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Graphene-based photonic crystal to steer giant Faraday rotation

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We present a graphene-based photonic-crystal schematic of enhancing and steering Faraday rotation angle of graphene. This concept is counter-intuitive because the giant Faraday rotation and high transmission can be simultaneously pronounced, which is distinguished from exisitng graphene structures reported before. It is found that chemical potential can be tailored to generate a controllable giant Faraday rotation via graphene with atomic thickness. By engineering the individual component thickness in the photonic crystal, the magneto-optical performance can be significantly improved. This is of fundamental importance in a wide range of magneto-optical applications, simply because the Faraday rotation makes sense only when the transmittivity is decently high. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4729134]

Magneto-optical (MO) effects describe the interaction between optic and magnetic materials, which plays a fundamental role in the technological applications, such as optical isolators and magnetic sensors.[1] The ability to enhance the MO effect is crucial for nano electrooptics, and the enhancement of MO effects have been presented in cavity-based, asymmetrical and symmetrical multilayered configurations with conventional MO materials.[2–5] On the other hand, the isolation of a single atomic sheet of graphene has attracted intensive attention.[6–14] Its carriers behave as massless Dirac fermions, resulting in many electric properties such as anomalous quantum Hall effect, universal conductivity, and special Andreev reflection.[8–10] Apart from the electronic cases, graphene also exhibits fascinating optical properties, such as the gate-tunable optical transitions, clocking, and transformation optics.[11–14] The recent achievements of giant Faraday rotation (FR) in graphene further provide the pavement to technological advances in MO devices.[15]

Unlike conventional magnetic materials in which the dielectric permittivity and magnetic permeability are fixed at the specified frequency, the optical conductivity of graphene is sensitive to chemical potential, magnetic bias, and temperature,[16] hence it allows tunable MO effects. It is interesting to note that the electronic properties of graphene grown on substrate SiC with Si- and C-terminations are significantly different.[17] In the recent experiment, graphene grown on Si-terminated surface leads to highly doped graphene with quasiclassical characteristics.[15] On the contrary, it exhibits the quantum behavior if it is grown on the C-terminated surface of SiC.[17] Recently, Ferreira *et al*. have fitted the experimental FR angles using both the semi-classical and quantum calculations.[18] Besides, a cavity geometry and Bragg mirror structure are proposed to obtain the enhanced FR angle of graphene.[18,19]

It is known that there is a tradeoff between FR angle (Kerr rotation) and transmission (reflection).[20,21] Hence, even if FR angle of graphene can be very substantial, the MO application still severely suffers because low transmission is less meaningful for practical use. Great effort has been made to identify proper configurations that allow high transmission while retaining large FR angles in conventional magnetophotonic crystals.[2–5] By contrast, the effective structure embedded with graphene possessing high FR angle and transmission remains unexplored. It is thus natural to seek a possible route of creating the enhanced FR angle as well as high transmission simultaneously in graphene-based hybrid structures, so that these structures can have larger impacts in practice.

In this connection, we first investigate the FR angle of a double-layer structure composed of graphene and SiC, and show that the FR angle shifts with the variation of the chemical potential. This provides a unique opportunity to probe the Landau levels (LLs) of graphene via optical routes. Furthermore, we explore a configuration to enhance FR angle as well as transmission by transferring graphene to a one-dimensional photonic crystal (1D PC). It is observed that an appropriately designed PC enables FR enhancement with reasonably high transmission. These characteristics provide an important paradigm for engineering and enhancing the MO effects of graphene-based PCs for practical development of optical switches.

