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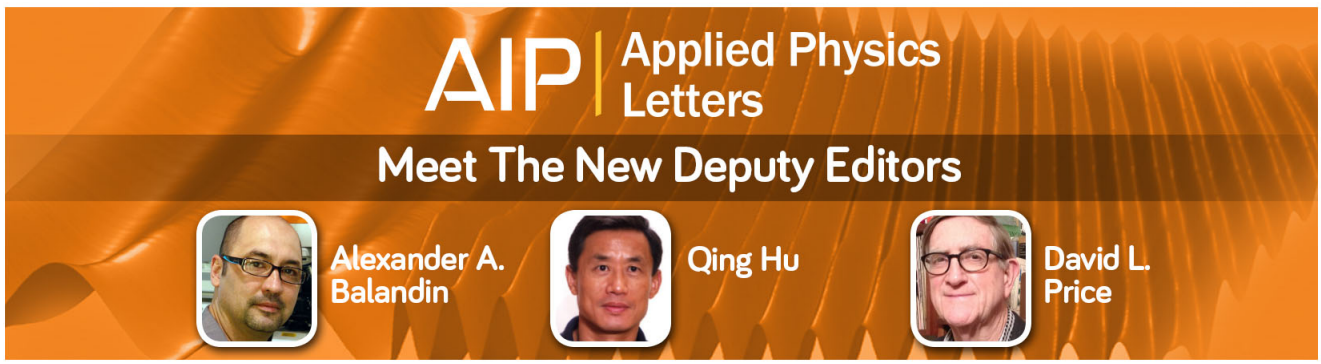

Tunable enhanced optical absorption of graphene using plasmonic perfect absorbers

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Enhancement and manipulation of light absorption in graphene is a significant issue for applications of graphene-based optoelectronic devices. In order to achieve this purpose in the visible region, we demonstrate a design of a graphene optical absorber inspired by metal-dielectric-metal metamaterial for perfect absorption of electromagnetic waves. The optical absorbance ratios of single and three atomic layer graphene are enhanced up to 37.5% and 64.8%, respectively. The graphene absorber shows polarization-dependence and tolerates a wide range of incident angles. Furthermore, the peak position and bandwidth of graphene absorption spectra are tunable in a wide wavelength range through a specific structural configuration. These results imply that graphene in combination with plasmonic perfect absorbers have a promising potential for developing advanced nanophotonic devices. © *2015 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4906996]

Graphene, a monolayer of carbon atoms in a two-dimensional honeycomb lattice, has been shown to possess exceptional electrical and optical properties for developing advanced nanoelectronic and nanophotonic devices.[1] Particularly, research of graphene with a thickness of 3.4 Å has boosted the development of advanced optics from nano-optics to angstrom-optics. In the terahertz and infrared regions, graphene with appropriate doping can generate surface plasmon polaritons (SPPs) and lead to strong light-graphene interactions.[2] In contrast, in the visible and near-infrared range, graphene does not support SPPs and acts as a lossy dielectric material with wavelength-independent absorption.[3] Over the past few years, several graphene-based optoelectronic devices have been demonstrated, such as photodetectors, optical modulators, and photovoltaic cells.[4–6] However, in the visible and near-infrared range, suspended graphene only absorbs about 2.3% of light at normal incidence due to its conical electronic band structure,[7] and it does not show spectral selectivity because of wavelength-independent absorption. This property is promising for developing flexible transparent electrodes, but the poor light-graphene interaction limits its further applications in optoelectronic devices. In order to enhance the light-graphene interaction, conventional plasmonic nanostructures based on noble metals can be combined with graphene for developing novel nanophotonic devices with high performance.[8] Therefore, a systematic structural design in combination with electromagnetic simulation is quite essential in order to enhance the light-graphene interaction and manipulate the optical spectra of graphene-metal hybrid nanostructures.

In view of the ultra-thin physical structure of graphene, we propose to take advantage of the nanostructure of a metal-dielectric-metal (MDM) perfect light absorber, which demonstrates tunable zero reflectance due to effects of a plasmon guided mode within an extra small dielectric gap.[9–11] Therefore, in this paper, we discuss the design of a nanostructure of metal/dielectric/graphene/dielectric/metal (MDGDM) to enhance and manipulate the light-graphene interaction in the visible region. Compared with other plasmonic nanostructures for graphene absorption enhancement,[12,13] the proposed nanostructure provides extraordinarily large absorption efficiency.

