Graphene-enabled tunability of optical fishnet metamaterial

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We present an effective method for actively controlling intrinsic resonances of optical metamaterials using graphene. Exploiting the Fermi level shift and associated variations in optical transitions of graphene due to voltage biasing, we attain the ability to significantly modulate the intrinsic resonance of the fishnet structure. Despite being atomically thin and having a weak optical response, graphene can be strongly coupled with the left-handed resonance of the fishnet metamaterial. We unambiguously demonstrate that the resonant transmission, absorption, and effective constitutive parameters of the graphene-coupled fishnet metamaterial can be precisely controlled by varying the bias voltage. © 2013 American Institute of Physics. [http://dx.doi.org/10.1063/1.4799281]

Recent progress in the design of optical metamaterials1–5 offers many intriguing ways of manipulating light. By spatially arranging metamaterials, one can make myriad of useful optical devices such as perfect lens with sub-wavelength precision,6 cloaks of invisibility,7 and electromagnetic black holes.8 However, owing to the reliance on resonances to sustain their features, most metamaterials are narrowband, which limits their use in practice.9 One of the ways to overcome this limitation is to use tunable metamaterials,10,11 having the ability to switch their operating characteristics in real time. Tunable metamaterials can be created by integrating active media (such as liquid crystals12,13 semiconductors,14,15 and ferrites16,17) with ordinary metamaterials. The permittivities and permeabilities of these metamaterials can be adjusted by controlling external stimulus, such as electric field, magnetic field, voltage, or temperature. Among all these techniques, voltage control is one of the most simplest ways in practical operations. However, voltage-controlled tunable metamaterials so far have only been demonstrated at terahertz (THz) frequencies, since semiconductors fail to sustain sufficiently high densities of injected free electrons outside this frequency range, especially at higher frequencies.18

Graphene, a single layer form of carbon with atoms arranged in a honeycomb lattice, has attracted significant attention in the scientific community, owing to its unique electric, mechanical, and thermal properties.19–21 Despite being atomically thin, graphene can strongly interact with light over a wide frequency range. Thanks to the tunability of its carrier mobility and conductivity at THz and optical frequencies, graphene seems to be a good candidate for designing tunable devices that operate in both THz and optical frequency ranges. Moreover, the atom-level thickness of graphene enables its integration to metamaterials and plasmonic devices. Recently, Lee et al.22 realized gate-induced persistent switching and linear modulation of THz waves using graphene-based metamaterials. Yan et al.23 fabricated a tunable far-infrared notch filter and a tunable THz linear polarizer using graphene/insulator stacks. Kim et al.24 studied a hybrid graphene-gold nanorods structure at near-infrared frequency and found its plasmonic resonance can be dynamically adjusted by voltage. These studies open an exciting avenue towards designing voltage-controlled tunable metamaterials at optical frequencies.

In this letter, we present an effective method for active controlling the resonances of optical metamaterials using voltage-biased graphene. Specifically, we study a graphene-coupled fishnet metamaterial at near-infrared frequencies. We show that the coupling between graphene and fishnet metamaterial can dramatically modify the resonances of both the graphene and the fishnet metamaterial. Such coupling can be controlled at will by changing the graphene’s Fermi level by biasing the graphene. The graphene-coupled, voltage-controlled optical metamaterials may find extensive applications at optical communications and integrated ultra-high speed circuitry.

The complex conductivity of voltage-biased graphene is contributed by intraband and interband terms, \( \sigma(\omega, E_F, \Gamma, T) = \sigma_{\text{intra}} + \sigma_{\text{inter}} \), which can be expressed according to the Kubo formula,25,26

\[
\sigma_{\text{intra}} = -\frac{ie^2}{\pi\hbar(\omega - 2i\Gamma)} \int_0^\infty \epsilon \left( \frac{\partial f_d(\epsilon)}{\partial \epsilon} - \frac{\partial f_d(-\epsilon)}{\partial \epsilon} \right) d\epsilon, \quad (1a)
\]

\[
\sigma_{\text{inter}} = \frac{ie^2}{\pi\hbar} \int_0^\infty \frac{f_d(\epsilon) - f_d(-\epsilon)}{\omega - 2i\Gamma - 4(\epsilon/h)^2} d\epsilon, \quad (1b)
\]

where \( e \) is the charge of an electron, \( \hbar \) is the reduced Planck’s constant, \( \omega = 2\pi\nu \) is the angular frequency, \( \Gamma \) is the phenomenological scattering rate, \( f_d(\epsilon) = 1/[e^{(\epsilon - E_F)/k_B T} + 1] \) is the Fermi-Dirac distribution, \( T \) is the absolute temperature, \( E_F \) is the Fermi level, and \( k_B \) is Boltzmann’s constant. The Fermi level of a graphene can be adjusted by many methods, including voltage biasing, exposure to magnetic fields, and/or chemical doping, which thus provide several avenues to deterministically control the electrical properties of the graphene.27

