Graphene-supported tunable near-IR metamaterials

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By integrating the metallic metamaterials (MMs) with a graphene layer, the resonant properties of an active tunable device based on the metal-SiO₂-graphene (MSiO₂,G) structure have been theoretically investigated in the near-IR spectral region. The results manifest that the influences of the graphene layer on the propagation properties are significant. Owing to the tunability of the Fermi level of graphene, the resonance of transmitted or reflected curves can be tuned in a wide range (160–193 THz). To an original metal unit cell structure, an elevated Fermi level of graphene layer enhances the resonance dips and shifts it to the higher frequency. Compared with the original structure, the corresponding complementary MMs structure shows a much sharper spectral curve and can be used to fabricate a switcher or filters. The results are very helpful for designing graphene plasmonic devices. © 2015 Optical Society of America

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Metamaterials (MMs), i.e., the composite materials designed to manifest exotic electromagnetic (EM) phenomena not available by natural materials, offer many intriguing ways of manipulating light and have been intensively investigated [1]. MMs provide a promising platform for the investigation of many phenomena, such as negative refractive index [2], super-focusing [3], and extraordinary transmission [4,5]. Similar to the original MMs, the complementary MMs based on the Babinet equivalent rule can also offer a simple means to control the EM wave propagation [6] and are very suitable to act as reflectors and antennae. Furthermore, the EM response of the MMs can be actively controlled through external stimulus. To realize the tunability of MMs, the typical methods that are currently used employ the inclusion of a semiconductor to alter the capacitance of the resonators or change the property of the surrounding media through optical, electrical, magnetic, or thermal means [1,2,7]. However, those tunable methods manifest serious limitations in the modulation range and are complex to fabricate, which hinders the practical applications of the tunable MMs.

With the rapid development in the fields of fundamental physics and enormous applications [8–10], graphene can be regarded as an alternative to traditional metallic materials and serve as a good platform for surface plasmons and MMs [11–15]. The graphene surface plasmons exhibit strong confinement [16–20]. Tunable devices can also be obtained by the combination of graphene with integrated MMs structures, which have been shown in the terahertz (THz) [21–23] and mid-IR [24] regimes. For instance, Valmorra et al. showed that on the basis of the hybrid graphene/MMs devices, the potential THz modulator can be achieved with the modulation depth about 12% [22].

The key waveguides devices, such as modulators or reflectors, are highly important for meeting the needs of wireless communication or ultrafast interconnects. But for current waveguide devices, many problems still exist, such as the modulation depth not being very large and cryogenic temperatures being required. Thus, further improvements of the performance characteristics are needed for practical applications. Currently, most of the investigations about tunable graphene plasmonic devices concentrate on the THz and mid-IR regimes, while developing tunable devices in the visible/near-IR (NIR) spectral regions is also very important from the technological viewpoint. By inserting the graphene layer between the original (or complementary) MMs layers and flexible polymer substrate, we suggest the metallic MMs-SiO₂-graphene (MSiO₂,G) structures to dynamically realize control of the propagation waves. Compared with most existing devices, the proposed MSiO₂,G structure displays much better modulation properties. Furthermore, the tunable transmission responses can also be realized based on the MSiO₂,G structures, which are different from the existing graphene reflectors or modulators.

Figure 1(a) shows the sketch of the side view of the metallic MMs structure, which is deposited on the flexible polymer substrate. The substrate is made from the polyimide with the thickness of 2 μm. The SiO₂/graphene layers are inserted between the metallic

![Fig. 1. (a) Side view of the MMs structure. The metallic MMs structure is deposited on the SiO₂/graphene layers; the thickness of the SiO₂ layer is 10 nm. The substrate is made from the polyimide layer. (b) Top view of the MMs unit cell based on the cross-shaped structures. (c) Top view of the complementary MMs unit cell structures based on the cross-shaped. The gray layer indicates the SiO₂.](image)
MMs structure and the substrate; the thickness of the SiO$_2$ layer is 10 nm. Figures 1(b) and 1(c) display the top views of the geometry for the original and complementary cross-shaped unit cell structure, respectively. The period lengths along the $x$ and $y$ directions are $d_x$ and $d_y$, respectively. The unit cells of MMs are made of Ag with the thickness of 100 nm. The incident waves are normally transmitted through the GSiO$_2$Si structure along $z$ direction.

