 μm in near-infrared region. The calculation unit of the hybrid structure is a sandwich structure, in which the monolayer graphene is sandwiched between the three gratings and the SiO_2 spacer on the Ag substrate, and the three individual Ag gratings and the Ag substrate can excite three independent magnetic dipole resonances, which leads to monolayer graphene absorption enhancement over three different wavelength bands, in addition the proposed hybrid nanostructure manufacturing process is simple. By finely tuning the structure parameters, we can make the three independent magnetic dipole resonances overlapped, which leads to broadened absorption bandwidth. We also figure out that thickness of SiO_2 and widths of gratings are critical parameters to the position of absorption peaks.

2. Structure and material

Fig. 1 shows the representation of the proposed hybrid nanostructure, which consists of silver (Ag) metal grating, monolayer graphene layer, silica (SiO_2) layer and Ag substrate from top to bottom. In the unit cell of the hybrid nanostructure, w_1, w_2 and w_3 are three gratings widths, respectively, s is grating spacing, h is the thickness of grating, d is the thickness of SiO_2 spacer, h_s is the thickness of Ag substrate and P is the period of unit cell.

In numerical calculations, the computational model is three-dimensional (3D), and the length in the y direction is 3 μm. The refractive index of SiO_2 is set to be 1.45, and the relative dielectric constant of Ag is expressed by drude model[19], as shown in Eq. (1), ε_{Ag} is the relative dielectric constant of Ag, $\omega_p = 1.39 \times 10^{16}$ rad/s is plasma frequency, $\gamma = 2.7 \times 10^{13}$ s^{-1} is attenuation rate, ω is the angular frequency of incident light.

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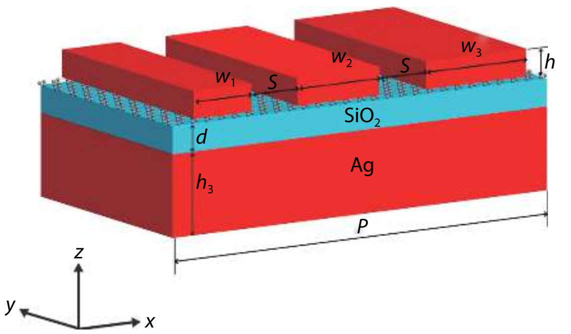

Fig. 1. (Color online) The proposed hybrid nanostructure to broaden graphene absorption bandwidth.

In order to enhance the absorption of graphene, the Ag substrate thickness must be greater than its skin depth in near-infrared region[20], so in this letter, h_s is taken to be 0.1 μm.

$$\varepsilon_{\rm Ag} = 3.4 - \frac{\omega_{\rm p}^2}{\omega^2 - {\rm i}\omega\gamma}. \tag{1}$$

Under the random-phase approximation, the complex frequency-dependent surface conductivity σ can be expressed as the sum of the intraband $\sigma_{\rm intra}$ and interband conductivity $\sigma_{\rm inter}$[21, 22]:

$$\sigma_{\rm intra} = \frac{{\rm i}e^2 k_{\rm B}T}{\pi\hbar^2(\omega + {\rm i}\varGamma)}\left[\frac{\mu_{\rm c}}{k_{\rm B}T} + 2\ln\left({\rm e}^{\frac{-\mu_{\rm c}}{k_{\rm B}T}} + 1\right)\right], \tag{2}$$

$$\sigma_{\rm inter} = \frac{ie^2}{4\pi\hbar}\ln\left[\frac{2\mu_{\rm c} - (\omega + {\rm i}2\varGamma)\hbar}{2\mu_{\rm c} + (\omega + {\rm i}2\varGamma)\hbar}\right], \tag{3}$$

where e is electron charge, $\hbar$ is reduced Planck's constant, μ_c is chemical potential, $\varGamma = 1/2\tau$ is phenomenological scattering rate[23], τ is momentum relaxation time, i is the imaginary unit, k_B is Boltzmann constant, T is temperature in K. On the basis of surface conductivity σ, the graphene's effective permittivity ε_g can be express as[24]:

$$\varepsilon_g = 1 + {\rm i}\frac{\sigma}{\omega\varepsilon_0 t_g}, \tag{4}$$

where ε_0 is vacuum dielectric constant, t_g is the thickness of monolayer graphene layer. In our calculations, T = 300 K, μ_c = 0.1 eV, t_g = 0.5 nm.

3. Results and analysis

Fig. 2 shows the calculated absorption spectra of monolayer graphene at normal incidence, under single-width and triple-widths conditions. These results are calculated by FDTD (finite-difference time-domain) simulation, FDTD can directly simulate the distribution of field and has high accuracy, and it is one of the most widely used numerical simulation methods at present. In single-width case, black, red and blue lines represent absorption efficiencies of graphene at grating width 0.14, 0.16, and 0.18 μm respectively. It can be clearly seen from Fig. 2 that for such single-width gratings, absorption bandwidth is very narrow, the bandwidth only 0.086 μm. The three absorption peaks are caused by magnetic dipole resonances.