In this work, we assume that the environmental temperature is fixed at \( T = 300 \) K, and the phenomenological...
scattering rate is $\Gamma = 2$ THz. Under such assumption, Fig. 1(a) gives the graphene’s intraband, interband, and total complex conductivities as functions of Fermi level at $\nu = 160$ THz, with the conductivities in Eq. (1) being normalized to $s_0 = e^2/4\hbar$. It is seen that Re$(\sigma_{\text{intra}})$ attains a value close to zero, which implies that the real part of the graphene’s conductivity is dominated by the interband transitions. On the other hand, both the negative Im$(\sigma_{\text{intra}})$ and the positive Im$(\sigma_{\text{inter}})$ make contributions to the imaginary part of graphene’s conductivity, which result in a transition of Im$(\sigma)$ from positive to negative. It is also seen that an abrupt change in the conductivity curve at $EF = 0.33$ eV is approximately equal to $\hbar\omega_0/2$. A small shift of the Fermi level around this value will significantly change the conductivity of the graphene.

In an environment free of external magnetic fields, graphene has an isotropic conductivity profile, and its Fermi level $E_F$ is determined by the carrier density $n_i = (\pi^2v_F^2)^{-1}\int_0^{E_F} [f(p) - f(E + 2EF)]dp$, where $v_F \approx 9.5 \times 10^5$ m/s is the Fermi velocity. Under a DC bias voltage $U$, the carrier density of the graphene is given by the expression $n_i = Ue\varepsilon_{\text{SiO}_2}/e\varepsilon_{\text{SiO}_2}$ where $\varepsilon_{\text{SiO}_2}$ and $\varepsilon_{\text{SiO}_2}$ are the thickness and relative permittivity of the SiO$_2$ layer, and $\varepsilon_0$ is the permittivity of vacuum. Figure 1(b) shows the complex conductivity under various bias voltages of $U = 6.27$, 7.03, 8.27, and 10.07 V, corresponding to the Fermi levels $E_F = 0.33$, 0.35, 0.38, and 0.42 eV, respectively. A clear blue shift of the graphene’s conductivity is found when increasing the bias voltage. It is worth noting that the maximal bias voltage of 10.07 V, used in our work, generates a dielectric strength of SiO$_2$ (around 1 MV/mm). The operation voltage can be further reduced by proper chemical doping, which is not discussed in this letter.

Figure 2 schematically shows the unit cell of the considered Ag–SiO$_2$–Graphene–SiO$_2$–Ag 5-layer graphene-coupled fishnet metamaterial, with detailed geometrical dimensions listed in the caption. The fishnet pattern, which is periodic in the $x$ and $y$ directions, can be fabricated by the focused ion beam technique. We assume that the fishnet metamaterial is oriented in a coordinate system such that the incident light is along the $z$ direction with electric field polarized along the $y$ direction. In this case, the fishnet metamaterial is expected to have a left-handed resonance with a negative refractive index (NRI) band close to 160 THz.

We now numerically study the coupling between the single-layer graphene and the fishnet metamaterial. The full-wave numerical simulations are performed by commercial finite integration package CST MICROWAVE STUDIO. In our simulation, SiO$_2$ is considered as a nondispersive dielectric with relative permittivity $\varepsilon_{\text{SiO}_2} = 3.9$, and the relative permittivity of silver is fit by the Drude model, $\varepsilon_{\text{Ag}} = \varepsilon_\infty - \omega_p^2/(\omega^2 + i\gamma\omega)$, with $\varepsilon_\infty = 6$, $\omega_p = 1.5 \times 10^{16}$ rad/s and $\gamma = 7.7 \times 10^{13}$ rad/s. Graphene is a single-layer honeycomb of carbon atoms, which, in principle, is one-atom thick. However, to simplify the numerical simulations, we assume the graphene to be a homogenous medium with a very small thickness $t$. The effective permittivity of the graphene can therefore be given by $\varepsilon = 1 + i\sigma/(\omega\varepsilon_0 t)$. In our simulations, we choose the thickness of the graphene to be $t = 0.5$ nm and the relevant effective permittivities can be found from Fig. 1(c). By comparing Figs. 1(b) and 1(c), one can see that when the graphene’s conductivity has a positive (negative) imaginary component, the effective permittivity comes to be negative (positive), in which case the graphene behaves as a thin metal (dielectric) layer.

