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# Magneto-optical responses of microcavity-integrated graphene photonic crystals in the infrared spectral region

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ABSTRACT

The magneto-optical responses and photonic band gap properties of the microcavity-integrated graphene photonic crystals were numerically studied. The structure consists of a graphene sheet embedded between two mirror symmetric Bragg reflectors, under the influence of an external static magnetic field. The properties of the microcavity resonance mode were investigated, considering the right- and left-handed circular polarization transmission coefficients and their phases, together with the Faraday rotation angle and ellipticity of the output light. The effects of the repetition number of the Bragg reflectors, thickness of the microcavity central layer and refractive indices of the graphene adjacent layers were considered. The obtained results revealed that a pure linear polarized output light with no ellipticity and high transmittance enhanced Faraday rotation can be achieved. These results can be utilized in designing a variety of graphene based photonic devices and magneto-optical integrated elements, such as miniaturized isolators or circulators.



## 1. Introduction

Magneto-optical effects originate from the influence of magnetic fields through the propagation of light in matter. In 1845, the first magneto-optical phenomenon, known as the Faraday effect, was discovered by Michael Faraday [1]. In the Faraday effect, the plane of light polarization is rotated pathing through a transparent material which is under a magnetic field with direction along the propagation vector. The poor value of the specific Faraday rotation angle of materials (in the order of 0.1 deg/micron) encouraged researchers to introduce magneto-optical materials into photonic crystal structures [2,3]. Then, merging the photonic band gap and defect mode properties of photonic crystals with the magneto-optical effects results enhanced Faraday rotations. The obtained structures called magnetophotonic crystals and intense attentions are attracted to these structures from their first introduction by Inoue et al. [4]. The magneto-photonic crystals were utilized in designing and fabricating many optical devices such as isolators, modulators, circulators etc. [5–8], and currently there are continuous theoretical and experimental examinations of their potential applications.

On the other hand, since the first production of graphene in 2004, it has spurred huge research interests due to its unique optical and electrical properties [9–13], and many related applications, such as graphene-based optical modulation, transformation optics, field-effect transistors have been introduced [14–16]. However, there are several literature

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which have studied the embedding the graphene into different kinds of photonic crystals [17–22]. Fan et al. studied the transmission characteristics of surface plasmons at the interface of a one-dimensional photonic crystal and a monolayer graphene sheet [19]. The dispersion relations of TE resonances in different graphene-dielectric structures were investigated by Werra et al. [20]. Madani et al. investigated the optical properties of defective one-dimensional photonic crystals containing graphene sheets in the Terahertz region [21,22]. Another promising property of graphene is its magneto-optical characteristics, when it is under the influence of a magnetic field. The opportunity of magneto-optical conductivity and the creation of giant Faraday rotations in single layer graphene have been identified theoretically and experimentally [23–25]. Furthermore, the incorporation of graphene into microcavity structures have been reported in a number of works. H. Da et al. reported that enhanced Faraday rotation can be achieved in a magnetophotonic crystal infiltrated with graphene, as a result of graphene's nonreciprocity [26]. Ferreira et al. showed that giant Faraday rotations can be generated and measured by enclosing graphene in an optical cavity. They presented the explicit expressions for the Hall steps of the Faraday rotation angle and developed an equation of motion method for calculation of the magneto-optical properties of metals and semiconductors [27]. However, H. Da et al. demonstrated a heterogeneous photonic metastructure which involves monolayer graphene in order to achieve a substantial Faraday rotation angle and a nearly perfect transmittance simultaneously due to the presence of an interface mode [28]. Beside these issues, sometimes incorporated graphene sheets into an optical cavity are studied prior to utilization in transistors and photodetectors [29–31].

But to the best of our knowledge, there is no study on the behavior of the circular eigenmodes spectra in microcavity-integrated graphene photonic crystals. Hence, this work aimed to study the magneto-optical responses of such structures in the infrared spectral region. The numerical calculations were made using the well-known 4 by 4 transfer matrix method. This method together with the model and theory of the work is presented in Section 2. Investigations on the circular polarization eigenmodes regarding the different parameters of the structure are presented in Section 3. Finally, Section 4 summarizes the obtained results.

## 2. Model and theory

A microcavity-integrated graphene photonic crystal was considered with the arrangement of $(A/B)^m/G/(B/A)^m$, as shown in Fig. 1A and B are two different isotropic dielectric layers having quarter-wavelength optical thicknesses and m represents the repetition number of the Bragg reflector layers of the structure. It is supposed that the entire structure is surrounded by air. The layers are placed in x-y planes and the periodicity of the structure lies in the z-direction. The G stands for the central layer of the structure with a thickness of dg, and this layer contains a graphene sheet. As shown in Fig. 1, the arrangements of the dielectric layers are mirror symmetric, with regards to the central G layer. However, it was assumed that the structure is under the influence of an external static magnetic field in the z-direction. Then the magnetic field induces the gyrotropic properties of the graphene sheet. In such circumstances, the optical conductivity tensor elements of the diagonal and off-diagonal, $\sigma_{xx}$ and $\sigma_{xy}$ ($\sigma_{yy} = \sigma_{xx}$ and $\sigma_{yx} = -\sigma_{xy}$) of the graphene sheet are described by Refs. [25,32]:

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

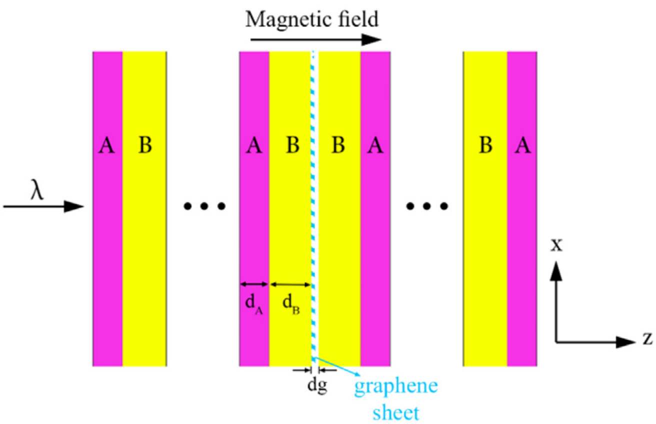


**Fig. 1.** Schematic representation of the microcavity-integrated graphene photonic crystal with the arrangement of $(A/B)^m/G/(B/A)^m$.