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Graphene-supported high-efficient modulation based on electromagnetically induced transparency in silica microcavity

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ABSTRACT

The combination of graphene and high quality (Q) factor microcavity provides a promising way for realizing high-efficient modulation. In this paper, an electro-optic tuning of a graphene–silica microdisk is investigated. Two graphene flakes, separated by Al_2O_3 isolation layer, are embedded in the silica microdisk to significantly enhance the light-matter interaction for the achievement of high-efficient modulation. Maximal resonant wavelength shift of 9.5 nm is presented as the bias voltage of about 189.5 V is applied on the graphene flakes, which is beneficial for realizing the optical modulation with the extinction ratio of about 16 dB. In addition, two partially reflecting elements are embedded in the waveguide which is side-coupled with the microcavity for realizing the electromagnetically induced transparency (EIT), subsequently achieving the high-efficient modulation with the extinction ratio of about 33.3 dB. Meanwhile, it is found that the 3 dB modulation bandwidth, maximum of as high as 58.1 GHz, gradually decreases as the thickness of Al_2O_3 isolation layer is reduced. As the potential applications, this improved study of graphene–silica microdisk opens up great potential for realizing high-efficient electro-optic devices such as modulator, optical switch and ultra-short pulsed laser.

1. Introduction

The optical modulator plays a crucial role in the integrated photonics, such as optical interconnect, biosensing and signal processing [1]. So far, various kinds of optical modulators with different modulation mechanisms, such as electro-optic effect [2,3] and thermo-optic effect [4], have been researched to modify the amplitude, phase and polarization of light. However, the conventional optical modulators suffer from narrow operating band, slow response time and high insertion loss, which limit their extensive application. Graphene with unique properties, such as ultra-high carrier mobility [5], electrically controllable conductivity [6,7], broad operation bandwidth and nonlinear saturable absorption [8], is considered as a potential material for the broadband optical modulation. For example, thermo-optic graphene modulators have been researched, which the corresponding refractive index could be changed by varying the surrounding temperature [9,10]. However, relatively slow thermal diffusivity limits the operating bandwidth of thermo-optic modulators.

Generally, electro-optic effect is one of the most popular methods for the high-speed optical modulator. By applying a bias on graphene, a high-speed broadband electro-optic modulator with the modulation bandwidth of 1 GHz is demonstrated based on the graphene–silicon waveguide in 2011 [11]. Thereafter, various kinds of electro-optic graphene modulators have been presented, combining with different materials such as silicon and silicon nitride and different structures including waveguide, photonic crystal cavity and microring resonator [12–15]. However, ~2.3% absorption of the monolayer graphene limits the light-matter interaction for the hybrid structure of graphene and waveguide, resulting in the low modulation depth [16]. Photonic crystal cavity and whispering-gallery mode (WGM) microring resonator could enhance the interaction between graphene and light. Recently, WGM silica microcavities with high-Q factors and small mode volumes, such as microdisk and microtoroid, have been widely researched in a variety of fields, including cavity optomechanics, microlasers and biosensors [17–19]. Therefore, combining graphene and these WGM silica microcavities is also a potential way for the realization of high-efficient modulation.

In this paper, an improved method based on a graphene–silica hybrid structure for the electro-optic modulation is devised and numerically studied. The proposed structure combines graphene and high-Q silica microdisk in a single device. The variation of effective mode index of

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the hybrid structure is researched by the finite element method. By electrically adjusting the chemical potential (ranging from 0.43 eV to 1 eV) of the graphene, resonant wavelength (maximal shift of 9.5 nm) of the silica microdisk could be strongly modulated, which is beneficial for realizing the optical modulation with extinction ratio of about 16 dB. In addition, two partially reflecting elements are embedded in the waveguide that is side-coupled with the microcavity for realizing the EIT-like effect, subsequently achieving the high-efficient modulation with the extinction ratio of about 33.3 dB. Meanwhile, it is found that the 3 dB modulation bandwidth, maximum of as high as 58.1 GHz, gradually decreases as the thickness of Al_2O_3 isolation layer is reduced.