Figure 3(a) displays the simulated transmission spectra of the fishnet metamaterial with and without graphene. It is seen that a well known left-handed peak occurs at 157.5 THz for the fishnet metamaterial without graphene. Around this peak, the effective refractive index is expected to be negative. In the event that a free of bias voltage graphene layer is coupled to the fishnet metamaterial, the transmission spectrum (not shown) does not exhibit any difference from that of the bare fishnet metamaterial in the frequency range of interest. When a bias voltage is applied, an additional resonance appears in the transmission ($S_{21}$) curve due to the
intrinsic transition of graphene from dielectric status to metal status, and its resonant frequency blue shifts as the voltage increases. This intrinsic resonance is relatively weak where its frequency is far from the resonant frequency of the fishnet metamaterial [see the $S_{21}$ curves in Fig. 3(a) for $U = 6.27$ and 10.07 V], owing to the weak coupling between graphene and fishnet metamaterial. The graphene’s resonance is dramatically enhanced when its frequency is close to that of the left-handed peak [see the $S_{21}$ curves in Fig. 3(a) for $U = 7.03$ and 9.15 V]. At the same time, the left-handed peak gets weaker, due to the high intrinsic loss in the graphene. When the resonance of the graphene overlaps with the fishnet’s resonance, these two resonances merge into one and the total resonance strength is greatly reduced. It is seen from Fig. 3(a) that the left-handed peak becomes very weak in the $S_{21}$ curve for $U = 8.27$ V. It is also seen that the left-handed peak has a clear red shift from 157.5 to 155.1 THz when the bias voltage increasing from 0 to 7.03 V, in which case the transmittance does not show a significant reduction. This behavior is similar to that exhibited by tunable metamaterials based on liquid crystals\textsuperscript{12,13} or ferrites.\textsuperscript{16,17} Similar results can also be found in the numerical absorptivity curves shown in Fig. 3(b). Without graphene, the fishnet metamaterial shows a single absorption peak around 156 THz because of its strong left-handed resonance. Voltage biasing of graphene introduces another absorption peak, the frequency of which can be adjusted by varying the bias voltage. When the absorption peak induced by the graphene is far from the resonance of the fishnet metamaterial, the absorptivity is relatively weak. In particular, the peak values of the graphene-induced absorptivity are 0.13 and 0.27 when the bias voltages are $U = 6.27$ and 10.07 V, respectively. A higher absorptivity can be achieved when the graphene-induced absorption peak is close to that of the fishnet’s intrinsic resonance. It is seen that the peak absorptivities increase to 0.38 and 0.48 for the cases of $U = 7.03$ and 9.15 V, respectively. When the resonant frequencies of the graphene layer and the fishnet metamaterial coincide, the total resonance is significantly suppressed and the peak absorptivity reduces below 0.11.

In order to have a deep insight on the underlying physics of different variations of these two resonances, we assume that the graphene-coupled fishnet metamaterial is equivalent to a 220-nm-thick homogenous medium and the effective constitutive parameters of the metamaterial can be retrieved numerically using scattering parameters.\textsuperscript{31,32} Figures 3(c), 3(e), and 3(f) show the frequency dependencies of the real parts of the effective refractive index, permittivity, and permeability with and without graphene. It is seen that without graphene, the fishnet metamaterial has a NRI band with $\text{Re}(n) = -3.62$ centered at the frequency $\nu = 155$ THz, where the real components of both the effective permeability and permittivity are negative. The incorporation of graphene introduces another NRI band, which is highly sensitive to the bias voltage. For instance, a NRI occurs close to 137 THz for the voltage of 6.27 V. Different from the intrinsic NRI band of the fishnet metamaterial, in the frequency region of the graphene-induced NRI, the permittivity has a negative real component, while the permeability has a positive real component. Such a NRI of the metamaterial is accompanied by a high propagation loss and is therefore of poor use in practice.

In Fig. 3(d), we also plot the figure of merit (FOM) of the metamaterial, defined as $\text{FOM} = |\text{Re}(n)/\text{Im}(n)|$,\textsuperscript{33} which is one of the most important parameters for evaluating the lossy characteristics of NRI metamaterials. The higher FOM corresponds to the lower loss and better performance of the NRI metamaterial. As we can see, the peak value of FOM for the graphene-induced NRI band is as small as 0.16 for $U = 6.27$ V compared to FOM = 6.99 for fishnet metamaterial without graphene. This implies that the graphene-induced negative refraction is highly suppressed by the loss. It is also seen that when the resonance of graphene is close to that of the fishnet metamaterial, these two NRI bands merge into a single band and the NRI band becomes wider, while the absolute value of NRI reduces significantly. In particular, for the case of $U = 8.27$ V, the NRI is almost vanished, where the related FOM is as small as 0.10. Clearly, the effective constitutive parameters of the graphene-coupled fishnet metamaterial can be flexibly adjusted by varying the bias voltage.

In conclusion, an effective method for actively controlling optical metamaterial’s intrinsic resonances using graphene has been presented. Owing to its uniquely voltage...
controllable conductivity, graphene could significantly affect the resonant properties of the fishnet metamaterial at near-infrared frequencies. Especially, the resonant transmission, absorption, and the effective constitutive parameters of the graphene-coupled fishnet metamaterial can be dynamically controlled by an external bias voltage. Similar idea can also be applied to other types of optical metamaterials, which provides a powerful way for voltage control of plasmon resonance at optical frequencies and could enable exciting applications, such as atom-level plasmonic sensing and tunable subwavelength focusing.

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