The MDGDM nanostructure consists of periodic gold nanoribbons on a SiO_2 layer coated with graphene supported by a flat gold substrate, and the graphene is sandwiched between two hexagonal boron nitride (*h*-BN) layers, as illustrated in Fig. 1. The geometry of the gold nanoribbon is

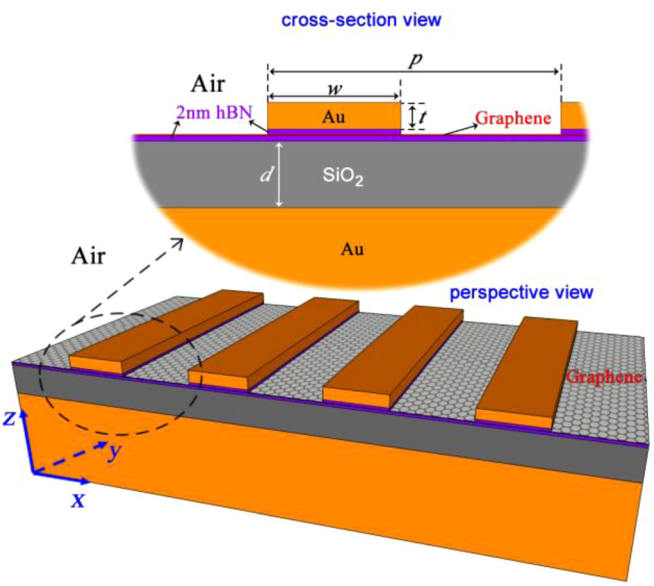

FIG. 1. Schematic drawing of an MDGDM nanostructure. The symbols *d* and *p* correspond to the thickness of the SiO_2 dielectric layer and periodic spacing of the gold nanoribbons, respectively.

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described by both its thickness t and width w. The thickness of h-BN layers is ~2 nm. They are used as insulating spacers to maintain higher carrier mobility of graphene in devices than only using a SiO_2 spacer and also prevent carrier transport between metal nanoribbons and graphene. The enhancement and tunability of light-graphene interaction are investigated using a 2D finite-difference time-domain (FDTD) method.

In FDTD simulations, materials including graphene are defined by their bulk properties. However, the incident light interacting with graphene is absorbed and only generates electron-hole pairs inside an atomic thin film. Therefore, we improve the past assumption,[14] and suppose that graphene is an anisotropic electromagnetic medium with a refractive index tensor $\boldsymbol{N}$ as

$$N = \begin{bmatrix} n_{xx}(\lambda) & 0 & 0 \\ 0 & n_{yy}(\lambda) & 0 \\ 0 & 0 & n_{zz} \end{bmatrix}, \quad (1)$$

where λ is the free space wavelength, $n_{xx}(\lambda)$ and $n_{yy}(\lambda)$ are in-plane components of a graphene layer with complex dielectric dispersion, and n_{zz} is an out-of-plane component with a constant non-dispersive refractive index. Based on Bruna's research work,[15] these components for the visible region are defined as

$$n_{xx}(\lambda) = n_{yy}(\lambda) = 3 + i\frac{C_1}{3}\lambda, \quad n_{zz} = 3, \quad (2)$$

where the constant $C_1 \approx 5.446\,\mu m^{-1}$. The optical absorption of graphene is calculated using the following equation:

$$A(\lambda) = \frac{4\pi c}{\lambda} \cdot \mathrm{Re}(N) \cdot Im(N) \cdot \int_V |E_l|^2 dV, \quad (3)$$

where c is the speed of light in free space, V is the volume of graphene, and E_l is the local electric field. The optical parameters of gold and anisotropic lossless h-BN in simulations are obtained from the literature.[16,17] In the physical model, we assume the effects of optical saturation and non-linear response are ignored.

