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All-optical high performance graphene-photonic crystal switch

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ABSTRACT

The all-optical switch is realized based on nonlinear transmission changes in Fano resonance of 2D photonic crystals (PhC) which enhances the light intensity on the graphene in PhC; and in this study, the graphene layer is used as the nonlinear material. The refractive index change of graphene layer leads to a shift in the Fano resonance frequency due to the input light intensity through the Kerr nonlinear effect. Through finite-difference time-domain simulation, it is found that the high performance of all-optical switching can be achieved by the designed structure with a threshold pump intensity as low as MW/cm^2. This structure is featured by optical bistability. The obtained results are applicable in micro optical integrated circuits for modulators, switches and logic elements for optical computation.

1. Introduction

Optical switches are among the most important devices in optical integrated circuits technology. Designing these devices with high efficiency, fast responsiveness and low power consumption is of major interest in scientific community [1]. In recent years, due to its special ability in tuning its absorption and refractive index by nonlinear effects and ultrafast response, graphene has become the focus of attention in designing optical switches [2–5]. The outstanding properties of graphene allow multiple functions of signal emitting, transmitting, modulating, and detection to be realized in one material [6]. A graphene monolayer has a constant absorption of 2.3% over a wide spectral range from UV to far infrared and microwave [7,8]. Although the Kerr nonlinearity of graphene is high ($n_2 \approx 10^{-7}\ cm^2/W$) over a broad spectral range, the thickness of single layer of graphene is low ($\sim$0.34 nm); therefore, graphene-based modulators and switches need high input intensity [9]. Li et al. illustrated that a graphene-clad microfiber all-optical modulator can achieve a modulation depth of 38% and a response time of ~2.2 ps that needs an input power density as high as $\sim GW/cm^2$ [10].

In this study, the Fano resonance property of photonic crystal is used to reduce the input intensity and power consumption and to enhance light intensity and the nonlinear effect of graphene. Photonic crystal is a periodic arrangement of dielectric materials, which molds the flow of light [11].

Due to the nonlinear effect of graphene, its refractive index will change by increasing input intensity, Fano resonance frequency, which has high sharpness, changes thus affecting the transmission of the device. In this article, based on 2D photonic crystal and monolayer of graphene, an all-optical switch, which has a modulation depth as high as 90% with an input intensity as low as $\sim MW/cm^2$, is designed.

The transient state of this structure is assessed and its optical bistability is examined. Optical bistability is an interesting phenomenon exhibited by a certain resonant optical structure with the possibility of having two stable steady transmission states for the device depending upon the history of the input [12]. Due to Fano resonance sharpness and high Kerr nonlinearity of graphene, this structure demonstrates a hysteretic behavior. A bistable device may be applied for all-optical switching, optical transistors, and optical memories, which can be used for high-speed processing of optical signals, thus providing a promising alternative to their electronic counterparts [13].

A finite-difference time-domain (FDTD) method is used to indicate that photonic crystal provides appropriate conditions in obtaining an all-optical switch by tuning the refractive index of graphene layers through Kerr nonlinear effect.

2. Theory

The investigated structure is shown in Fig. 1, consists of silicon photonic crystal on SiO_2 substrate. The 2D PhC consists of cylindrical air holes with $2r$ diameter and a depth of h. Graphene is located on SiO_2 substrate in air holes. The filling factor

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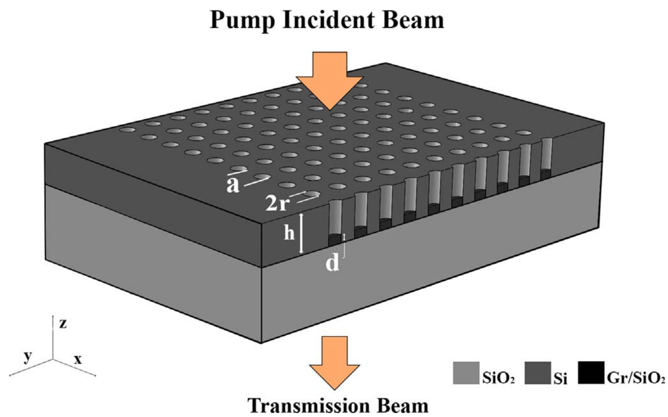

Fig. 1. Schematic representation of the studied structure. The designed structure consists of the 2D PhC, which is illuminated vertically. The PhC has a rectangular lattice with a lattice constant that includes a cylindrical air hole with 2r diameter.

$\left(F = 1 - \pi r^2/a^2\right)$, the thickness of Si layer in the PhC are 0.924, h=0.135a, respectively, where a is the period of PhC that is considered to be a ≈ 0.74 µm for operation at the optical communication wavelength at λ=1.5 µm. In order to achieve a sharp Fano resonance, the input light should have the well coupling in the Si photonic crystal waveguide. On the other hand, Fano resonance should have well shifting by refractive index change of graphene; hence, by changing h and F in the range of [0.02a, a] and [0.33, 0.96], respectively, the thickness and filling factor of Si are optimized to yield the well shifting and maximum quality factor for normalized frequencies ($f = a/\lambda$) in the range of [0.2–0.9].

