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Magneto-optical Faraday effects in dispersive properties for three-dimensional magnetized plasma photonic crystals

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ABSTRACT

The dispersive properties of three-dimensional magnetized plasma photonic crystals composed of homogeneous magnetized plasma spheres immersed in isotropic dielectric host with face-centered-cubic lattices are theoretically studied based on plane wave expansion method, as the magneto-optical Faraday effects of magnetized plasma are considered. The equations for calculating the band structures are theoretically deduced. The photonic band gap and a flatbands region can be obtained. The influences of host dielectric constant, plasma collision frequency, filling factor, external magnetic field and plasma frequency on the dispersive properties are investigated in detail, respectively, and some corresponding physical explanations are also given. The numerical results show that the photonic band gap can be manipulated by the plasma frequency, filling factor, external magnetic field and host dielectric constant, respectively. However, the plasma collision frequency has no effects on photonic band gap. The location of flatbands region cannot be tuned by any parameters except for the plasma frequency and external magnetic field.

1. Introduction

Since the first independently proposed by Yablonovitch [1] and John [2], the photonic crystals (PCs) have attracted a tremendous interest in investigating their properties in the theory and experiment. The PCs are artificially engineered materials with spatially modulated different refractive indices. Similar to the electronic band gaps in a semiconductor, the PCs can exhibit frequency regions named photonic band gaps (PBGs) which can be useful in confining and guiding the propagation of electromagnetic wave (EM wave). The main mechanisms responsible for the PBGs formation are based on Bragg scattering and the localized resonances [3]. Thus, the PCs have potential application in designing and manufacturing of many novel applications [4–6]. In recent years, the plasma photonic crystals (PPCs) have attracted great attention due to their fascinating physics and promising application in novel tunable devices, such as tunable filter [7], omnidirectional reflector [8] and polarization splitter [9]. The PPCs were firstly proposed by Hojo and Mase [10], which can realize the tunable PBGs in microwave region. The plasma can be looked as metamaterial [11], and the properties can be easily tuned by the external magnetic field, plasma density and the temperature of plasma, respectively [12]. Compared to the conventional PCs, there are some interesting properties of the PBGs [13–15]. The experiments on the PPCs also have been done by some research groups [16–19]. Although the generated microplasma is looked as one-dimensional (1D) or 2D structure in those experiments, but in fact is a 3D structure. On the other hand, the 3D PPCs are more suitable to design the devices compared to 1D and 2D PPCs since the 1D and 2D structures cannot be found in the real applications for the finite periodic structures. However, 3D structure is closer to the actual situation. For example, if we want to design waveguide in PCs slabs, the 1D and 2D models cannot describe this structure well, and 3D model have to be considered [20,21]. Thus, it is necessary to investigate the dispersive properties of 3D PPCs. As we know, if the external magnetic field is used to manipulate the plasma, there are two kinds of magneto-optical effects. One configuration, in which the external magnetic field is parallel to the EM wave vector, gives rise to so-called Faraday effects. The other is that the EM wave vector is perpendicular to the external magnetic field. In this case, the Voigt effects can be obtained [12]. Therefore, the magnetized plasma photonic crystals (MPPCs) have triggered a flood of researches.

Liu et al. [22] and Zhang et al. [23] used finite-difference time–domain (FDTD) method to investigate the transmission

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properties and periodic characteristics of 1D MPPCs in frequency–domain as magneto-optical Faraday effects are considered, respectively, and they found that the transmission and periodic PBGs are dependent strongly on the external magnetic field. Zhang et al. [24], Qi et al. [25] and Kong et al. [26] investigated the magneto-optical effects in transmission characteristics of 1D MPPCs with dielectric and plasma defect layer by FDTD and transfer matrix method (TMM), respectively, and demonstrated that defect mode can be modulated by the magnetized plasma in a larger frequency region. Qi et al. [27,28] also analyzed Vogit effects in the dispersion and defect characteristics for 1D and 2D MPPCs by TMM and plane wave expansion (PWE) method, respectively, and demonstrated that defect mode and PBGs can be modulated by the plasma or external magnetic field in a larger frequency region. Hamidi et al. [29] investigated the optical and magneto-optical properties of 1D magnetized coupled resonator PPCs, and found the magneto-optical properties can be tuned by the parameters of magnetized plasma. On the other hand, Zhang et al. [30] and Qi et al. [31] arranged plasma periodically by the external magnetic field to form a new kind of 2D and 1D MPPCs, which are only composed of the plasma, and proclaimed that the PBGs also can be tuned by the external magnetic field. Consequently, the MPPCs have some interesting properties compared to the unmagnetized PPCs.

All the works mentioned above just only focused on the dispersive characteristics of the 1D and 2D MPPCs, respectively. To our knowledge, there are few reports about magneto-optical Faraday effects in 3D MPPCs since Zhang et al. [32] proposed the PBGs properties for 3D unmagnetized PPCs. As we know, the PBGs for 1D and 2D MPPCs depend on the polarization of EM wave (TE and TM mode) but the PBGs for 3D MPPCs are complete PBGs [33–35], which do not depend on the polarizations (TE and TM mode). Thus, 3D MPPCs can be more widely used to design various modern devices. Compared to the conventional 3D solid-material PCs, the larger PBG can be obtained in the 3D MPPCs (see Fig. 2), and an additional flatbands region can be gotten. In this paper, we limit our consideration to the dispersive properties of 3D MPPCs with face-centered-cubic (fcc) lattices based on a modified plane wave expansion (PWE) method as the magneto-optical Faraday effects of magnetized plasma are considered. The 3D fcc MPPC is that magnetized plasma spheres immersed in dielectric background. The influences of host dielectric constant, plasma collision frequency, filling factor, external magnetic field and plasma frequency on the dispersive properties of 3D fcc MPPCs are studied in detail, respectively. An $e^{j\omega t}$ time-dependence is implicit through the paper, with ω the angular frequency, t the time, and $j=\sqrt{-1}$. We consider c is light speed in vacuum.

