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Tunable Broadband Reflective Filter Based on a Graphene-Dielectric Multilayers

Chunyu Li [a], Juan Wang [b], Tieyan Zhang [c], Lu Liu [d], Xiangxiao Ying [e] and Zhijun Liu*

School of Optoelectronic Science and Engineering, University of Electronic Science and Technology of China, Chengdu, Sichuan 610054, China

*Corresponding author: liuzhijun@uestc.edu.cn, [a]649377423@qq.com, [b]2421852566@qq.com, [c]2952648034@qq.com, [d]liululspring@qq.com, [e]456789ying_xiangxiao@163.com

Abstract. In this paper, we reveal tunable broadband reflective filtering property in graphene-dielectric multilayers using transfer matrix method and effective medium theory. A dramatic reflectance change from near-zero value to close-to-unit is shown to be achievable with its spectral band widely tunable from 3.5 μm to 21 μm by changing graphene Fermi energy. Our proposed multilayered graphene-dielectric metamaterial has great potential for developing tunable infrared filters and switches.

1. Introduction

Hyperbolic metamaterials, as a kind of uniaxial anisotropic metamaterials, have attracted a great deal of interest due to their potential applications in waveguiding, imaging, sensing and enhancing spontaneous emission [1]. Generally, these materials are characterized by a permittivity tensor of diagonal form $\overline{\overline{\varepsilon}}=\mathrm{diag}(\varepsilon_{xx},\varepsilon_{yy},\varepsilon_{zz})$ whose principal components have the opposite signs, i.e., $\varepsilon_{xx}=\varepsilon_{yy}>0$, $\varepsilon_{zz}<0$ (Type I), or $\varepsilon_{xx}=\varepsilon_{yy}<0$, $\varepsilon_{zz}>0$ (Type II) [2]. Traditional hyperbolic metamaterials are based on metal-dielectric multilayers and nanowire arrays, which have been realized across a broad electromagnetic spectrum [1-3]. Various interesting effects have been demonstrated, including subwavelength imaging [4-6], epsilon-near-zero property [7-9], and negative refraction [10, 11] etc. Considering the importance of multi-functional development of devices, tunable hyperbolic metamaterials have recently attracted a widespread attention as compared to previous static designs. In traditional multilayer structures, metal is used as negative permittivity material spaced by dielectric layers, overall creating a negative permittivity effect for the electric field components tangential to the layers. Graphene, which behaves as a tunable two-dimensional material, can substitute for the metallic layers in metal-dielectric multilayer structures. The charge carrier concentration or chemical potential of graphene can be tuned via voltage biasing or chemical doping [12, 13]. Prior studies have illustrated unique optical properties in graphene-dielectric multilayers, including tunable reflection and transmission [14-16], absorption [17-20], negative refraction [21, 22] and epsilon-near-zero property [23-25]. Recently, Kieliszczyk et al. presented an infrared spatial filter based on graphene-dielectric multilayers, whose bandwidth is dynamically controlled over 3-5μm spectral range [15]. Here, we further demonstrate that by properly designing the graphene material proeprties, the spectral filtering effect can be extanded to the far-infrared region of 3.5-21μm.

2. Structure design

Our considered graphene-dielectric multilayer structure is depicted in Figure 1(a). Its unit-cell is composed of a graphene monolayer and a dielectric spacer with thicknesses of t_g and t_d, respectively. The surrounding media are semi-infinite air ($\varepsilon = 1$). The in-plane permittivity of graphene can be written as [26]:

$$\varepsilon_g = 1 - j\frac{\sigma(\omega, \mu_c)}{\omega\varepsilon_0 t_g} \quad (1)$$