A schematic of the double layer structure composed of graphene and SiC is shown in Fig. 1(a), where graphene lies

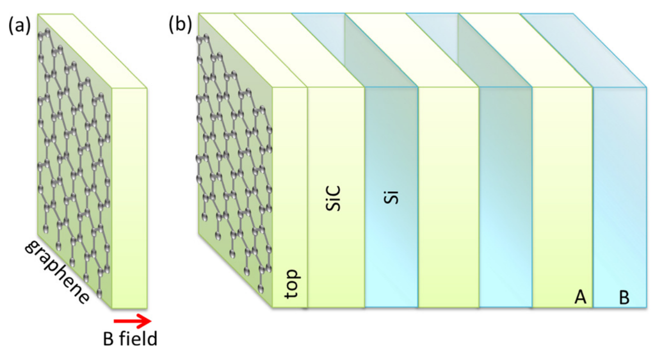

FIG. 1. (a) A schematic diagram of a double-layer structure consisting of graphene and SiC substrate and (b) one-dimensional graphene-based PC structure. An external magnetic field is indicated by an arrow, which is perpendicular to graphene.

in *x-y* plane and an external magnetic field aligns with z direction. A linearly *p*-polarized monochromatic electromagnetic wave is impinged normally onto the configuration. The permittivity and thickness of SiC are ε_s and d_s, respectively.

Graphene has the asymmetrical optical conductivity tensor upon the magnetic biased field. The diagonal and off-diagonal terms σ_{xx} and σ_{xy} ($\sigma_{yy} = \sigma_{xx}$ and $\sigma_{yx} = -\sigma_{xy}$) are characterized by[16]

$$\sigma_{xx} = \frac{e^2 v_F^2 |eB| \hbar(\omega - j2\Gamma)}{-j\pi} \sum_{n=0}^{\infty} \left\{ \frac{1}{M_{n+1} - M_n} \times \frac{n_F(M_n) - n_F(M_{n+1}) + n_F(-M_{n+1}) - n_F(-M_n)}{(M_{n+1} - M_n)^2 - \hbar^2(\omega - j2\Gamma)^2} + (M_n \to -M_n) \right\};$$

$$\sigma_{xy} = -\frac{e^2 v_F^2 |eB|}{\pi} \sum_{n=0}^{\infty} [n_F(M_n) - n_F(M_{n+1}) + n_F(-M_{n+1}) - n_F(-M_n)] \left[\frac{1}{(M_{n+1} - M_n)^2 - \hbar^2(\omega - j2\Gamma)^2} + (M_n \to -M_n) \right].$$

where $n_F(\omega) = \frac{1}{\exp[(\hbar\omega - \mu)/T] + 1}$ is the Fermi distribution, $M_n = \sqrt{\Delta^2 + 2n|eB|\hbar v_F^2/c}$ denotes the LL energies with the LL index n. v_F, e, c, and $\hbar$ are fermi velocity, charge of the electron, the velocity of light, and Planck constant. μ, Δ, and T are the chemical potential, an excitonic gap and temperature, respectively. Γ is the scattering rate and B is the magnitude of magnetic field. Here, the generalized optical conductivity of graphene is considered to take into account its quantum response. It is beyond the classical Drude model in our previous study,[19] which is valid when the optical conductivity is dominated by the intraband transitions at the low frequency.

Calculations of the FR angle and transmission were performed by employing transfer matrix method.[18] It has been used and proved to be an effective technique to handle the optical properties of various materials. Given the field vectors of incident and transmitted waves, we have

$$\begin{pmatrix} E_t^p \\ E_t^s \end{pmatrix} = \begin{pmatrix} t_{pp} & t_{ps} \\ t_{sp} & t_{ss} \end{pmatrix} \begin{pmatrix} E_i^p \\ E_i^s \end{pmatrix},$$

where t_{mn} is the ratio of the transmitted *m*-polarized electric field and the incident *n*-polarized electric field. Then we can obtain the FR angles and transmission versus the frequency. The exciton gap and temperature in graphene are taken as $\Delta = 0$ and $T = 10\,K$, respectively. The scattering rate, magnetic field, and the fermi velocity are $\Gamma = 15\,K$, $B = 1\,T$, and $v_F = 10^6\,m/s$, respectively. The thickness of graphene is chosen as $d_g = 0.335\,nm$.[22] The ambient medium is vacuum, i.e., $n_0 = 1$.