In order to reveal the physical insight, we investigate the reflectance of an MDGDM nanostructure and the absorbance of graphene under illumination of p-polarized and s-polarized incident light, as shown in Fig. 2(a). The electric field of s-polarized light is parallel to the nanoribbon (y-axis), in which conditions plasmonic resonance is poorly excited. As a result, the graphene absorbance of s-polarized light is extremely weak (about 3.6%) in the visible range. In contrast, the electric field of p-polarized light on the x-z plane excites electrons of gold nanoribbons to vibrate in the finite width w and induces the localized plasmonic resonance. For p-polarized light, the suppressed reflectance around the resonant wavelength of 668 nm is analogous to typical MDM structures, and the absorbance of graphene has been significantly enhanced up to 37.5% at $\lambda = 670$ nm, which shifts slightly away from the resonant wavelength. The effects of polarization dependence imply a promising potential for applications of polarized light filters. Since s-polarized light generates a low absorption rate in graphene, we focus on the optical properties with p-polarized incident light in the following discussion. In order to further demonstrate the absorption enhancement advantages of an MDGDM structure, we compare the p-polarized light spectrum of an MDGD structure with an infinite SiO_2 substrate instead of a gold substrate, as shown in the inset of Fig. 2(a). The inset shows that the maximum absorbance of graphene in the MDGD structure is only 13%, much less than the proposed nanostructure.

In view of the metamaterial theory in an MDM perfect absorber,[9] the suppression of the reflected wave is attributed to matching of the wave impedance between air and the artificial structure, which is further derived from the superposition of inverse optical fields that are induced by electric and magnetic surface currents excited by the incident wave. The minimum reflection in the MDM structure corresponds to the maximum absorption at the resonance wavelength. Based on

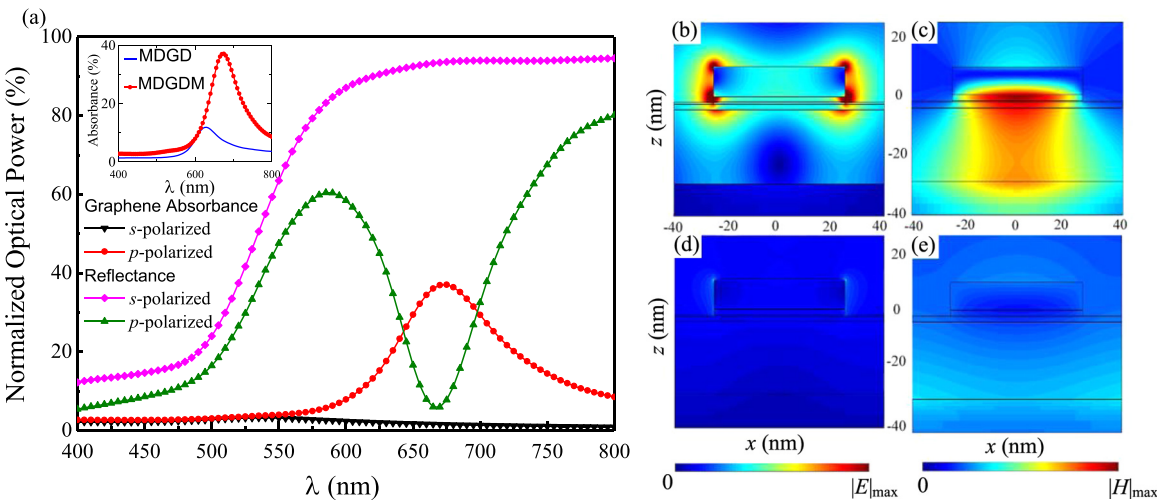

FIG. 2. (a) Light absorption of monolayer graphene and reflection of the MDGDM nanostructure with s- and p-polarized normal incident light. The inset is the absorbance inside monolayer graphene of an MDGD structure and an MDGDM structure under p-polarized light. (b)–(e) Field distributions for p-polarized light, where $w = 50$ nm, $t = 10$ nm, $d = 25$ nm, $p = 120$ nm, and black lines sketch the profile of different materials. (b) Electric field and (c) magnetic field at $\lambda = 670$ nm. (d) Electric field and (e) magnetic field at $\lambda = 450$ nm.