Where ε_0 is the vacuum permittivity and σ is the conductivity of a single-layer graphene, which is given by Kubo formula [26]

$$\sigma = -\mathrm{i}\frac{e^2 k_B T}{\pi\hbar^2\left(\omega - \mathrm{i}\tau^{-1}\right)}\left[\frac{\mu_c}{k_B T} + 2\ln\left(e^{\frac{\mu_c}{k_B T}} + 1\right)\right] - i\frac{e^2}{4\pi\hbar}\ln\left[\frac{2|\mu_c| - \left(\omega - i\tau^{-1}\right)\hbar}{2|\mu_c| + \left(\omega - i\tau^{-1}\right)\hbar}\right] \quad (2)$$

Where ω is the angular frequency, μ_c is the Fermi energy and τ denotes the electron scattering time. $k_B T$ Indicates the thermal energy of 26 meV taken at room temperature, e is the electron charge, $\hbar$ is the reduced Plank constant. Here, we assume the electron scattering time τ as 1 PS [23]. The out-of-plane permittivity of grapheme is 1. The dielectric constant of the spacer layer is taken to be 2.2, like the one of silica in [14].

The electromagnetic fields in each layer can be determined by the transfer matrix method (TMM) for isotropic homogeneous planar multilayers [27]. An algorithm has been formulated considering uniaxial anisotropic media for a multilayer slab using the effective medium theory (EMT) [2]. The effective medium theory method is a simple weighting of the permittivities parallel to the grapheme-dielectric interfaces ($\varepsilon_{//}$) and perpendicular to the interfaces ($\varepsilon_{\perp}$) which are given by [2]

$$\varepsilon_{//} = \rho\varepsilon_g + (1-\rho)\varepsilon_d \quad (3)$$

$$\varepsilon_{\perp} = \frac{\varepsilon_g \varepsilon_d}{\rho\varepsilon_d + (1-\rho)\varepsilon_g} \quad (4)$$

Where ε_d the permittivity of the spaer layer and the filling ratio is is $\rho = t_g / (t_g + t_d)$. Here, the thicknesses of the graphene and the dielectric spacer are assumed to be 1 nm and 20 nm, respectively. The reflectance of the graphene-dielectric multilayers can be calculated using both the TMM method and the EMT method.

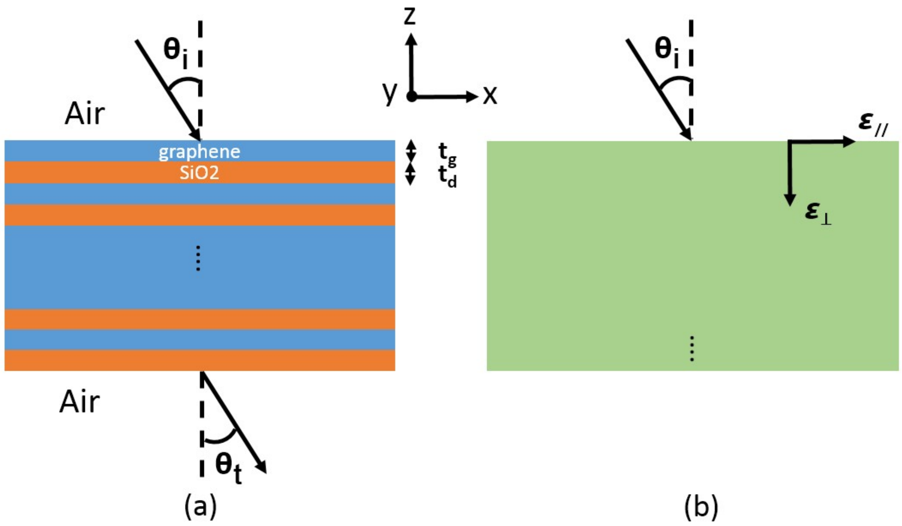

Figure 1. Schematic illustrations of (a) designed graphene-dielectric multilayers and (b) their equivalent effective medium as treated by EMT.

