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Electrically tunable switching based on photonic-crystal waveguide loaded graphene stacks

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ABSTRACT

Through applying gate voltage to tune the chemical potential of graphene, the relative permittivity of multilayer graphene/Al_2O_3 stack can be dynamically adjusted over a wide range. In this paper, we mainly design novel photonic-crystal waveguides based on graphene stacks including a side-coupled waveguide with two defect cavities as well as a two-channel multiport waveguide, and aim to modulate the propagation of incident light wave via controlling the permittivity of graphene stack. It is demonstrated according to simulations that tunable switching property can be achieved in our proposed structures, such as blue shift of resonant stopband, adjustable coupled-resonator-induced transparency, and tunability of output quantity. These results could be very instructive for the potential applications in high-density integrated optical devices, photoelectric transducer, and laser pulse limiters.

1. Introduction

In the last decade, silicon has been the material of choice of the photonics industry due to its easy integration with silicon electronics as well as its optical transparency in the near-infrared telecom wavelengths [1]. Composed by periodical silicon medium elements, 2D photonic crystals have inspired great interests for optical communication because of their potential ability to control the propagation of light [2,3]. A significant application is formed by removing a specific row of elements to realize guiding and trapping light wave in the remaining empty space, which is called photonic-crystal waveguide (PCW) [4]. So far, embed reflectors or side-coupled cavity into PCWs is a effective method to control the resonant frequency either toward or away from the signal frequency [5,6] and obtain a ideal on/off switching property. However, it is difficult to vary the optical dispersion relations, symmetries, and spatial distribution [7,8] after fabrication, which means the switching property is just appropriate for the constant frequencies once the physical parameters of PCWs are fixed.

Since its discovery in 2004, graphene, a single two-dimensional plane of carbon atoms arranged in a honeycomb lattice, has raised much concern due to its unique atomic thickness, electrical, and thermal properties [9]. Especially, graphene has been found to support surface plasmons at THz and optic frequency ranges and to show lower Ohmic loss compared to conventional noble metal [10], meanwhile its conductivity can be tuned under electric/magnetic biasing or chemical doping [11–13]. Thus, these excellent metal-like characteristics make graphene be promising for the design of tunable photoelectric devices. For example, Pan et al. designed a hybrid modulator implemented by a compact photonic crystal nanobeam cavity coupled to a bus waveguide with monolayer graphene on top, made it possible to vary the quality factor and resonance wavelength through applied current [11]. Qi et al. realized the electrically tunable switching based on multimode interference effect in dielectric loaded graphene plasmon waveguide [12]. However, it is still generally believed that monolayer graphene does not conduct well enough to used for the modulation of light wave, since it is too thin to sustain an intense resonance [13]. Besides, the surface defects could probably cause electrons to deflect and back scattering, leading to an increase of resistance in silicon waveguides.

It is indicated that the distributing Dirac fermions in monolayer graphene disks into multiple layers of closely stacked graphene disks can drastically increase the plasmonic resonance [14–16]. Thereby, we propose electrically tunable switching based on PCW loaded multilayer graphene/Al_2O_3 stacks over the infrared region in this paper, including a PCW with two side-coupled cavities as well as a two-channel multiport PCW. With the capacity of tuning the permittivity of graphene stacks over a wide range, we can modulate the propagation of light wave effectively in our proposed structures, which also shows a good adjustable switching property.