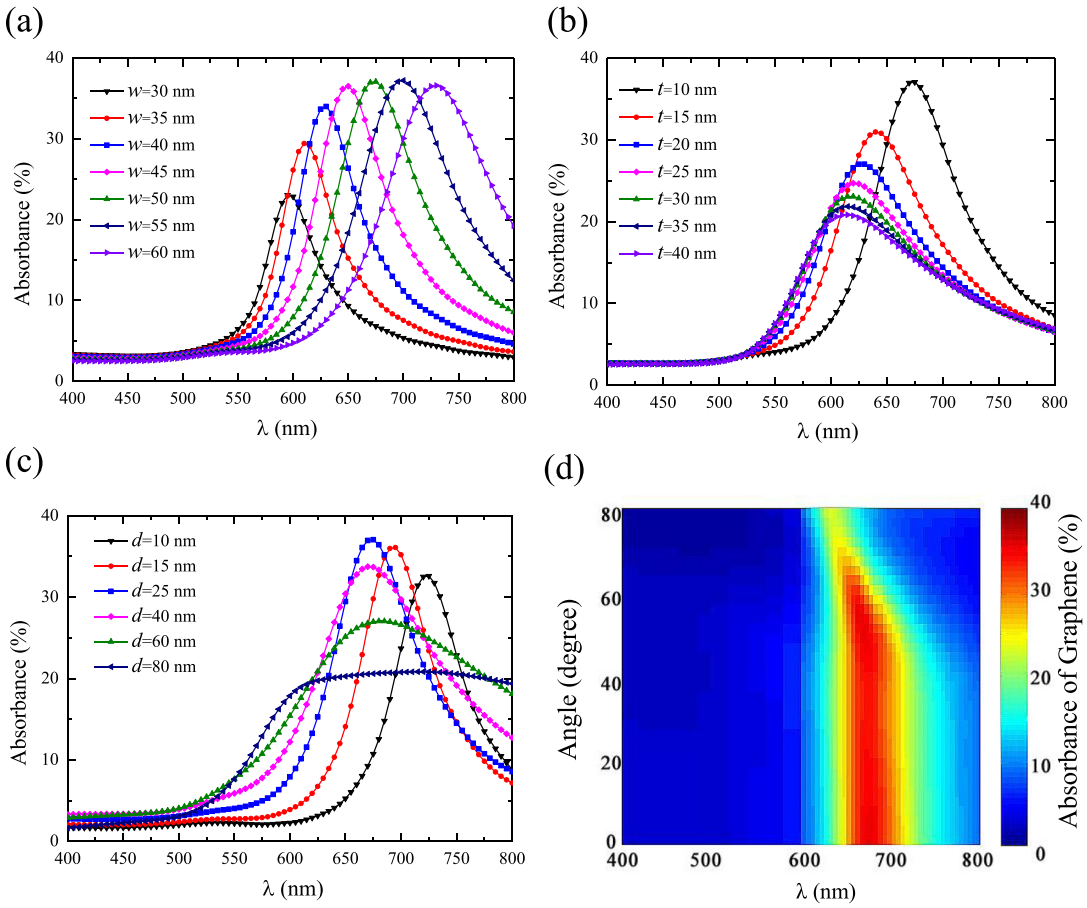

FIG. 3. (a)–(c) Light absorption of monolayer graphene under normal incident p-polarized light, for $p = 120$ nm. (a) Using different w values, for $t = 10$ nm, $d = 25$ nm. (b) Using different t values, for $w = 50$ nm, $d = 25$ nm. (c) Using different d values, for $w = 50$ nm, $t = 10$ nm. (d) Absorbance of monolayer graphene as a function of the wavelength and angle of incidence under p-polarized light, where $w = 50$ nm, $t = 10$ nm, $d = 25$ nm, and $p = 120$ nm.