2. Device structure and simulation

The 3-D view and the corresponding enlarged cross-section of the proposed graphene–silica hybrid structure are illustrated in Fig. 1(a) and (b). The silica microdisk with the silica thickness of 400 nm and the diameter of 80 μm can be fabricated by several steps such as photolithography, buffered HF etching, and XeF_2 etching [20]. Thereafter, two CVD prepared graphene flakes, separated by a 50 nm thick Al_2O_3 dielectric layer with the permittivity of 1.78^2 [13], are transferred on the microdisk to form a capacitor structure by using the methods such as the wet process method or the all-dry alternative transfer method [21,22]. Importantly, graphene and Al_2O_3 dielectric layer are circled on the microdisk for the ultra-strong enhancement of light-matter interaction while still maintaining a relatively high quality factor for the silica microdisk. Another silica film with the thickness of 400 nm and the width of 6 μm is grown on the graphene flake, which is sufficient wide to avoid the influence of electrode on the whispering-gallery mode. Two 5 nm thick Al_2O_3 isolation layers are respectively used to isolate the upper and lower graphene flakes from the silica microdisk. The metal palladium and Au with the thicknesses of respectively 30 nm and 50 nm are successively deposited on the graphene to act as the electrodes owing to the very low Pd/graphene contact resistance at the room temperature [23]. Two electrodes and upper silica are 0.5 μm away from each other. The electrode is crucial for the *RC* time constant of the device, which limits the modulation speed. In addition, we believe that the future experimental fabrication of this hybrid structure could be realized by the current nanofabrication and micromanipulator technology, which several similar experiments have been realized for the modulation based on microring cavities coated by the graphene with electro-optic effect such as the Ref. [13].

The conductivity of graphene can be modified by the two parts, which is $\sigma_g = \sigma_{intra} + \sigma_{inter}$ [24], corresponding to the intraband and interband transition contributions respectively. The intraband transition contribution can be defined as:

$$\sigma_{intra}(\omega, \mu_c, \Gamma, T) = \frac{-ie^2}{\pi\hbar^2(\omega + i2\Gamma)} \int_0^\infty \varepsilon\left(\frac{\partial f_d(\varepsilon)}{\partial \varepsilon} - \frac{\partial f_d(-\varepsilon)}{\partial \varepsilon}\right) d\varepsilon \tag{1}$$

and the interband transition contribution can be written as:

$$\sigma_{inter}(\omega, \mu_c, \Gamma, T) = \frac{ie^2(\omega + i2\Gamma)}{\pi\hbar^2} \int_0^\infty \frac{f_d(-\varepsilon) - f_d(\varepsilon)}{(\omega + i2\Gamma)^2 - 4(\varepsilon/\hbar)^2} d\varepsilon \tag{2}$$

where ε represents the energy, $f_d(\varepsilon) = (e^{(\varepsilon-\mu_c)/K_BT} + 1)^{-1}$ is the Fermi–Dirac distribution that contains the parameter of chemical potential (μ_c), ω is the angular frequency, and Γ is the scattering rate. As the chemical potential is varied by the external applied voltage, graphene's conductivity could be modified and the corresponding permittivity can also be tuned as [25]:

$$\varepsilon = 1 + \frac{i\sigma}{\omega\varepsilon_0\Delta} \tag{3}$$

where $\Delta = 0.35$ nm stands for the thickness of graphene monolayer. In addition, the chemical potential can be expressed as [6]:

$$\mu_c = \hbar v_F \sqrt{\pi \frac{\varepsilon_0\varepsilon_r}{de} \left|(V_0 - V_D)\right|} \tag{4}$$

