Multichannel Absorption Enhancement in Graphene Based on Metal-Photonic Crystal Hetero-Structure

Jun Wu*

Abstract

The multichannel enhanced absorption effect in monolayer graphene is investigated. The proposed absorber is composed of a monolayer graphene sandwiched between a metal film and an asymmetric photonic crystal. A narrow absorption channel with absorbance above 88% at the near-infrared wavelength is realized, which is attributed to the Tamm plasmon polaritons (TPP). The electric field intensity distributions are calculated to provide an intuitive physical understanding of this multi-band absorption phenomenon. Moreover, the channel number of absorptions can be adjusted by controlling the period of the photonic crystal, which should be interesting for practical application. Besides, the dependence of the absorption performance on the structural dimensions is investigated detailedly to direct the subsequent production of the designed absorber. Our results have great value in applications for developing novel graphene-based tunable devices.

Keywords: Graphene; Tamm plasmon polaritons; Photonic crystal; Spectrum selective absorption.

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1. Introduction

Graphene, constructed with monolayer carbon atoms arrayed in a honeycomb lattice, has emerged as a potential material for photoelectronic applications thanks to its excellent optical and electric natures.^[1-3] Since its firstly peeling by Novoselov *et al.*,^[4] graphene has already motivated a variety of tunable photonic functional devices including transformation optical devices,^[5] absorption devices,^[6-7] photodetection and modulation devices,^[8-9] image devices,^[10] waveguide,^[11-12] optical tweezers and sensors,^[13-15] *etc.* However, because of its short interaction length (0.34 nm), a graphene monolayer can only absorb 2.3% of the incident wave. This leads to a weak electromagnetic wave-graphene interaction, limiting its substantial applications in graphene-based photoelectronic devices. Therefore, it is highly desirable to boost the absorption in monolayer graphene.

From the mid-infrared to THz frequencies, the strong plasmonic response can be excited^[2] owing to the Drude-like properties of graphene,^[7] which gives rise to a strong light-graphene interaction with extremely light confinement to the interface.^[11,16] In addition, benefiting from its tunable conductivity, the properties of the devices with graphene can be dynamically controlled by means of chemical or

electrostatic gating.^[17] Therefore, benefiting from plasmonic resonance in these frequencies, various types of schemes have been designed to boost the graphene absorption, including the doped graphene periodic nanodisks,^[6] graphene periodic ribbon arrays^[7] and double-layer graphene periodic ribbon arrays,^[18] *etc.* In contrast, for light in the visible to the near-infrared region (with $\lambda < 2 \mu\text{m}$), the undoped graphene can only absorb about 2.3% of the normally incident light.^[19] To boost the light absorption in monolayer graphene, many meaningful schemes have been proposed and demonstrated, including photonic crystal structure,^[20] inserting graphene into metal metamaterial,^[21] employing guided mode resonances in traditional grating structure,^[22] the effect of critical coupling,^[23-24] a multilayer subwavelength grating^[25] and Tamm plasmon polaritons with multi-layer photonic configuration.^[26] However, these absorbers usually possess a single absorption channel,^[19-26] which may limit the potential applications in areas requiring multiple channels with narrow bandwidths, such as multichannel filters, thermal detectors, multiparameter sensing, and optical communication.

In this paper, the TPP-assisted multichannel enhanced absorption effect in graphene monolayer is theoretically studied. The absorber consists of a metal film and a monolayer graphene in a dielectric spacer backed with a photonic crystal. A narrow absorption channel with absorbance above 88% at the near-infrared wavelength is achieved. In addition, the channel number can be modulated by controlling the period

College of Electrical Engineering, Anhui Polytechnic University, Wuhu 241000, China.

* Email: mailswj2011@163.com (J. Wu)

number of the asymmetric photonic crystal. To provide a physical understanding of this phenomenon, the distribution of electric field intensity at the resonant wavelength is illustrated. Furthermore, the influence of the incident angle and the structure dimensions on the multi-channel absorption performance is also investigated detailedly, to present the flexible tunability of the designed absorber and also provide useful guidance for practical fabrication.