such consideration, the absorption enhancement of graphene in the MDGDM structure can be explained by analyzing electric and magnetic field distributions, as illustrated in Figs. 2(b)–2(e). At the graphene absorption peak of 670 nm, the complex refractive index of gold is $n_{Au} = 0.13767 + 3.7917i$, so the skin depth of gold $\delta \approx \lambda/[2\pi Im(n_{Au})] \approx 28$ nm is much larger than the thickness of gold nanoribbons. This leads to electromagnetic coupling of both optical fields at the air/nanoribbon interface and h-BN/nanoribbon interface. Therefore, it is observed from Fig. 2(b) that the electric field surrounding the corners of gold nanoribbons is concentrated and enhanced, and magnetic field is guided between each gold nanoribbon and the gold substrate as shown in Fig. 2(c). The incident fields are trapped surrounding the graphene layer as the guided gap-plasmon mode and induce the effects of near field enhancement and light energy concentration. The enhanced optical fields penetrating graphene dissipate in the lossy dielectric and contribute to the enhanced absorption inside graphene. In contrast, for $\lambda = 450$ nm as presented in Figs. 2(d) and 2(e), there is no enhanced optical near field for absorption enhancement in graphene because this wavelength is far away from the gap-plasmon resonance wavelength on the spectrum.

We next consider effects of changing the width of gold nanoribbons on the optical absorption of graphene as shown in Fig. 3(a). In our investigation, the separation between adjacent nanoribbons is fixed to be relatively larger than their width in order to ignore the electromagnetic coupling between nanoribbons. The nanoribbon acts as a Fabry-Perot resonator for the horizontal plasmon guided mode, and the resonant wavelength is significantly sensitive to the width of nanoribbons, so the center wavelength of the graphene absorption band is determined by w. As w increases from 30 nm to 60 nm, the absorption spectra of graphene are red-shifted due to the increment of the effective resonance wavelength of the localized surface plasmon. On the other hand, the absorption efficiency of graphene is related to the filling factor of gold nanoribbons, which is defined by $F = w/p$. The resonances are localized to individual nanoribbons, so the absorption enhancement in graphene occurs surrounding the corners of nanoribbons. When w is increased from 30 nm to 45 nm, F becomes larger, and the intensity of the field concentration and enhancement between neighboring nanoribbons and inside graphene are significantly strengthened,[18] so the absorption efficiency remarkably rises from 22.6% to 36.1%. As w changes from 45 nm to 60 nm, the levels of absorption enhancement are slightly changed, but there is an optimal width of 50 nm, at which the absorption peak is maximized to 37.5%. When F is too large, too much of an area of graphene is covered by gold nanoribbons, thus degrading the absorption efficiency.

After discussing the effects of the gold nanoribbon width, we investigate the influence of the gold nanoribbon thickness on the absorption of graphene, as demonstrated in

Fig. 3(b). When $t = 10$ nm, the thickness of the gold nanoribbon is relatively small compared to the skin depth δ, and the optical fields at the air/nanoribbon interface and h-BN/nanoribbon interface are effectively coupled to each other and enhance the optical absorption of graphene. As the thickness of gold nanoribbons increases from 10 nm to 40 nm, the absorption of graphene drops from 37.5% to 21.7% and the peaks of the spectra are blue-shifted from 670 nm to 609 nm. This is because the wave diffraction around the gold nanoribbons is enhanced, and the plasmon coupling strength between the top and bottom surfaces of gold nanoribbons is reduced, which weakens the selective absorption effect of the MDGDM structure. On the other hand, increasing the thickness of gold nanoribbons also brings about a higher optical loss ratio inside the gold nanoribbons. Thus, the effects due to the thickness reduction of gold nanoribbons dramatically cut down the absorbance of graphene.