where v_F is the Fermi velocity of graphene [24], the d and ε_r are respectively the thickness and permittivity of the Al_2O_3 dielectric layer that is deposited between two graphene flakes. For simplicity, $|(V_0 - V_D)|$ can be considered as the external applied voltage. Combining of Eqs. (1) to (3), the relationship between the permittivity and chemical potential could be obtained as shown in Fig. 1(d), where large variation of permittivity happens under different chemical potentials. The incident wavelength is set at around 1420 nm and $T = 300$ K. The relationship between the chemical potential and the applied voltage is also shown in Fig. 1(c), which is derived from Eq. (4). Combining these four formulas, the permittivity of graphene could be modified by the applied voltage, consequently changing the resonant wavelength and quality factor of the silica microdisk.

The variation of effective mode index (N_{eff}) of the graphene–silica microdisk calculated from a full-vectorial eigen-mode solver is shown in Fig. 2 [26], where Fig. 2(a) stands for the TE mode and Fig. 2(b) presents the TM mode. It can be drawn that the change of effective mode index for TE mode is similar to that of the permittivity of graphene while that of TM mode is very different. In Fig. 2, the maximal change of real part of effective mode index, usually known as electro-refractive, is 0.009 for TE mode and 0.0011 for TM mode, respectively. The maximal tuning of imaginary part of effective mode index that is usually regarded as electro-absorption is 0.0052 for TE mode and 0.0012 for TM mode, respectively. It is clearly demonstrated that larger light-matter interaction exists between graphene and TE mode. Obviously, comparing with the ΔN_{eff} of traditional modulator at the order of 10^{-4}, the variation of 0.009 for TE mode is distinctly enlarged. The insets of Fig. 2 are the optical profiles for TE mode and TM mode respectively, which present that the maximum of energy intensity is in the narrow Al_2O_3 dielectric layer for TE mode resulting in the ultra-strong light-matter interaction while the energy mainly distributes in the silica material for TM mode. Therefore, fundamental TE mode is chosen for the following investigation.

The enlarged variation of effective mode index of the graphene–silica microdisk could be conveniently applied for the optical modulation. Fig. 3 shows the quality factor and resonant wavelength of the graphene–silica microdisk as the functions of chemical potential of graphene monolayer and external applied voltage, respectively. The total loss of silica microdisk (corresponding to the total quality factor) mainly contains several parts, i.e. the intrinsic loss of silica microdisk that is ultra-low and could be ignored, and the absorption of graphene which is the focus in this paper. Fig. 3(a) shows the variation of quality factor of the fundamental TE mode as the chemical potential of graphene monolayer shifts from 0.43 eV to 1 eV. At least, two valuable points could be observed from this figure. Firstly, the change tendency of quality factor is just opposite to that of the imaginary part of effective mode index that stands for the electro-absorption of graphene, as shown in Fig. 2(a). Secondly, it is presented that the quality factor induced by the graphene could be changed from 205.48 to 4791.32. Fig. 3(b) shows the resonant wavelength of fundamental mode as a function of the external applied voltage. As the chemical potential shifts from 0.43 eV to 1 eV, the variation of applied voltage is 189.5 V, and the corresponding quasi-linear shift of resonant wavelength is 9.5 nm, indicating that the tunability of resonant wavelength is 0.05 nm/V. It is beneficial for the electro-optic modulation based on the system consisting of waveguide side-coupled with the microcavity. Compared to the other related works which are about the optical modulation based on the waveguide side-coupled with the microcavity, the wavelength shift of about 9.5 nm in our work is much large. For example, the wavelength shifts in the Refs. [2] and [13] are usually at the order of about 0.1 nm. The wavelength shift in the Ref. [12] is 4.21 nm. The transmission of waveguide side-coupled with microcavity is the Lorentzian line shape which its theory has been reported in plenty of references such as the Refs. [12,27]. It can be found that the transmission coefficient would be zero at the resonance and consequently experience a rapid change as the phase of microcavity shifts, which can be regarded as the "0"