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

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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 intuitive physical understanding of this multi-band absorption phenomenon. Moreover, the channel number of absorptions can be adjusted through 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 so as to direct the subsequent production of the designed absorber. Our results have great value of applications in developing of 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 properties.\(^\text{[1-3]}\) Since its firstly peeling by Novoselov et al.,\(^\text{[4]}\) graphene has already motivated a variety of tunable photonic functional devices including transformation optical devices,\(^\text{[5]}\) absorption devices,\(^\text{[6-7]}\) photodetection and modulation devices,\(^\text{[8-9]}\) image devices,\(^\text{[10]}\) waveguide,\(^\text{[11-12]}\) optical tweezers and sensors,\(^\text{[13-15]}\) 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 of highly desirable to boost the absorption in monolayer graphene.

From the mid-infrared to THz frequencies, strong plasmonic response can be excited\(^\text{[16]}\) owing to the Drude-like properties of graphene,\(^\text{[17]}\) which gives rise to a strong light-graphene interaction with extremely light confinement to the interface.\(^\text{[11,16]}\) In addition, benefited from its tunable conductivity, the properties of the devices with graphene can be dynamically controlled by means of chemical or electrostatic gatings.\(^\text{[17]}\) Therefore, benefited from plasmonic resonance in these frequencies, various types of schemes have been designed to boost the graphene absorption, including the doped graphene periodic nanodisks,\(^\text{[18]}\) graphene periodic ribbon arrays\(^\text{[19]}\) and double-layer graphene periodic ribbon arrays,\(^\text{[20]}\) etc. In contrast, for light in the visible to the near-infrared region (with \( \lambda < 2 \mu m \)), the undoped graphene can only absorb about 2.3% of the normally incident light.\(^\text{[19]}\) To boost the light absorption in monolayer graphene, many meaningful schemes have been proposed and demonstrated, including photonic crystal structure,\(^\text{[21]}\) inserting graphene into metal metamaterial,\(^\text{[22]}\) employing guided mode resonances in traditional grating structure,\(^\text{[23]}\) the effect of critical coupling,\(^\text{[24]}\) a multilayer subwavelength grating\(^\text{[25]}\) and Tamm plasmon polaritons with multi-layer photonic configuration.\(^\text{[26]}\)

However, these absorbers usually possess a single absorption channel,\(^\text{[19-26]}\) 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, 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 through controlling the
period 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, so as 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 SiO$_2$ spacer, a 1D periodic photonic crystal and a SiO$_2$ spacer backed with a metal mirror, which is denoted by MC$_2$GC$_2$(BA)$^n$(AB)$^m$C$_3$N. The metal is selected as silver (Ag), with its refractive index ($n_m$) taken from Ref.[27]. The thicknesses of metal layers M, N are $h_m$, $h_n$, respectively. C$_1$ is the SiO$_2$ spacer between the top Ag film and the monolayer graphene, and C$_2$ is the SiO$_2$ spacer between the monolayer graphene and the 1D periodic photonic crystal (BA)$^n$(AB)$^m$. Their thicknesses are denoted by $h_1$ and $h_2$, respectively. The photonic crystal consists of two dielectric layers A and B arranged with sequence of $F(n) = (BA)^n(AB)^m$, where $n$ is positive integers denoted as the periodic number of the photonic crystal. A and B are materials SiO$_2$ ($n_a = 1.45$) and Si ($n_b = 3.48$) with thicknesses of $h_a$ and $h_b$, respectively. C$_3$ is the SiO$_2$ spacer between the photonic crystal and metal mirror. At the near-infrared regions, the refractive index of graphene is obtained according to $n = 3.0+iC_1\omega/3$, with $C_1 \approx 5.446 \mu$m$^{-1}$ ($\omega$ denotes the working wavelength). The thickness of the monolayer graphene is $h_g = 0.34$ nm. The absorber is assumed to be supported by a dielectric (such as SiO$_2$) substrate. In this work, we consider both TE and TM polarizations (with the electric field and magnetic field paralleled to y-axis, respectively).

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, $h_a = 120$ nm and $h_b = 50$ nm. The thicknesses $h_a$ and $h_b$ are set to satisfy $n_dh_a = n_bh_b$. Without loss of generality, the designed absorber with one absorption channel is considered firstly, thus $n$ is set to 1. To obtain the absorption in graphene, we employ the formula:[31-32]

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

where, $\varepsilon_0$ and $\varepsilon$ are the vacuum permittivity and the relative permittivity of the active material, respectively; $E$ is the electric field and $\omega$ 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. 1](image1.png) The scheme of the designed graphene absorber based on multilayer structure MC$_2$GC$_2$(BA)$^n$(AB)$^m$C$_3$N.

![Fig. 2](image2.png) 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 form Fig. 3(a), the electric field intensity are 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
results in a relatively small energy loss in metal film and a large absorption of light in graphene monolayer. To clearly shown the large intensity enhancement at the graphene plane, we also plot the corresponding intensity profiles along the \( z \)-axis at \( x = 0 \) 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 investigated the angle sensitivity, the absorption properties for light under 0°, 20°, and 40° incident angle 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 shorter wavelength when increasing the angle of incidence. \(^{[13]}\) 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 as 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 inefficient exciting of TPP. In addition, the light absorption in 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 the channel number increases accordingly with the increasing of \( n \). Although the absorption peak drops slightly, the absorptivity of all resonant peaks are all 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 application.

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 increasing of \( h_a \) or \( h_b \), which exhibits a redshift. However, the redshift with the increasing 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 transformation of the structural index section. 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 with 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 large geometric dimension range, which should be attractive for practical applications.
4. Conclusions
In conclusion, the multichannel enhanced absorption properties in graphene monolayer based on 1D metal-graphene-photonic crystal multilayers is investigated. The results show that TPPs with wavelength locating at photonic stopband of the photonic crystal can be excited, which leads to absorption enhancement in graphene monolayer. This phenomenon is demonstrated by illustrated 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 graphene monolayer located. In addition, the channel number of absorption can be controlled through 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 developing of next-generation tunable devices with graphene, such as multichannel filters, absorber and thermal detectors.

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Supporting information
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Conflict of interest
There are no conflicts to declare.

References

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