If we put these three different gratings stripe in a period, forming a triple-widths grating, the graphene absorption bandwidth with absorption efficiency over 30% can reach 0.311 μm, as denoted by the gray line in Fig. 2. The broadening of graphene absorption bandwidth is due to the spectrally overlapping of magnetic dipole resonances caused by the three different gratings. However, it should be noticed that absorption peaks of triple-widths grating is slightly shifted from single-width gratings.

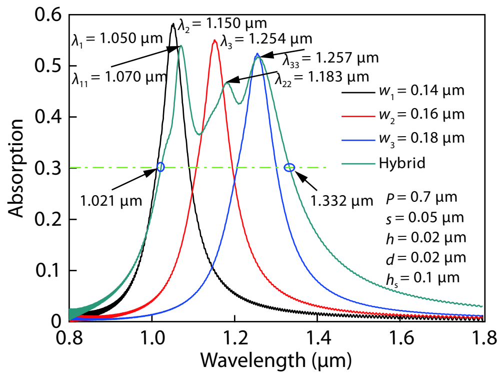

Fig. 2. (Color online) The absorption spectra of monolayer graphene in the wavelength range from 0.8 to 1.8 μm under normal incidence. Structure parameters: P = 0.7 μm, s = 0.05 μm, h = 0.02 μm, d = 0.02 μm, h_s = 0.1 μm.

By calculating Maxwell's equations and combining with boundary conditions, the magnetic field distribution at resonance wavelength is obtained. The magnetic field distribution of the hybrid nanostructure at resonance wavelength of λ_{11}, λ_{22}, λ_{33} are shown in Fig. 3, which are related to magnetic dipole resonances. At resonance wavelength λ_{33}, the magnetic fields are mainly confined to the SiO_2 spacer under the third Ag grating with a width w_3 (see Fig. 3(c)), whereas at the resonance wavelength λ_{11}, the magnetic fields are not only highly limited to SiO_2 spacer under the first Ag grating with a width w_1, but also some magnetic fields are confined to the SiO_2 spacer under the second Ag grating with a width w_2 (see Fig. 3(a))[14, 21]. When the resonance wavelength is λ_{22}, although most of he magnetic fields are confined to the SiO_2 spacer under the second Ag grating with a width w_2, but also there are some magnetic fields in the SiO_2 spacer under the first and third Ag gratings with width w_1 and w_3 (see Fig. 3(b)). Briefly speaking, the wide absorption bandwidth of graphene is caused by the three magnetic dipole resonances overlapped.

Fig. 4 shows effect of grating width on absorption peaks. From Fig. 4(a) to Fig. 4(c), the width w_1, w_2 and w_3 of Ag gratings are increased gradually. It can be seen from Fig. 4 that when the widths of gratings are decreased, the absorption peaks will be blue-shifted. This phenomena can be explained by formula[19,25]:

$$\lambda_{\rm MP} = 2\pi c_0\sqrt{(L_{\rm m} + L_{\rm e})C}, \tag{5}$$

where c_0 is the speed of light in free space, λ_{MP} is magnetic dipole resonance wavelength, C is the capacitance, which is introduced by the Ag grating and Ag substrate, the capacitance is determined by SiO_2 spacer thickness, contact area between grating and substrate , electronic distribution on metal surface. L_m and L_e are mutual inductance and self-inductance, which are also introduced by the Ag grating and Ag substrate[19, 24]. When the widths of gratings reduced or increased,

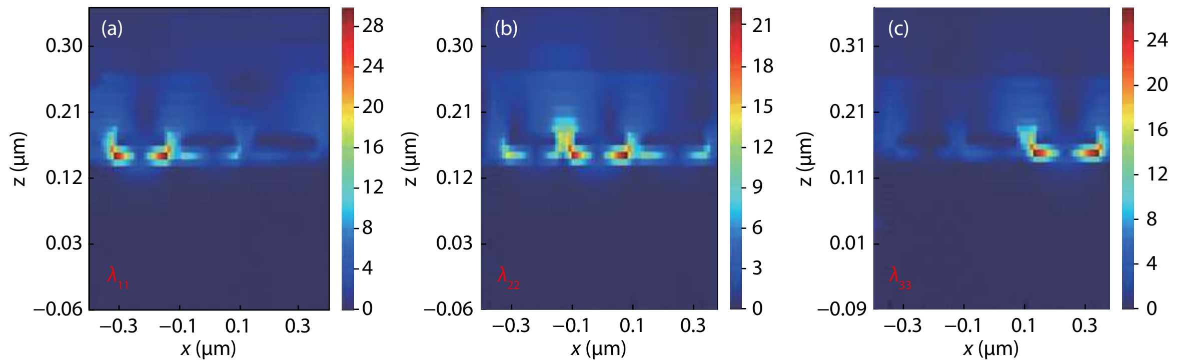

Fig. 3. (Color online) Distribution of magnetic field at different resonance wavelengths on the *xoz* plane. Structure parameters: $P = 0.7$ *μ*m, $s = 0.05$ *μ*m, $h = 0.02$ *μ*m, $d = 0.02$ *μ*m, $h_s = 0.1$ *μ*m.