2. Design and analysis

As is presented in Fig. 1, the designed graphene absorber consists of a metal film, a monolayer graphene embedded in a SiO₂ spacer, a 1D periodic photonic crystal, and a SiO₂ spacer backed with a metal mirror, which is denoted by MC₁GC₂(BA)ⁿ(AB)ⁿC₃N. The metal is selected as silver (Ag), with its refractive index (n_m) taken from Ref.^[27] The thicknesses of metal layers M, and N are h_m , and h_n , respectively. C₁ is the SiO₂ spacer between the top Ag film and the monolayer graphene, and C₂ is the SiO₂ spacer between the monolayer graphene and the 1D periodic photonic crystal (BA)ⁿ(AB)ⁿ. Their thicknesses are denoted by h_1 and h_2 , respectively. The photonic crystal consists of two dielectric layers A and B arranged with a sequence of $F(n) = (BA)^n(AB)^n$, where n is a positive integer denoted as the periodic number of the photonic crystal. A and B are materials SiO₂ ($n_a = 1.45$) and Si ($n_b = 3.48$) with thicknesses of h_a and h_b , respectively. C₃ is the SiO₂ spacer between the photonic crystal and metal mirror. At the near-infrared regions, the refractive index of graphene is obtained according to $n = 3.0 + iC_1\lambda_0/3$, with $C_1 \approx 5.446 \mu\text{m}^{-1}$ (λ_0 denotes the working wavelength).^[28] The thickness of the monolayer graphene is $h_g = 0.34$ nm. The absorber is assumed to be supported by a dielectric (such as SiO₂) substrate. In this work, we consider both TE and TM polarizations (with the electric field and magnetic field paralleled to the y-axis, respectively).

Fig. 1 The scheme of the designed graphene absorber based on multilayer structure MC₁GC₂(BA)ⁿ(AB)ⁿC₃N.

In the subsequent calculations, we employ the rigorous coupled-wave analysis (RCWA) to theoretically study the properties of the graphene absorber.^[29-30] The detailed parameters of the proposed absorber are: $h_m = 20$ nm, $h_n = 100$ nm, $h_1 = 150$ nm, $h_2 = 210$ nm, $h_3 = 300$ nm, $h_a = 120$ nm, and $h_b = 50$ nm. The thicknesses h_a and h_b are set to satisfy $n_a h_a = n_b h_b$. Without loss of generality, the designed absorber with one absorption channel is considered first, thus n is set to 1. To obtain the absorption in graphene, we employ the formula:^[31-32]

$$A(\lambda) = \frac{1}{2} \varepsilon_0 \omega (\text{Im} \varepsilon(\omega)) \int_V |E|^2 dv \quad (1)$$

where, ε_0 and ε are the vacuum permittivity and the relative permittivity of the active material, respectively; E is the electric field and ω denotes the angular frequency. The integral is performed over the graphene monolayer. For light under normal incidence, the absorption spectra of TE-polarized and TM-polarized light are identical due to the symmetry of the structure. Therefore, we only take into account the case of TE-polarized light. The simulated absorption spectra in graphene are shown in Fig. 2. As is clearly illustrated in Fig. 1, one absorption channel with peak absorbance above 88% is achieved at the wavelength of about 1084 nm. Besides, the full width at half maximum (FWHM) is about 18 nm, which exhibits a narrow wavelength bandwidth.

Fig. 2 Absorption spectra of the graphene absorber for normally incident light.

To intuitively reveal the physical origin of this enhanced absorption phenomenon, the distributions of electric field intensity at $\lambda = 1084$ nm are calculated and presented in Fig. 3. As can be seen from Fig. 3(a), the electric field intensity is strongly enhanced and intensively concentrated in the spacer where monolayer graphene located, which results in a strong absorption of incident light in graphene. This phenomenon is attributed to the TPP excited at the boundary between the asymmetric photonic crystal and the metal film, which leads to a field concentrated mainly in the dielectric spacer layer and

Fig. 3 (a) Distributions of electric field intensity at the resonant wavelength of 1084 nm, the white solid line denotes the position of graphene; (b) The corresponding intensity profile along the z -axis at $x = 0$ planes, the red solid line denotes the position of graphene.

results in a relatively small energy loss in metal film and a large absorption of light in graphene monolayer. To clearly show the large intensity enhancement at the graphene plane, we also plot the corresponding intensity profiles along the z -axis at the $x = 0$ plane, which is illustrated in Fig. 3(b). It is found that the monolayer graphene is located at the position where the electric field intensity enhancement is nearly maximized.

3. Discussion

When the light departs from normal incidence, the absorption spectra of TE polarization and TM polarization are different due to the break of symmetry. Thus, to investigate the angle sensitivity, the absorption properties for light under 0° , 20° , and 40° incident angles for TE polarization and TM polarization are calculated and plotted in Fig. 4(a) and 4(b), respectively. As shown in Fig. 4, the resonant peaks of both polarizations present blueshift as the incident angle increase, which is attributed to the shift of photonic stopbands to a shorter wavelength when increasing the angle of incidence.^[33] Besides, we also found that the peak absorptivity of TE polarization sees almost no change with the increase of

incident angle. However, the peak absorptivity of TM polarization decreases a little correspondingly. The resonant wavelength can be tuned nearly linearly with little degradation of the absorption performance by changing the incident angle. This can be considered an efficient method to tune the operating wavelength of the device, which can be used as a highly directed thermal emitter.