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2. Theoretical analysis and device structures

To prove the feasibility of our proposed PCWs as tunable optic switching, we firstly analyze the electrical tunability of the permittivity of graphene stacks in theory. In general, the monolayer graphene is electrically modeled either as a 2D infinitesimally thin conductive layer by the complex surface conductivity σ_g [17], or as a 3D actual medium by the permittivity ε_g [18]. The relationship is $\varepsilon_g = 1 + j\sigma_g/\omega\varepsilon_0 h_g$, where ω is the angular frequency of incident wave, ε_0 is the permittivity of air, h_g(~1 nm) is the thickness of monolayer graphene. In terms of conductivity, σ_g can be calculated as $\sigma_g = \sigma_{\text{intra}}(\omega) + \sigma_{\text{inter}}(\omega)$, which contains two contributed portions [19–21]: $\sigma_{\text{intra}}(\omega)$ represents absorption due to intraband electron–photon scattering, while $\sigma_{\text{inter}}(\omega)$ is caused by interband electron transition process. Their expressions are given by [20]

$$\sigma_{\text{intra}}(\omega) = j\frac{q^2}{\pi\hbar\left(\hbar\omega + j\Gamma_c\right)}\left[\mu_c + 2k_B T\ln\left(e^{-\mu_c/k_B T} + 1\right)\right], \tag{1}$$

$$\sigma_{\text{inter}}(\omega) = j\frac{q^2}{4\pi\hbar}\ln\left[\frac{2|\mu_c| - \left(\hbar\omega + j\Gamma_c\right)}{2|\mu_c| + \left(\hbar\omega + j\Gamma_c\right)}\right], \tag{2}$$

where q is the charge of electron, $\hbar$ is the reduced Planck constant, k_B is the Boltzmann constant, and μ_c is the chemical potential of graphene. Γ_c represents the damping constant which can be defined as $\Gamma_c = q\hbar v_f^2/\mu\mu_c$, where v_f(~ c/300 m/s) is the Fermi velocity and μ(~10 000 cm^2/Vs) is the electron mobility [22]. Hence, it is clearly seen from Eq. (1) and (2) that the conductivity of monolayer graphene is in connection with its chemical potential.

As shown in Fig. 1(a), through alternately coating the dielectric Al_2O_3 layer and monolayer graphene, we can obtain the multilayer graphene/Al_2O_3 stack with desirable shapes such as cylinder or cuboid. While in Fig. 1(b), the graphene layers are separated by Al_2O_3 layers with thickness h_d(~100 nm) and relative permittivity ε_d(~4.9). In addition, h_d is deep subwavelength but is still thick enough to avoid the interaction between graphene layers (e.g., interlayer transitions). Under this assumption, effective medium theory can be utilized for the characterization of graphene stacks [23]. Considering the fact that graphene layers have negligible thickness meanwhile the graphene stack is an anisotropic uniaxial medium, thereby the components of its relative permittivity can be expressed as [24,25]

$$\varepsilon_{\parallel} = \varepsilon_d + \frac{i\sigma_g(\omega)}{\omega\varepsilon_0 h_d},$$
$$\varepsilon_{\perp} = \varepsilon_d, \tag{3}$$

where $\varepsilon_{\parallel}$ and $\varepsilon_{\perp}$ are the permittivity components of graphene stack parallel and perpendicular to the graphene surface, respectively. That means the graphene stack is isotropic in horizontal direction while anisotropic in vertical direction. On the basis of Eqs. (1) to (3), $\varepsilon_{\parallel}$ can be directly controlled by varying the chemical potential of graphene while $\varepsilon_{\perp}$ is equivalent to the permittivity of Al_2O_3. Furthermore, the relationship between the chemical potential of graphene and applied voltage can be denoted by the formula [26]

$$\mu_c = \hbar v_F\sqrt{\pi\left(n_0 + \frac{C|V|}{q}\right)}, \tag{4}$$

where v_F is the Fermi velocity for graphene and C is the effective capacitance per unit area, V is the biased voltage, n_0 is the intrinsic carrier concentration, and q is the charge of electron. It is verified from Eq. (4) that improving the gate voltage could result in a enlargement of the chemical potential of graphene. Therefore, the permittivity of graphene stack can be conveniently modulated by the gate voltage, makes it possible to use the graphene stacks as a promising candidate for the application of electrically tunable switching.