For this simulation, a 3D FDTD code with uniform mesh size of 10 nm in x, y direction with periodic boundary condition; and 20 nm in z direction with perfectly matched layer boundary condition are applied. The dielectric constant of Si and SiO_2 are taken as 12 and 2.1, respectively.

Graphene is electrically modeled through the local isotropic sheet conductivity $\sigma=\sigma'+i\sigma''$, which provides both the inter-band and intra-band contributions to the total electronic transport [14]. The sheet conductivity σ is computed through the Kubo formula, which yields a function of frequency, ω and temperature, T. The real conductance of a graphene monolayer can be calculated as follows [15–17]:

$$\sigma(\omega) \approx \frac{\sigma_0}{2}\left[\tanh\left(\frac{\hbar\omega+2E_F}{4K_BT}\right) + \tanh\left(\frac{\hbar\omega-2E_F}{4K_BT}\right)\right] \tag{1}$$

$$\sigma_0 = \frac{e^2}{4\hbar}=6.08\times10^{-5}\,\Omega \tag{2}$$

where, E_F, T, K_B and ω are the graphene Fermi energy, temperature, Boltzmann constant and angular frequency, respectively. By considering E_F=0, T=300K and λ=1550 nm, we have:

$$(\sigma - \sigma_0)/\sigma_0 \ll 1 \tag{3}$$

so, in this simulation, we consider

$$\sigma=\sigma_0 \tag{4}$$

From the obtained optical conductivity, the dielectric constant of graphene can be calculated as follows [17,18]:

$$\varepsilon_g=1+i\frac{\sigma}{\omega\varepsilon_0 d_g} \tag{5}$$

where, d_g=0.34 nm and ε_0 are the thickness of graphene and vacuum permeability, respectively.

Since a layer of graphene is very thin [16] requiring a high memory space and a long processing time for simulation, it is replaced with an equivalent composite layer having an equivalent dielectric constant.

Because a single graphene sheet is very thin, the conduction current is always along the sheet. Hence, the permittivity experienced in z-directed electric field is not affected by graphene, which leads to:

$$\varepsilon_z = \varepsilon_d \tag{6}$$

The relative effective permittivity parameter for transversely (TE) polarized field, is considered as [18]:

$$\varepsilon_t = \varepsilon_t' + i\varepsilon_t'' = \varepsilon_d + i\frac{\sigma}{\omega\mathcal{E}_0 d} = \varepsilon_d + i\frac{\sigma}{\omega\mathcal{E}_0 d_g}\rho \tag{7}$$

where, ε_d, d and ρ=d_g/d are the SiO_2 dielectric constant, thickness of the composite layer and volume contribution of the graphene inside the composite layer, respectively. The thickness of composite layers located in cylindrical air holes on SiO_2 substrate are considered as d=20 nm.

The nonlinear refractive index of graphene is a function of light incident intensity presented as:

$$n(I) = n_{0g} + n_2 I \tag{8}$$

where, n_{0g} is the refractive index of graphene in low intensity and n_2=10^{-7} cm^2/W. The increment of the equivalent dielectric constant of this composite layer is calculated through:

$$\Delta\varepsilon_c = \rho\Delta\varepsilon_g \tag{9}$$

where, $\Delta\varepsilon_g$ can be obtained through:

$$\Delta\varepsilon_g=\Delta n_g^2-\Delta k_g^2 \tag{10}$$

where, k_g is the imaginary part of graphene refractive index.

In this simulation, the absorption saturation is neglected. It is noted that due to saturation, with an increase in intensity, absorption is reduced; that is, Δk_g^2<0, which leads to $\Delta\varepsilon_g$>Δn_g^2. This means that considering the saturation absorption leads to larger $\Delta\varepsilon_g$ and slightly improves the switch performance.

The increment of the dielectric constant of the graphene is a function of incident light intensity:

$$\Delta\varepsilon_g = \varepsilon_g(I) - \varepsilon_g(0) \approx n_g^2 - n_{0g}^2 \tag{11}$$

where, $\varepsilon_g(I)$ and $\varepsilon_g(0)$ are the graphene dielectric constant for I, 0 incident light intensities, respectively. Using Eqs. (8)–(10), the refractive index of the composite layer yields:

$$n_c^2(I) = n_{0c}^2 + \left(n_2^2 I^2+2n_{0g}n_2 I\right) \times \rho \tag{12}$$

where, $n_c(I)$ and n_{0c} are the refractive indices of the composite for incident light intensities I and 0, respectively.

3. Design the switch

At first, this simulation is conducted without considering nonlinear effects for determining the appropriate photonic crystal-graphene structure and the Fano resonance frequency. For this purpose, the PhC is illuminated with a plane wave and a polarization orienting in x-y plane. By changing the height and filling factor of PhC, a sharp Fano resonance frequency is obtained with the high ratio of maximum to minimum in transmission. The power transmission coefficient from top to bottom in the PhC versus normalized frequency (a/λ) is shown in Fig. 2.

In Fig. 2, a few Fano resonances are observed. A Fano resonance is considered around f = 0.493 (for λ=1.5 µm, the a must be ~740 nm), which has the high ratio of maximum to minimum and