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Analysis of tunable photonic band structure in an extrinsic plasma photonic crystal

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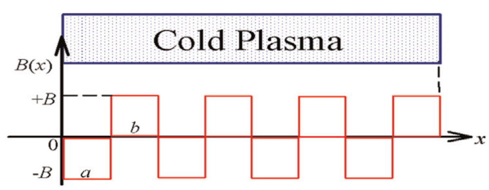
HIGHLIGHTS

- Tunable PBSs in an extrinsic plasma photonic crystal are analyzed.
- The gap width is strongly dependent on the applied magnetic field.
- Wide gap can be obtained at a higher electron density.

GRAPHICAL ABSTRACT



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ABSTRACT

In this work, we theoretically investigate the tunable photonic band structure (PBS) for an extrinsic plasma photonic crystal (PPC). The extrinsic PPC is made of a bulk cold plasma layer which is influenced by an externally periodic static magnetic field. The PBS can be tuned by the variation of the magnitude of externally applied magnetic field. In addition, we also show that the PBS can be changed as a function of the electron density as well as the thickness variation.

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1. Introduction

In 1987, the field of photonic crystals (PCs) was initialized by two pioneering works of Yablonovitch and John [1,2]. After two more decades, it continues to be of much interest to the community today. The fundamental physics of PCs can be extracted from the so-called photonic band structure (PBS) which is analogous to the electronic band structure (EBS) in solids. It is known that in a PC there exists the photonic band gap (PBG), in which an electromagnetic wave with frequency inside the PBG is forbidden to propagate through the structure.

In general, a PC is an artificially periodic structure formed by two kinds of materials with distinct refractive indices. Such a PC can be defined as an intrinsic PC. There is another kind of PC called the extrinsic PC because it is not periodic in structure. An extrinsic PC is formed from a bulk material which is influenced by externally periodic applied field in space [3]. With the spatially applied field, the permittivity function in the bulk material will become a periodic function in space. Thus, the bulk material can be effectively regarded as a PC which is referred to as an extrinsic PC. The PBS for a doped semiconductor extrinsic PC has been studied recently [3,4].

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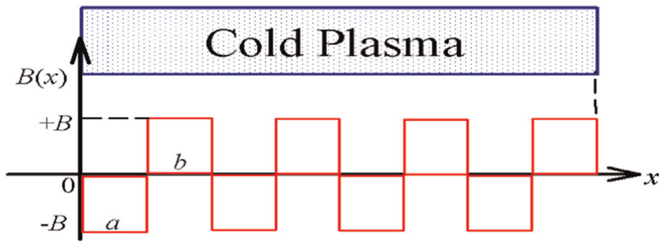

Fig. 1. The structure of 1D extrinsic PPC established by the presence of externally and spatially alternating static magnetic field. Here, a is the width of negative magnetic field (layer 1) and b is the width of the positive magnetic field (layer 2). The magnetic is applied along the x direction, i.e., $\mathrm{B} = \hat{x}B$ or $\mathrm{B} = -\hat{x}B$.

In this work, we shall consider an extrinsic plasma photonic crystal (PPC) as shown in Fig. 1, in which a bulk cold plasma system with a total length of L is influenced by an alternating square-wave-like magnetic field, the lower part of Fig. 1. As a result, the bulk plasma can thus be regarded as an effective PC constituted by two effective media of thicknesses a and b, respectively. With this effective PC in hand, it is thus of interest to have the knowledge of PBS. In this study, we shall investigate the tunable PBS for this extrinsic PPC. Tunable PCs have been of much interest to the community in recent years. For examples, there have been many reports on tunable PCs made of semiconductors [3,5–8]. Feng et al. report that the magnetic-field tunable negative refraction can be realized in a two-dimensional square PC with magnetically active semiconductor constituents of GaAs [5]. As for the tunable PPC, we mention some of the related works [9–12]. In Ref. [9], Kong et al. study the tunable filter featuring by making use of a magnetized plasma layer as defect in a dielectric PC. The magnetic field dependence of PBS in a magnetized PPC in the case of oblique incidence has been studied by Qi et al. and Guo, respectively [10–12].

We show that the PBS can be tuned by the static magnetic field, electron density, and the thickness ratio as well. The PBS will be calculated based on the transfer matrix theory together with Bloch theorem [13]. In addition, our results will be investigated in the region of gigahertz (GHz) frequency. Investigation of effect of thickness ratio of the layers on PBS at GHz is also available for a metamaterial PC composed of negative index materials [14].