3. Results and discussions

Figure 2 shows the claculated reflectance of the graphene-dielectric multilayer structure with different numbers of units calculated by TMM (solid lines) and the EMT (dashed line). Here, the Fermi energy and electron scattering time of graphene are assumed to be 0.1 eV and 1 ps, respectively. As the numbers of units increase from 50 to 500, the reflection spectrum of the graphene-dielectric multilayers gradually approaches the result of EMT with minor deviations in the short wavelength region as resulted from the finite thickness of the material.

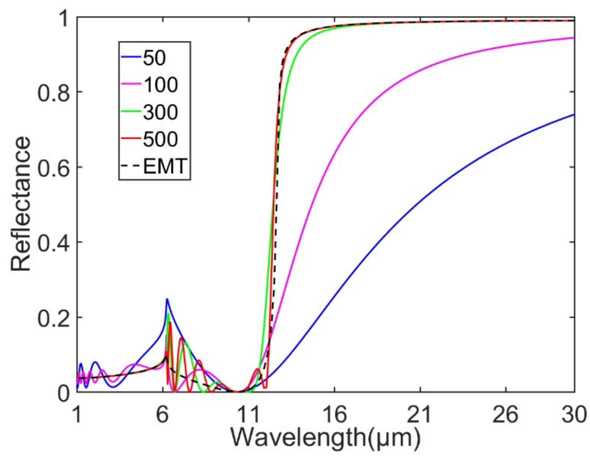

Figure 2. Calculated reflectances of the graphene-dieletric multilayer structure by using TMM and EMT.

We next investigated the filtering property the graphene-dielectric multilayers. Figure 3(a) shows the calculated reflectance of 500 units for different graphene Fermi energies. The reflection spectrum at each Fermi energy has close-to-zero reflectance at shorter wavelengths and a close-to-unit high reflectance at longer wavelengths, thus exhibiting a spectral filtering effect. The transition wavelength, at which the relfectance dramatically changes from near-zero to close-to-unit, shifts from 3.5 μm to 21 μm, as the Fermi energy of graphene decreases from 1 eV to 0.05 eV. Therefore, the reflective filtering property is widely tunable by changing the graphene Fermi energy. In order to better understand these phenomena, the permittivities parallel to the graphene-dielectric interfaces as a function of wavelength for different Fermi energies were calculated by using EMT as shown in Figure 3(b). Taking the Fermi energy to 0.1 eV as an example, the imaginary part of permittivity approaches zero and the real part is positive, forming an elliptic dispersion, which makes the material highly transparent in 7-12 μm spectral range. As the wavelength increases from 12 μm to 30 μm, the real part passes through the zero point and becomes a negative value, and the imaginary part gradually increases. Meanwhile, the permittivity perpendicular to the interfaces is a positive real value according to Eq. (4), thereby forming a hyperbolic dispersion (Type II) with high reflectance of the material. When the wavelength is less than 12 μm, it can be considered as a normal lossy material, leading to a low reflectance. Therefore the different characters of the effective permitivity explain the swicthing between low and high reflectances.