Analogous to an MDM plasmonic nanostructure, the resonance properties of MDGDM nanostructures are highly sensitive to the thickness variation of the dielectric spacer layers, which facilitates tuning the absorption band of graphene in an MDGDM configuration by slightly changing the spacer thickness. This property is shown in Fig. 3(c). As the thickness of SiO_2 increases from 10 nm to 40 nm, the absorbance spectrum shows obvious resonance peaks, and the peaks shift from 722 nm to 673 nm due to an expansion of the plasmonic gap. There is an optimal thickness of the dielectric layer, at which the absorption peak of graphene reaches the maximum. When $d = 25$ nm, the absorbance of graphene can be up to 37.5% at the wavelength of 670 nm and the Full Width Half Maximum (FWHM) is 102 nm. Such high absorption of graphene is consistent with the reflection spectrum of the MDGDM structure, which is due to the coupling of plasmon near fields between each nanoribbon and the continuous gold substrate. As d increases from 10 nm to 40 nm, the plasmon coupling strength gets stronger until a maximum absorption rate is achieved at an optimum value and becomes weaker subsequently. When each gold nanoribbon is far away from the gold substrate ($d \geq 60$ nm), the entire nanostructure cannot be assumed as a homogeneous effective medium, because the conditions for being a sub-wavelength structure are broken.[11] Consequently, the optical properties of such a configuration are mainly determined by the substrate. The optical absorption of the gold substrate dominates the total absorption, leading to a broadband absorption spectrum for graphene. These effects can be utilized for designing both broadband graphene absorbers and multicolor selective absorbers in the visible spectrum for novel optoelectronic devices.

The discussion above is based on normal incident light, but in the application of graphene-based photonic devices, the proposed device structures should ensure high optical absorption efficiency working on a wide range of light incident angles. For this reason, we demonstrate graphene optical absorption as a function of the free space wavelength and angle of incidence, as shown in Fig. 3(d). When the incident angle increases to 67°, the maximum absorbance of graphene remains greater than 30%, although the bandwidth becomes slightly narrower. The absorbance is still greater than 22% even if the incident angle is up to 80°. It is observed from Fig. 3(d) that the absorption band and absorption efficiency of graphene are almost independent of the incident angle, which is in accordance to the common features of MDM resonators. These features are attributed to the explanation, that the direction of the magnetic field for p-polarized light remains constant when the incident angle is changed, so the strength of magnetic resonance can be sufficiently kept and further ensures the high ohmic loss in graphene, for almost all incident angles.

Obviously, the absorption band of an MDGDM nanostructure is limited by the bandwidth due to the localized surface plasmon resonance. However, it is desirable to broaden the absorption band of graphene in some practical device applications. With regards to this purpose, we improve the MDGDM configuration and obtain a new structure with distinct widths of gold nanoribbons in a fixed period, which is named as a biMDGDM nanostructure. In Fig. 4(a), the absorbency of the two MDGDM structures with $w = 50$ nm and $w = 60$ nm, respectively, are plotted and compared with the absorbance of a biMDGDM structure with a combination

