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Original research article

Dual-band enhanced optical absorptance of graphene with resonant tunneling in total internal reflection regime

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ABSTRACT

We propose a stratified structure, where the monolayer graphene is sandwiched between two thin film stacks with optimized period number. A band-pass filter based on the stratified structure is realized. The dual-band enhanced optical absorptance of graphene with resonant tunneling in total internal reflection (TIR) regime is investigated theoretically. Both absorptance peaks are enhanced up to almost 100% in the pass-band filter based on resonant tunneling through a graphene sheet over the communication wavelength range due to the strong light field confinement. With the increasing of the bottom mirror layers, the values of the dual-band absorptance peaks improve accordingly while the peak locations are unchanged. The variation of the angle and wavelength can be exploited to realize tunable filters with good rejection.

1. Introduction

Band-pass filters (BPFs) have attracted research interest as a promising platform in optics and photonics [1–3]. A BPF is a device that passes frequencies within a certain range and rejects frequencies adjacent to that range. A BPF is characterized by many factors, such as pass-band shape and spectral bandwidth, the value of peak within the pass-band, out-of-band rejection and out-of-band blocking range [4]. BPFs are usually required for high power-handling capability and good rejection over the communication wavelength range, especially in the application of laser-based super continuum sources [5]. An ideal BPF would have a completely flat pass band (e.g. with no gain/attenuation throughout) and would completely attenuate all frequencies out of the pass band range, while the transitional width out of the pass band would be rather small.

Graphene, a truly two-dimensional honeycomb gapless semiconductor [6,7], has been recognized as a revolutionary material for potential optoelectronic applications due to its wide range of unique physical properties [8]. However, Monolayer graphene has a wavelength-independent low absorptivity of about 2.3% in the visible and near-infrared (NIR) wavelength range [9–12]. Graphene can be deposited between some dielectric thin materials to enhance the absorptance of graphene [13], with the development of ion-beam sputtering in techniques [14–16].

In the present paper, we describe a design procedure to combine the BPF and graphene, and show experimental results for a BPF based on resonant tunneling in TIR regime with a single embedded graphene layer. The filter consists of two nominally identical thin film stacks with different period number. The dual-band and perfect optical absorptance of graphene has been

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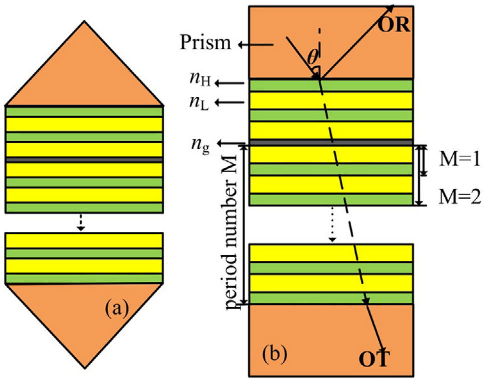

Fig. 1. (a) Schematic of the TIR regime with the monolayer graphene sandwiched between two mirror layers with optimized pair number. (b) It shows a representative structure with more details. In the structure, the dark gray region represents a monolayer graphene, green and yellow regions mean the high refractive material and low refractive material layers, respectively. The orange regions represent the two identical prims at the input and output, which is used to couple the incident light into the multilayer structure. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

attained with transfer matrix method (TMM). It is theoretically investigated that the number of bottom mirror layers in the graphene-based BPF has a great influence on the optical absorptance in the TIR regime. Furthermore, the combined effect of angle/refractive index and wavelength on the enhancement absorptance of graphene in the stratified filter structure has been shown in TIR regime.

2. Theoretical background

The proposed filter structure is illustrated in Fig. 1 (a). The two identical prisms are standard glass prisms and convenient to the light with the incidence angle of 45° [13]. For off-normal incidence, the method of tilted admittance can be used to describe the film properties easily [17,18]. A monolayer graphene is embedded between two thin film stacks with different number of pairs. Each pair comprises alternative layers of high and low reflective dielectric material. Consider the representative structures shown in Fig. 1 (b), they refer to a Si layer and a SiO_2 layer, and other material combinations may be suitable as well. Each thin film is typically a quarter-wave stack Bragg mirror at a specified angle of incidence. The thickness of Si and SiO_2 layers are determined by the quarter-wave condition $n_L d_L = n_H d_H = \lambda_{res}/4$, where λ_{res} is the center wavelength of the resonant region. And n_L (n_H) is the refractive index of the SiO_2 (Si) layer at λ_{res}, respectively. In our structure, the multilayer thin films play a very significant role in making admittances (η) in prism and graphene to match well with each other. When a quarter-wave layer of admittance η_j added to the prism with admittance η_{in}, the admittance of the front surface is getting to ($\eta_j{}^2/\eta_{in}$) [2]. If the first layer is high refractive material (η_H), the second low refractive material (η_L), and then alternating high and low admittance layers are added, the front-surface admittance evolves as (η_{H2}/η_{in}), ($\eta_{L2}\eta_{in}/\eta_{H2}$), ($\eta_{H4}/\eta_{L2}\eta_{in}$), etc. Lossless materials with real refractive indices are assumed for simplification. In that case, the tilted admittance η_j for TE and TM polarized light in medium j can be expressed as $n_j\cos\theta_j$ and $n_j/\cos\theta_j$, respectively. Here, n_j is the refractive index, $\theta_j = sin^{-1}\{(n_{in}/n_j)\sin\theta_{in}\}$ is the propagation angle from Snell's law, and n_{in} and θ_{in} are the refractive index and angle in the incident medium. Furthermore, the phase thickness of a given layer is given by $\delta_j = (2\pi/\lambda)n_j d_j \cos\theta_j$, where λ is the free-space wavelength and d_j is the physical thickness of the layer[19]. If a thin film stack is suitable for admittance-match light with one polarization state (TE/TM), the other polarization state will be highly mismatched.

According to the TMM, we analysis the absorptance of graphene at any position based on the electromagnetic boundary conditions that Maxwell's equations required. The filter structure is incident by a light beam with a certain angle. The electric field in the condition of TE polarization is given by

$$\hat{E}(\mathrm{x},\mathrm{z}) = (A\mathrm{e}^{\mathrm{i}k_z \mathrm{z}} + B\mathrm{e}^{-\mathrm{i}k_z \mathrm{z}})\,\mathrm{e}^{-\mathrm{i}k_x \mathrm{x}}\hat{e}^{\mathrm{y}}, \tag{1}$$

and the magnetic field in the condition of TM polarization is given by

$$\hat{H}(\mathrm{x},\mathrm{z}) = (A\mathrm{e}^{\mathrm{i}k_z \mathrm{z}} + B\mathrm{e}^{-\mathrm{i}k_z \mathrm{z}})\,\mathrm{e}^{-\mathrm{i}k_x \mathrm{x}}\hat{e}^{\mathrm{y}}, \tag{2}$$

where$\mathrm{k}_z = \sqrt{\left(w/c\right)^2\varepsilon - \mathrm{k}_x{}^2}$ is the z component of multilayer structure and $\mathrm{k}_x = k_0\sin\theta$ is the transverse wave vector component that persevered across all in terfaces. TE/TM polarization is the component of the electric/magnetic field parallel to the interface of any thin film layer. The propagation matrix is given by

$$P_l = \begin{bmatrix} \exp\left(-ik_{l,z}d_l\right) & 0 \\ 0 & \exp\left(ik_{l,z}d_l\right) \end{bmatrix}. \tag{3}$$