2. BASIC equations

The structure of one-dimensional (1D) extrinsic PPC is depicted in Fig. 1. In the aforementioned description, we know that the bulk cold plasma with a total length L can be effectively regarded as a photonic crystal which is now denoted as air/(12)^N/air. Here, layer 1 with a thickness of a is the region under the negative magnetic field of $-B$, i.e., the magnetic field is applied in the $-x$ direction. Similarly, layer 2 denotes the region of thickness of b under the positive magnetic field $+B$. In this case, the magnetic field is applied in the $+x$ direction. The spatial period is defined as $d=a+b$, the number of periods is N, and thus $L=Nd$ is satisfied.

Let us now describe the permittivity function for the cold plasma in the presence of static magnetic field. The permittivity in magnetized cold plasma under the configuration of Fig. 1 can be expressed as [15]

$$\varepsilon_{plasma}(\omega) = \mathrm{Re}\,(\varepsilon_{plasma}) - i\mathrm{Im}(\varepsilon_{plasma}) = 1 - \frac{\omega_{pe}^2}{\omega^2\left[\left(1 - i\frac{\gamma}{\omega} \mp \frac{\omega_{le}}{\omega}\right)\right]}. \tag{1}$$

where ω_{pe} is the plasma frequency given by

$$\omega_{pe} = \left(\frac{n_e e^2}{m\varepsilon_0}\right)^{1/2}, \tag{2}$$

where m is the electronic mass, e is the electronic charge, and n_e is the electron density, ω_{le} is the gyrofrequency expressible as

$$\omega_{le} = \frac{eB}{m}, \tag{3}$$

and γ is the effective collision frequency, respectively. In Eq. (1), the minus sign in ω_{le} corresponds to the magnetic field in the $+x$ direction and is called the right-hand polarization (RHP). This will be assigned to the layer 2 in Fig. 1, i.e., $\varepsilon_{plasma}(\omega) = \varepsilon_2$. On the other hand, the positive sign in ω_{le} corresponds the magnetic field in the $-x$ direction and is referred to as the left-hand polarization (LHP). This will belong to the layer 1 in Fig. 1. In this case, the permittivity of layer 1 is $\varepsilon_{plasma}(\omega) = \varepsilon_1$. It is worth mentioning that Eq. (1) holds for the parallel configuration, i.e., with $\mathbf{B}//\mathbf{k}$, where $\mathbf{k}$ is wave vector also parallel x direction. As for the permittivity function in

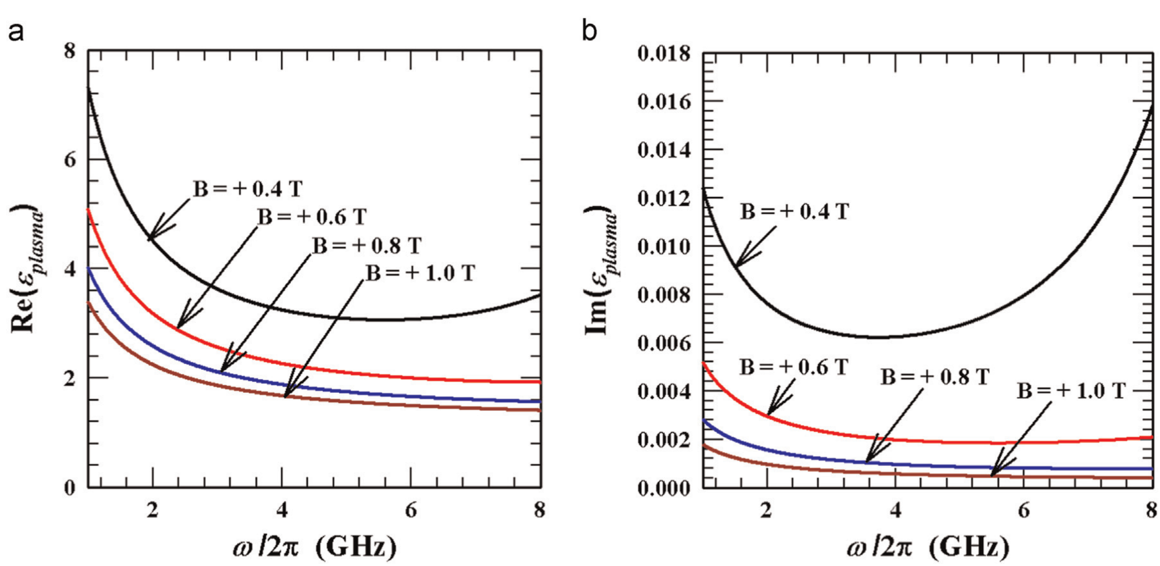

Fig. 2. Calculated real part (a) and imaginary part (b) of permittivity function in Eq. (1) in the RHP for different magnitudes of static field, $B=+0.4$, $+0.6$, $+0.8$, and $+1$ T, respectively.

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