Figures 2(a) and 2(b) show the spectrum of FR angles (θ_F) and transmission coefficients (TC) of the double-layer structure, where the thickness of SiC is 37 nm. The solid, dash, and dash-dotted lines correspond to the FR angles as a function of frequency under different chemical potentials $\mu = 50\,K$, 510 K, and 660 K, respectively. In experiments, the chemical potential of graphene can be varied by gate voltage or chemical doping, leading to its flexible range.

A strong transition resonance was clearly identified by observing a FR peak in the vicinity of 10 THz at $\mu = 50\,K$. As chemcial potential increases, the FR peak shifts toward lower frequencies and the FR angle increases too. Such the giant FR peak is directly related to the anomalous absorption line graphene exhibits,[23] it can be attributed to the existence of the lowest LL (n = 0) energy of grpahene. The external magnetic field causes the massless Dirac carriers of graphene to circulate in cyclotron orbits with quantized energies. These energies are not equally spaced due to its energy-independent carrier velocities and there is a unique zero-energy LL state, which is in remarkable contrast to the case of two-dimensional electron gas. It is the zero-energy LL state that is referred to as the first absorption line including both interband and intraband transitions, contributing to an obvious FR peak.

Another minor peaks were observed in the spectral range of 15–30 THz when $\mu = 510\,K$ and 660 K. But such the second peak is missing at $\mu = 50\,K$, which is determined by the unique relativistic Dirac characteristics graphene has. Only one transition from n = 0 to n = 1 has a contribution to non-diagonal optical conductivity. These are important results in themself as they indicate the possibility of revealing the characteristics of graphene's massless quasi-particles by terahertz FR measurements without electrical contacts. Additionally, the positions of FR peaks correspond to those of peaks in the real part of the non-diagonal optical conductivity Re[σ_{xy}] and the positions of the dips in transmission spectrum exactly coincide with those of the peaks in real part of diagonal optical conductivity Re[σ_{xx}]. The presence of these peaks in transmission spectrum can be explained by the transformation from the Drude peak to the resonance peaks in the optical conductivity of graphene induced by the magnetic field. It is different from those results obtained by the Drude model for graphene, where only one cyclotron resonance is visible within the frequency region of our current

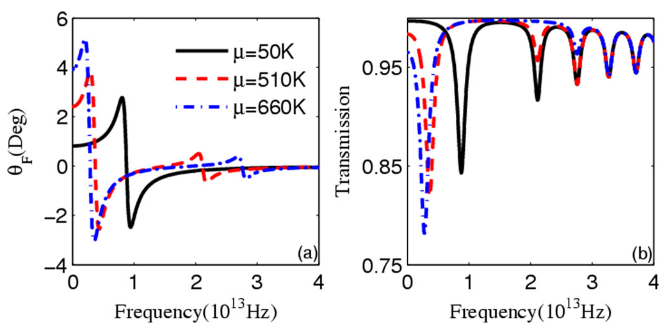

FIG. 2. Dependence of FR angle of the double-layer structure on frequency and chemical potential. (a) FR angle as a function of frequency at $\mu = 50$ K (solid line), 510 K (dash line), and 660 K (dash-dotted line), respectively. (b) Transmission as a function of frequency with the same chemical potentials in Fig. 2(a).

interest. These observations unveil the intrinsic MO behaviors of Dirac fermions in graphene. Finally, slight change in the thickness of SiC has a negligible effect on FR angle but thicker substrate will decrease the transmission coefficient at high frequency.