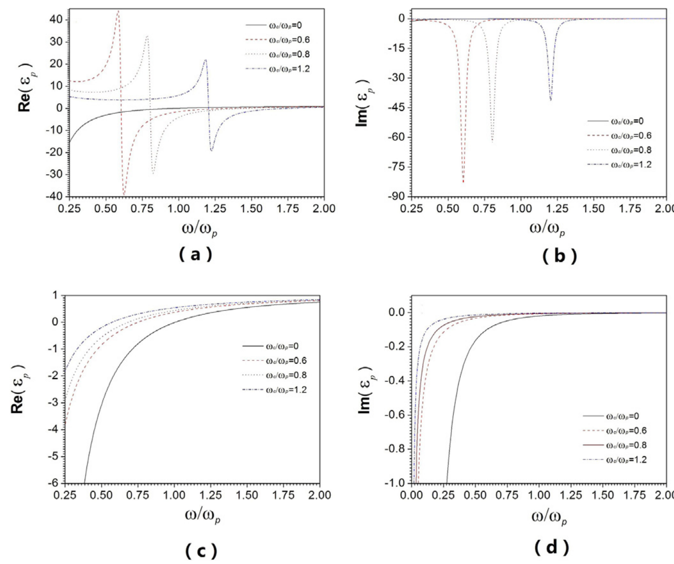

Fig. 1. The real and imaginary parts of left and right circular polarizations in term of ω_c. (a) Re(ε_p) of right circular polarization, (b) Im(ε_p) of circular right polarization, (c) Re(ε_p) of left circular polarization, and (d) Im(ε_p) of left circular polarization.

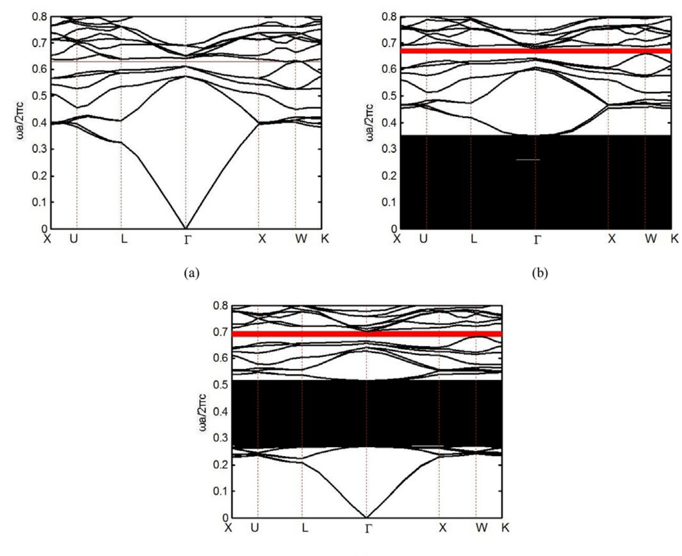

Fig. 2. Band structures for 3D fcc PCs with ε_a = 14 and f = 0.6 but with different ω_p, ω_c and ν_c, respectively. (a) ω_p = 0, ν_c = 0, ω_c = 0, (b) ω_p = 0.35ω_{p0}, ν_c = 0.02ω_{p1}, ω_c = 0 and (c) ω_p = 0.35ω_{p0}, ν_c = 0.02ω_{p1}, ω_c = 0.8ω_{p1}, respectively. The red shaded regions indicate PBGs.

2. Theoretical model and numerical method

We consider the incidence wave vector is parallel to the external magnetic field at any time. Assumed magnetized plasma and dielectric are homogeneous, and the relative dielectric functions are ε_p and ε_a, respectively. Consider the radius of the spheres and lattice constant are R and a, respectively. As we know, the expression of dielectric function ε_p is determined by the angle between the wave vector and the external magnetic field [12]. In Faraday geometry, the effective dielectric function of magnetized plasma ε_p can be written as [12,23]:

$$\varepsilon_p(\omega)=1-\frac{\omega_p^2}{\omega^2-j\nu_c\omega\pm\omega_c\omega} \quad (1)$$

where ω_p, ν_c, and ω_c are plasma frequency, plasma collision frequency and plasma cyclotron frequency, respectively. Plasma frequency $\omega_p=(e^2n_e/\varepsilon_0 m)^{1/2}$ in which e, m, n_e and ε_0 are electric quantity, electric mass, plasma density and dielectric constant in vacuum, respectively. $\omega_c=(eB/m)$ in which B is the external magnetic field. Here, the "+" sign in the third term of denominator involving plasma cyclotron frequency ω_c is effective dielectric function for the left circular polarization whereas it is the case for right circular polarization if the "−" sign is taken [12]. In Fig. 1, we plot the real Re(ε_p) and imaginary parts Im(ε_p) of the right and left circular polarizations varying with ω_c, respectively. All parameters are same as mentioned as in Fig. 2 except for ν_c = 0.02ω_p. One can see that there exists a cyclotron resonance in Fig. 1(a) as the imaginary part attains a maximum, and the corresponding magnitude of Re(ε_p) reaches a peak near the cyclotron resonance frequency. This phenomenon is caused by the Lorentz force [12,31]. As shown in Fig. 1(b), the cyclotron resonance frequency increases, and the magnitude of Im(ε_p) decreases with increasing ω_c. What is more important is the change of ω_c, which changes the solution of Re(ε_p)