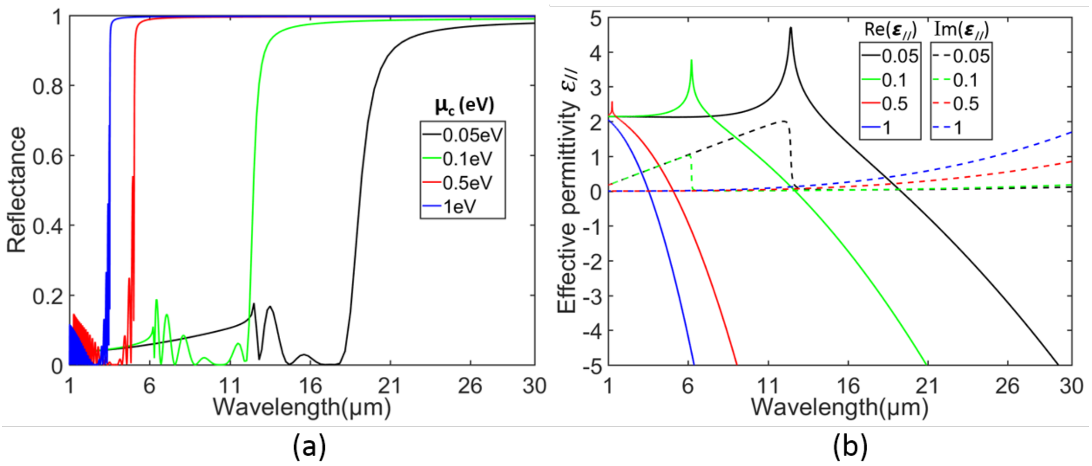

Figure 3. (a) Reflectances of the graphene-dielectric multilayers with 500 units and (b) their effective permittivities parallel to the graphene-dielectric interfaces for different graphene Fermi energies.

Finally, the effect of electron scattering time on reflection efficiency and modulation depth of the multulayer with 500 units were considered. Figure 4(a) shows the reflectances with different electron scattering times for the Fermi energies of 0.05 eV and 1 eV, respectively. It can be seen that the reflectance increases as the electron scattering time increases at the same Fermi energy. To more intuitively investigate the effect of electron scattering time on the reflective filtering characteristics of the material, we calculated the modulation depth corresponding to the different electron scattering time in Figure 4(a) as shown in Figure 4(b). As the electron scattering time increases from 30 fs to 1.5 ps, the modulation depth remains over 0.85 and increases from 0.86 to 1. Thus, our designed hyperbolic metamaterial can achieve a high modulation efficiency with a low quality graphene in practice.

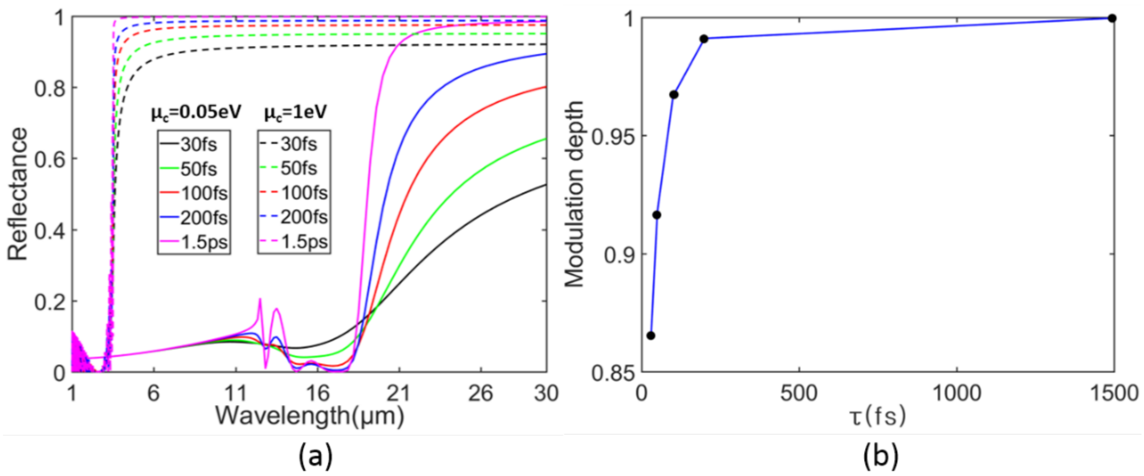

Figure 4. Calculated (a) reflectanes and (b) modulation depths of the graphene-dielectric multulayer for different electron scattering times.

4. Conclusion

In conclusion, tunable broadband reflective filtering properties have been revealed in graphene-dielectric multilayers. The spectral filtering band can be dynamically tuned from 3.5 μm to 21 μm by changing the Fermi energy from 1 eV to 0.05 eV. We also showed that a larger electron scattering time of graphene benefit the reflection efficiency and modulation depth. Our proposed graphene-dielectric multilayers have potential applications for developing tunable reflective infrared filters and switches.

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