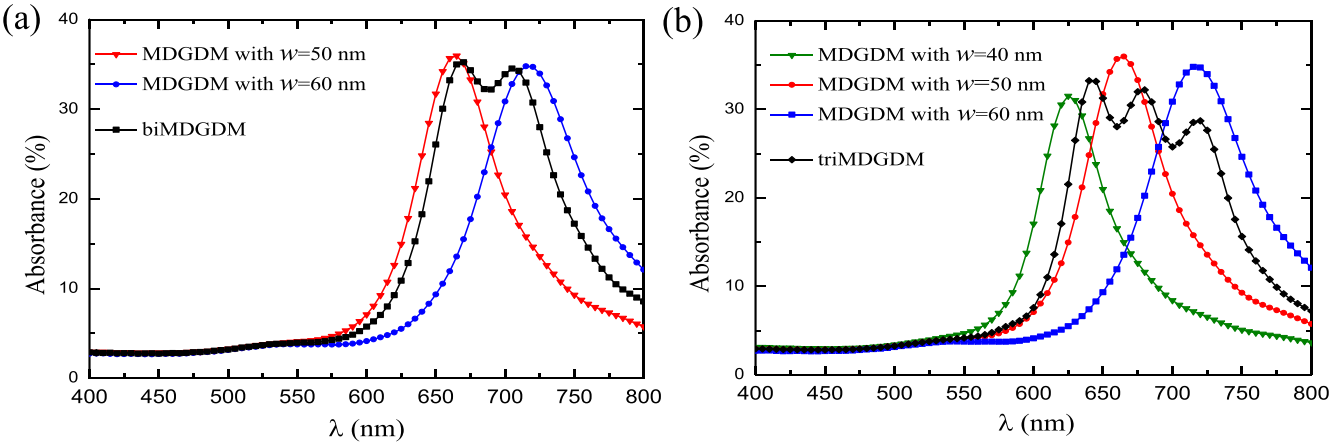

FIG. 4. (a) Monolayer graphene absorption of a biMDGDM structure with $w_1 = 50$ nm and $w_2 = 60$ nm, $p = 350$ nm compared with monolayer graphene absorption of two single MDGDM structures of $w_1 = 50$ nm, $p_1 = 170$ nm and $w_2 = 60$ nm, $p_2 = 180$ nm, under p-polarized normal incident light, where $t = 10$ nm, $d = 25$ nm. (b) TriMDGDM structure compared with three single MDGDM structures, where $w_1 = 40$ nm, $w_2 = 50$ nm, $w_3 = 60$ nm, $p_1 = 160$ nm, $p_2 = 170$ nm, $p_3 = 180$ nm, and $p = 510$ nm.

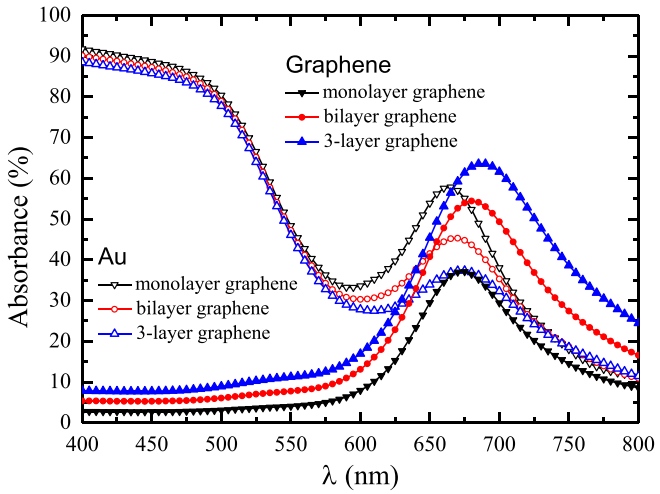

FIG. 5. Light absorption of Au and graphene in MDGDM structures with graphene of different atom layers under p-polarized normal incident light, where $w = 50$ nm, $t = 10$ nm, $d = 25$ nm, and $p = 120$ nm.

of $w_1 = 50$ nm and $w_2 = 60$ nm. As illustrated in Fig. 4(a), the biMDGDM structure exhibits a graphene absorption peak of 35.8%, and the FWHM is significantly broadened compared with each MDGDM structure. Based on such consideration, three or more gold nanoribbons with various widths can be combined in the same space period. As shown in Fig. 4(b), the triMDGDM structure also exhibits a much broader absorption band with three peaks. The results in Figs. 4(a) and 4(b) originate from the fact that gold nanoribbons with different widths perform as distinct resonators working at different resonance wavelengths.[19] If the separation between neighboring gold nanoribbons of different widths is chosen properly, these nanoribbons will behave as uncoupled antennas, which sort photons at their resonant wavelengths, forming a broadband multi-MDGDM structure.

Finally, we discuss the route to improving absorption efficiency of graphene in MDGDM resonators. Based on the above study, an MDGDM structure can be regarded as an MDM optical resonator loaded with a lossy medium of graphene, and the resonator possesses inherent loss due to light dissipation in the material of gold, which is undesirable for an optical absorber of graphene. In order to enhance the light absorption ratio of graphene, we utilize multilayer graphene as the lossy load, as shown in Fig. 5. The high absorbance of gold from 400 nm to 550 nm is attributed to the intrinsic loss in gold because of the higher imaginary part of permittivity, which contributes little to the absorption enhancement of graphene. The plasmonic resonance results in absorption enhancement of graphene as well as inherent resonant losses in gold. The absorbance of graphene around the resonant wavelength is significantly enhanced as the number of graphene atom layers increases from 1 to 3. The peak absorbance of three-layer graphene rises to 64.8%, while the peak absorbance of gold drops from 58.7% to 37.7% compared to using monolayer graphene.

In summary, we have investigated the optical properties of MDGDM structures for light energy harvesting in graphene. The research achievements reveal the potential implementation of plasmonic perfect absorbers for graphene absorption in novel optoelectronic devices and provide a guide to design related nanostructures and devices.

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