Graphene can be considered as a two-dimensional material and described by a surface conductivity $\sigma_g$, which is related to the radiation frequency $\omega$, chemical potential $\mu_c$ (Fermi level $E_f$), environmental temperature $T$, and relaxation time $\tau$. The conductivity of the monolayer graphene can be obtained from the Kubo formula [29]:

$$\sigma_g(\omega, \mu_c, \tau, T) = \sigma_{\text{inter}} + \sigma_{\text{intra}} = \frac{j\epsilon_0(\omega-j\tau^{-1})}{\pi\hbar^2} \times \left[ \frac{1}{(\omega-j\tau^{-1})^2} \int_0^\infty \frac{df_d(\epsilon)}{d\epsilon} - \frac{df_d(-\epsilon)}{d\epsilon} d\epsilon \right. $$

$$- \int_0^\infty \frac{f_d(-\epsilon)-f_d(\epsilon)}{(\omega-j\tau^{-1})^2-(4\epsilon/h)^2} d\epsilon \right] .$$  (1)

where $f_d(\epsilon)$ is the Fermi–Dirac distribution, $j$ is the imaginary unit, $\epsilon$ is the energy of the incident wave, and $\hbar$ is the reduced Planck’s constant. The Fermi level of the graphene layer can be determined by the carrier concentration:

$$n_d = \frac{1}{\pi\hbar^2v_F^2} \int f_d(\epsilon)-f_d(\epsilon+2E_f)\epsilon d\epsilon ,$$  (2)

in which $v_F \approx 1 \times 10^6$ m/s is the Fermi velocity and $E_f$ is the Fermi level of the graphene layer. The dielectric constant of graphene layer can be expressed as

$$\epsilon_g = 1 + j\frac{\sigma_g}{\omega\epsilon_0\Delta} .$$  (3)

where $\Delta$ is the graphene layer thickness and $\epsilon_0$ is the permittivity of free space.

Figure 2 shows the propagation properties of the incident light through the original and complementary MSiO$_2$G structure based on the cross-shaped unit cell. The length and width of the cross structure are 450 and 90 nm, respectively. The polarization of the incident light is along the $y$ direction. Each piece of the MMs is a square lattice. Its periodic lengths along the $x$ and $y$ directions ($d_x$ and $d_y$) are both 900 nm. The simulation results have been obtained from the well-established CST Microwave Studio. The frequency domain solver is adopted with the unit-cell boundary conditions in the $x$–$y$ plane and Floquet ports in the $z$ direction to terminate. The transmission, reflection, and absorption can be obtained from the $S$-parameters, i.e., $T = |S_{21}|^2$, $R = |S_{11}|^2$, and $A = 1.0 - T - R$ [13].

Figure 2(b) shows that the transmission curve of the metallic MMs is based on the cross-shaped unit cell. The cross-shaped symmetric MMs structures yield identical optical responses along the $x$ and $y$ directions, which can be used to fabricate the polarization insensitive devices. The thickness of the graphene membrane is small, only about 0.34 nm, but it can be found from Fig. 2(b) that as the Fermi level increases, the influence of the graphene layer on the transmission curve is significant. The possible reasons are shown as follows. The surface conductivity of the graphene layer includes the intraband and interband contributions. In the NIR regime, the energy of the incident light is large. The effects of the interband contribution take an important role and should be taken into account. This is different from the case in the THz regime, where the intraband contribution dominates. When the Fermi level of the graphene layer is low, e.g., 0.1 eV, the interband contribution dominates, and the graphene layer behaves like a dielectric layer with a large value of real part of the permittivity. The transmission resonance of the MSiO$_2$G structures is noticeably damped because of the energy dissipation in the graphene membrane. As the Fermi level increases, the interband contribution decreases, resulting in the values of the graphene permittivity and losses decreasing. The resonant dips of the transmission curve decrease, and the dip position shifts to a higher frequency. When the Fermi level increases further, about $2|\mu_c| \approx \hbar\omega$, the number of final states allowed for an interband contribution reduces drastically, and the interband process is blocked. When the Fermi level is 0.5 eV, the value of the graphene permittivity ($\epsilon_m$) is very small and shows a dip near 1.55 μm (193.5 THz). Thus, the effect of the graphene layer on the transmission curve is little. This is verified by the simulation results. For example, as shown in Fig. 2(b), the transmission curve of MSiO$_2$G structure at the Fermi level of 0.5 eV (the pink line) is close to the results without the graphene layer (the black line). Compared with the conventional MMs structure without the graphene layer, the transmission curve of the proposed MSiO$_2$G
structure can be tuned in a wide range. When the Fermi level of the graphene layer changes in the range of 0.1–0.5 eV, the resonant frequency of the transmission can be changed in the range of 170.7–194.2 THz, and the value of the transmission can be modulated in the range of 0.01–0.32, the modulation depth of the frequency \( f_{\text{mod}} = (f_{\text{max}} - f_{\text{min}})/f_{\text{max}} \) is 12.1%, and the modulation depth of the transmission \( T_{\text{mod}} = (T_{\text{max}} - T_{\text{min}})/T_{\text{max}} \) is 96.9%. If the Fermi level of the graphene layer is beyond 0.5 eV, the sign of the real part of the graphene layer changes from positive to negative, manifesting metallic properties.