According to the theoretical analysis above, we design a PCW consists of two side-coupled defect cavities which is schematically visualized in Fig. 2(a). In general, the side-coupled defect cavity is created by removing the center cylindrical element [27], but in our proposed PCW, two graphene stacks are severally embedded into the defect cavities. The photonic crystal array is made up by the square lattice of silicon rods with lattice constant d, while cavities are placed at a distance $2d$ away from the center of PCW. Fig. 2(b) shows the section-view along the red dashed line as plotted in Fig. 2(a), the radius of silicon rods and graphene stacks are defined as r_1 and r_2 respectively, and the distance between two cavities in x-$axis$ is equal to $4d$. In the xoy plane, the light wave is incident from the excitation port with the width $2d$ and transmits in the PCW along z-$axis$ as illustrated in Fig. 2(c). Meanwhile, silicon is considered to be a non dispersive dielectric material with a relative permittivity of 11.9 in the mid-infrared spectral region.

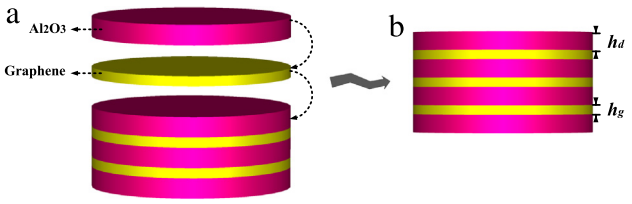

Fig. 1. (a) Fabrication process of graphene stack: coat the Al_2O_3 layer and monolayer graphene alternately. (b) Side view of graphene stack.

To demonstrate the feasibility of electrically tunable switching property based on the side-coupled PCW loaded graphene stacks, the perturbation theory is introduced. Assume that E_0, H_0, and ω_0 represent E-field intensity, H-field intensity, and eigenfrequency of cavity before perturbation, while E, H, and ω is corresponding to values after perturbation. Since the perturbation caused by the change of relative permittivity of graphene stacks is tiny enough, we can consider that the field intensity distribution in resonant cavity is invariable consistently before and after perturbation. In this case, the relationship between ω and ω_0 can be written as

$$\frac{\omega - \omega_0}{\omega} \approx -\frac{\iiint_V\left(\Delta\varepsilon|E_0|^2 + \Delta\mu|H_0|^2\right)dV}{\iiint_V\left(\varepsilon|E_0|^2 + \mu|H_0|^2\right)dV}, \tag{5}$$

where ε and μ is the relative permittivity and permeability of dielectric material, $\Delta\varepsilon$ and $\Delta\mu$ is the variation on account of perturbation, V is the volume of resonant cavity. The resonant frequency of incident light wave in PCW almost coincides with the eigenfrequency of the localized cavity mode of an isolated cavity [28]. Thus, it can be verified through the perturbation theory that the transmission of incident wave can be modulated distinctly by controlling the permittivity of graphene stack with applied voltage, which enables the adjustable switching capacity based on side-coupled PCW.

Furthermore, since the graphene stacks can also be directly utilized in rectangular waveguide and dynamically tune the cut off frequency [29,30], we also design a two-channel multiport PCW based on graphene stacks with the aim to modulate the incident wave export from specified output waveguides. The schematic view of the proposed multiport PCW is plotted in Fig. 3. Two pairs of graphene stacks ($Gs1$, $Gs2$, $Gs3$, $Gs4$) with radius r_3 are placed at the middle of interfaces between input waveguide and two output waveguides, $Gs1$ and $Gs2$ correspond to output waveguide A while $Gs3$ and $Gs4$ correspond to output waveguide B. The structural parameters of silicon rods and lattice constant are equal to the definitions in Fig. 2.

3. Simulation results and further discussion

Using rigorous finite element method implemented in the COMSOL Multi-physics commercial software, the transmission coefficient of PCW coupled with two graphene stack cavities as shown in Fig. 2 is calculated over the wavelength range from 1230 nm to 1335 nm. Meanwhile, to draw a comparison, the usual PCW with no cavity is also discussed as