Subsequently, the effect of the top Ag film thickness h_m on the graphene absorption is studied, which is presented in Fig. 5(a). As shown in the figure, the absorption spectra shift rapidly toward the shorter wavelength when h_m increases from 10 nm to about 30 nm, and then exhibit a slow blueshift for larger h_m . The peak absorption is large with h_m between about 15 nm to 30 nm. However, when h_m is smaller than 15 nm, the light absorption in the monolayer graphene will decrease owing to the inefficiently exciting of TPP. In addition, the light absorption in the graphene monolayer also significantly decreases with h_m larger than 30 nm, this is because now the evanescent field at the top Ag film for near-infrared wavelengths cannot penetrate through the metal layer. Furthermore, the effect of n on the absorption channel number is investigated, which is presented in Fig. 5(b). It is found that

Fig. 4 Absorption spectra of the proposed absorber for (a) TE-polarized and (b) TM-polarized light versus the change of incident angle.

Fig. 5 (a) Absorption in monolayer graphene versus the wavelength and h_m ; (b) Effect of n on the channel number of the absorber.

the channel number increases accordingly with the increase of n . Although the absorption peak drops slightly, the absorptivity of all resonant peaks is above 65%. It is worth noting that the FWHM decreases accordingly as n increases. In general, multichannel absorption can be easily obtained by adjusting n , which is beneficial for real applications.

Lastly, to direct the real fabrication of the proposed absorber later, the dependence of the absorption properties on the structure parameters is also investigated. In Fig. 6, we show the simulated absorption spectra versus the change of h_a , h_b , h_1 , h_2 , and h_3 , respectively. As illustrated in Fig. 6(a) and 6(b), the resonant peak shifts to longer wavelengths with the increase of h_a or h_b , which exhibits a redshift. However, the redshift with the increase of h_b is larger than that of h_a . It arises that the shift of photonic stopbands with the increasing of h_b is

larger than that by increasing h_a , which has been explained by a technology based on the Fourier transform of the structural index section.^[34] As depicted in Fig. 6(c)-6(d), the resonant peak exhibits a redshift with the increases of h_1 , h_2 , or h_3 . It is worth noting that the amount of redshift caused by the increase of h_1 (h_2) is significantly larger than that by increasing h_3 , which is attributed to the far away from the graphene monolayer for spacer C_3 . In general, the wavelength of the resonant peak can be tuned nearly linearly without degrading the absorbance performance, which can be employed as an efficient method to tune the operating wavelength. In addition, the absorption performances remain stable within a large geometric dimension range, which should be attractive for practical applications.

Fig. 6 Absorption spectra of the designed graphene absorber versus different (a) h_a , (b) h_b , (c) h_1 , (d) h_2 , and (e) h_3 , respectively.

4. Conclusions

In conclusion, the multichannel enhanced absorption properties in graphene monolayers based on 1D metal-graphene-photonic crystal multilayers are investigated. The results show that TPPs with wavelength located at the photonic stopband of the photonic crystal can be excited, which leads to absorption enhancement in the graphene monolayer. This phenomenon is demonstrated by illustrating the electric field distributions at the resonant wavelength, which clearly shows that the TPP modes with large intensity enhancement are highly confined in the spacer where the graphene monolayer is located. In addition, the channel number of absorption can be controlled by adjusting the period of the photonic crystal, which should be interesting for practical application. Last, the effect of the incident angle and structure dimensions on the absorption properties are studied in detail, which should be interesting for practical fabrication. It is hoped that the results have great value for applications in the development of next-generation tunable devices with graphene, such as multichannel filters, absorbers, and thermal detectors.

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Supporting information

Not Applicable.

Conflict of interest

There are no conflicts to declare.

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Author information

Jun Wu is an associate research fellow of Anhui Polytechnic University, working in nanophotonics, diffractive optics and metasurface. He received Ph.D degree from Shanghai Institute of Optics and Fine Mechanics in 2013. He was once an assistant research fellow from 2013 to 2015 and an associate research fellow from 2015 to 2018, working in Shanghai Institute of Optics and Fine Mechanics. He has published 28 journal and conference papers.

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