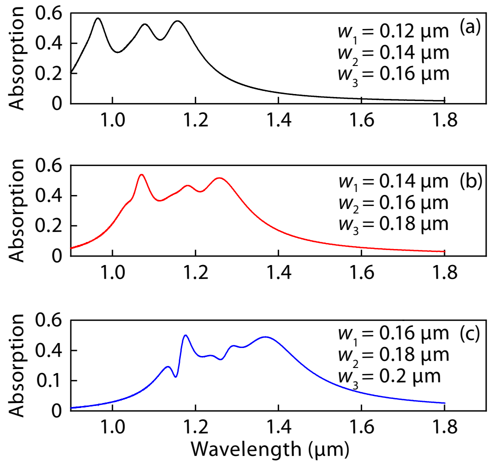

Fig. 4. (Color online) Effect of grating width on absorption peaks. Structure parameters: $P = 0.7$ *μ*m, $s = 0.05$ *μ*m, $h = 0.02$ *μ*m, $d = 0.02$ *μ*m, $h_s = 0.1$ *μ*m.

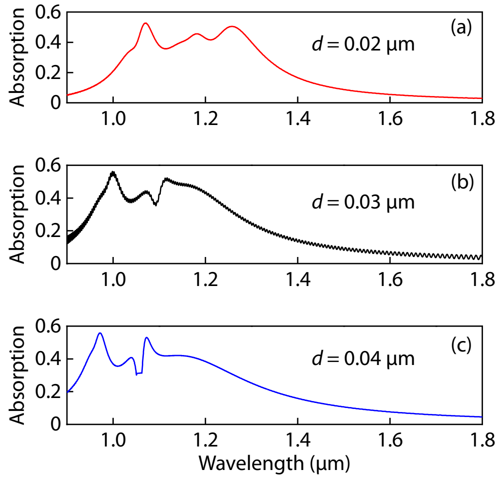

Fig. 5. (Color online) Effect of SiO_2 spacer thickness on absorption peaks. Structure parameters: $P = 0.7$ *μ*m, $s = 0.05$ *μ*m, $h = 0.02$ *μ*m, $h_s = 0.1$ *μ*m, $w_1 = 0.14$ *μ*m, $w_2 = 0.16$ *μ*m, $w_3 = 0.18$ *μ*m.

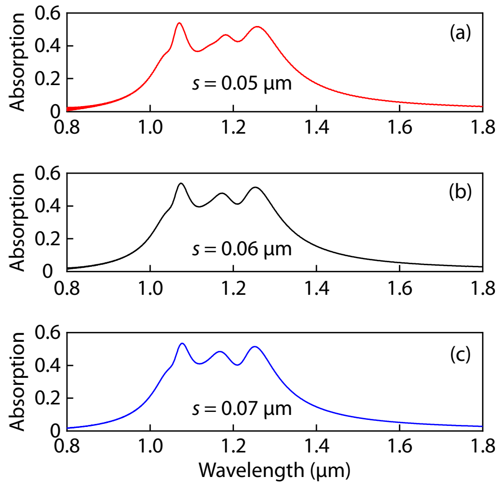

Fig. 6. (Color online) Effect of grating spacing on absorption peaks. Structure parameters: $P = 0.7$ *μ*m, $d = 0.02$ *μ*m, $h = 0.02$ *μ*m, $h_s = 0.1$ *μ*m, $w_1 = 0.14$ *μ*m, $w_2 = 0.16$ *μ*m, $w_3 = 0.18$ *μ*m.

the capacitance *C* will reduce or increase, for the contact area between grating and substrate is smaller or larger. Therefore as the widths of gratings increase, the graphene absorption peaks will be red-shifted, as depicted in Fig. 4.

Not only widths of gratings can affect graphene absorption peaks, but also the SiO_2 spacer thickness, as shown in Fig. 5. In Fig. 5 we can clearly see as the SiO_2 spacer thickness increases, the graphene absorption peaks will be blue-shifted, the phenomenon can also be explained by Eq. (5): when the SiO_2 spacer thickness increases, the spacing between Ag gratings and Ag substrate will get larger, which leads to capacitance *C* gets smaller, therefore λ_{MP} will be blue shifted.

We then investigate the influence of grating spacing *s* on graphene absorption peaks. From Fig. 6 we can find that the grating spacing almost has no effect on the graphene absorption peaks, owing to the fact that most of magnetic fields are almost confined to the SiO_2 spacer directly under the Ag gratings, only small magnetic fields is concentrated near the left and right edges of the Ag gratings (see Fig. 2).

4. Conclusion and perspective

In summary, a hybrid nanostructure consisting of a monolayer graphene sandwiched between three Ag gratings with different widths and a SiO_2 spacer on an Ag substrate is proposed to broaden monolayer graphene absorption bandwidth. The wide absorption bandwidth is related to the magnetic dipole resonances, which are excited between the three different widths Ag grating and Ag substrate. Absorption bandwidth of 0.311 *μ*m in near-infrared region is demonstrated with the absorption efficiency over 30% and the dependence of absorption peaks on Ag grating widths and SiO_2 spacer thickness is also studied.

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