It is known that creating periodic structure is an effective way to achieve desirable optical properties. Various possible applications have been demonstrated to be implemented with PC structure, such as optical transparency, cloaking, imaging, and the high efficiency of solar cell.[24–27] It has been reported that a graphene-based PC device has a better visibility than that of suspended graphene.[28] As shown in Fig. 1(b), we design a structure in which graphene and SiC (top layer) are supported by a 1D PC structure composed of two alternating dielectric materials, e.g., Si and SiC. Here, the working frequency is chosen to be 25 THz away from cyclotron frequency. The refractive indices are $n_{Si} = 1.5$ and $n_{SiC} = 2.55$, respectively.[29] The thicknesses of top layer and two components of PC are $d_{top} = 0.52\,\mu$m, $d_{Si} = 6.38\,\mu$m, and $d_{SiC} = 4.01\,\mu$m, respectively. The chosen components' thicknesses are determined by the working frequency and the slight deviations will not ruin the results greatly. For better MO performance with reasonable complexity, we consider 6 Si-SiC pairs as the PC structure.

Figures 3(a) and 3(b) show the FR angle and transmission as a function of frequency at normal incidence under different chemical potentials. It is noted that the PC itself does not provide MO effects if there is no graphene involved. At a fixed chemical potential, we observe that there is an obvious oscillation behavior in θ_F spectrum, which can be ascribed to Fabry-Perot resonances induced by the periodic structure. At the specified 25 THz working frequency, the FR angle ($\theta_F = -0.14°$) is around two times of that of double layer structure ($\theta_F = -0.075°$) when $d_{top} = 0.52\ \mu$m. This can be explained from the transmission characteristics. From Fig. 3(b), one can see that the transmission spectrum exhibits a corresponding oscillating behavior and the band edge stays around 25 THz. Thus the device gets an extremely high transmission (TC = 0.98) at the specified frequency 25 THz. This result suggests that an increased FR angle and high transmission can be simultaneously kept in the present structure.

The co-existence of large FR angle and transmission demonstrates that the enhancement of FR angle is determined by the the strong localization of electromagnetic wave, which stems from near-zero group velocity at the band edge. Further enhancement of FR angle ($\theta_F = -0.27°$ at $\mu = 510$ K) is obtained for an increased chemical potential at the specified frequency 25 THz, which may even cause FR angles from negative to positive. The corresponding transmission remains almost the same while chemical potential is drastically varying, and is still significantly larger than that of double-layer structure. The change of FR angle results from the variation of intrinsic optical transition in graphene, where Re[σ_{xy}] first increases and then becomes negative with an increase of chemical potential. It is interesting to feature the functionality of our graphene-based PC that one can vastly adjust chemical potential in graphene to achieve variable FR angles, with transmission less unaffected. We know MO properties are sensitive to the frequency. Such a mechanism works for other frequencies and large FR angle can be obtained at low working frequency with appropriate thicknesses for PC's components.

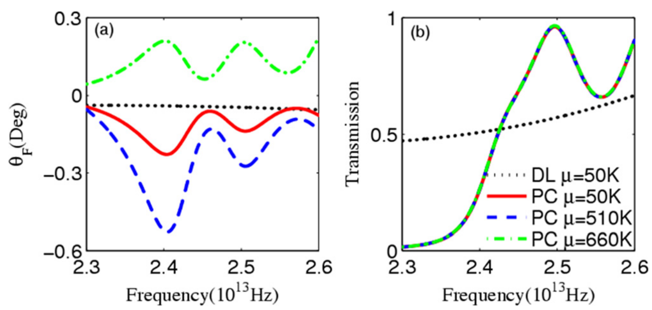

FIG. 3. Dependence of FR angle of the hybrid structure on frequency and chemical potential. (a) FR angle (b) transmission as a function of frequency with the same chemical potentials used in Fig. 2. The results of the double-layer structure (dotted line) are also shown for comparison.

In summary, we present the FR angles and transmission in a graphene-based PC structure. The large FR angle as well as high transmission are attainable by exploiting the combined effects of graphene's unique MO property and strong EM wave localization due to the periodic PC structure. Our findings indicate that the MO effect of graphene can be greatly enlarged by structural resonances, and high MO performance can be controlled by chemical potential while transmission is less affected during such a control. We expect that further improvement of MO performance can be reached by engineering different materials and geometrical configurations. It may power promising applications of tunable graphene-based MO devices.

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