Additionally, Figs. 2(c) and 2(d) show the tunable reflection and absorption response curves versus frequency, respectively. Compared with the results without the graphene layer, the absorption increases and the reflection decreases. As the Fermi level increases, the loss of the graphene layer decreases, the reflections increase, and the absorptions decrease. When the Fermi level of the graphene layer changes in the range of 0.1–0.5 eV, the resonant frequency of the reflection can be modulated in the range of 160.3–194.5 THz, and the value of the reflection can be modulated in the range of 0.31–0.80, the modulation depth of the frequency is 17.6%, and the modulation depth of the reflection is 61.3%. The reason behind this can be explained by the fact that the effective permittivity of the graphene membrane changes with the increase of the Fermi level, as shown in Fig. 4(a). For instance, at the frequency of 193.5 THz, the permittivity of the graphene layer is 0.78 + 81.9i, 12.46 + 80.12i, and −5.01 + 2.31i, when the Fermi levels are 0.1, 0.3, and 0.5 eV, respectively, which can be obtained from Eq. (3). When the Fermi level is low, due to the larger loss of the graphene layer, the absorption dominates and the reflection is little. But with the increase of the Fermi level, the permittivity of the graphene layer decreases, the loss and absorption decreases, and the reflection increases. For a case far above the resonance frequency, the imaginary part of the effective permittivity tends to a certain value regardless of the Fermi energy, and the transmission and reflection curves of the graphene MMs in Fig. 2 merge together at high frequencies. Finally, the resonant transmission and reflection spectrum of the MSiO2G structure are relatively broad; thus the suggested graphene supported MMs structure is very suitable for fabricating the broadband modulators.

Figure 3 shows the results for the complementary metal cross-shaped MMs structure. The unit cell structure can be found in Fig. 3(a). The polarization of the incident light is along the \( x \) direction. As shown in Fig. 3(b), the transmission of the complementary structure shows a peak, which is different from the results for the original structure. With the help of the graphene layer, the transmission can be tuned in a wide range. When the Fermi level of the graphene layer is about 0.1 eV, the transmission of the structure decreases significantly due to the large loss of the graphene layer. But with the increase of the Fermi level, the dielectric constant of the graphene layer decreases drastically. When the Fermi level of the graphene layer is about 0.5 eV, the interband process is blocked, its corresponding permittivity is very small, and the effects of the graphene layer is little so the transmission of the structure reaches a relatively large value. The resonant peak shows blue shift with the increase of the Fermi level. Figures 3(c) and 3(d) display the reflection and absorption of the complementary structure. For the results without the graphene layer, the transmission and absorption dominate, and the influence of the reflection is small. But for the MSiO2G structure, it is much more difficult. When the Fermi level is low, the interband contribution plays an important role, the losses of the graphene layer are large, and the reflection and absorption dominate. As the Fermi level increases, the dielectric constant of graphene layer decreases, the influence of reflection decreases, and the transmission and absorption dominates. When the Fermi level of the graphene layer changes in the range of 0.1–0.5 eV, the resonant frequency of the reflection can be changed in the range of 183.9–193.4 THz, and the value of the reflection can be modulated in the range of 0.16–0.69, the modulation depth of the frequency is 4.9%, and the modulation depth of the reflection is 76.8%. In addition, compared with the results shown in Fig. 2, the resonant transmission and reflection spectrum of the complementary MSiO2G structure are sharper. Furthermore, as the Fermi level of the graphene layer increases, the FWHM of the transmission and reflection spectrum decreases. The complementary structures are very suitable for fabricating the filters and switches.

Figure 4(a) shows the permittivity of the graphene layer in the NIR spectral range. As the Fermi level of the graphene layer increases, the interband contribution decreases, leading to the value of the dielectric constant being reduced. When the Fermi level of the graphene layer is 0.5 eV, the interband contribution is blocked, and the dielectric constant of the graphene layer shows a dip near the wavelength of 1.5 \( \mu \)m. Figures 4(b)–4(d) show the surface current density, the \( x(E_x) \) and \( y(E_y) \) components of the electric field for cross-shaped MMs structure. The simulation results are plotted at the resonant frequency with the value of 193.5 THz, which is in accordance with the resonant dip shown in Fig. 2(b). The direction and size of the arrows in Fig. 4(b) indicate the direction and relative value of the surface current density, and the color map in Figs. 4(c) and 4(d) shows...
the relative local electric field amplitude. Figures 4(e)–4(g) show the surface current density, $E_x$ and $E_y$, of the electric fields based on the cross-shaped MMs structure. The polarization direction of the incident light is along the $y$ direction. (e)–(g) show the surface current density, $E_x$ and $E_y$, for the complementary structure. The polarization direction of the incident light is along $x$ direction.

In summary, by depositing the planar arrays of original and complementary metal MMs patterns on the polymer substrate, the tunable propagation properties of the proposed MSiO$_2$G structure have been given and discussed in the NIR regime. The results show that with the help of the graphene layer, the transmission and reflection can be tuned in a wide range. As the Fermi level of the graphene layer increases, the resonance of the MSiO$_2$G structure become stronger, and the resonant dips of the transmission and reflection shift to the higher frequency, resulting from the fact that the dielectric constant of graphene decreases in the NIR spectral range. The spectral curve of the original (complementary) MMs structures is broad (sharp), which can be used to fabricate modulators (switcher or filters). The results are very helpful in designing plasmonic devices and are useful for the application of biomedical sensing and optical communications.

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