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Negative refraction in one-dimensional plasma photonic crystals

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ABSTRACT

We have theoretically explored the negative refraction (NR) in one-dimensional plasma photonic crystals (PCs) consisting of plasma and dielectric materials. By using the transfer matrix method and Bloch theorem, we have studied the group velocity and we have obtained the NR in plasma PCs with the help of the group velocity. The results show that plasma PCs can also exhibit the NR although they have a periodically modulated positive permittivity ε and permeability μ. It is also shown that the NR in plasma PCs exhibits difference behaviour in different frequency regions, $\omega < \omega_p$ and $\omega > \omega_p$, respectively. The parameter dependence of the effects is also examined and discussed.

1. Introduction

Photonic crystals (PCs), which one type of materials is being developed in the area of photonics, have attracted considerable attention for fundamental studies as well as potential applications in many areas in recent years [1–3]. PCs are novel class of optical media represented by natural or artificial structures with periodic modulation of the refractive index. Such optical media have some novel properties which give an opportunity for a number of applications to be implemented on their basis. Since the pioneering works of Yablonovitch [2] and John [3] on this field, many new innovative ideas have been developed. Recently, this active field has been extended to plasma PCs [4–13] which has aroused great interest and increasing research activities. In comparison with conventional PCs, one of the outstanding feature of plasma PCs is that plasmas enable us to realize tunable PCs device since the plasmas can be controlled rapidly by changing the applied voltage, the gas pressure, and the gas temperature. In addition, plasmas are loss dispersive media and act as a dielectric, a metal and, what is more, a new material which has unexplored physical parameters. Furthermore, by replacing the solid materials with plasmas, two important features are added to usual PCs: time-varying controllability and strong dispersion around the electron plasma density. These facts will lead to electromagnetic (EM) waves ranging from microwaves to terahertz waves according to the scale and the electron density of such plasmas [14].

It is well konwn that PCs significantly modify the spectral properties of EM waves. Changing spatial distribution of the dielectric constant, one can effectively control the fundamental optical properties like band structure, reflectivity, group velocity and effective group index, etc [1]. The optical properties of EM waves propagation in PCs which is given by the relation $n = \sqrt{\varepsilon \cdot \mu}$, here ε is the permittivity and μ the permeability of the medium. General speaking, ε and μ both are positive values for ordinary medium. ε may be negative values for some specific materials, such as metals, or plasma (when the frequency of incidence is less than plasma frequency), but materials with negative μ cannot be found in natural world. However, for some man constructed materials, which are called metamaterials [15], the permittivity and permeability can take negative values. It means that in such materials the index of refraction is less than zero. Therefore, phase and group velocity of EM waves can propagate in opposite direction in these materials, which named NR phenomenon. Such materials are also known as negative-index materials, which first proposed by Veselago [16]. Negative-index materials are a subgroup of metamaterials, as first proposed, require the permittivity ε, and permeability μ, simultaneously less than zero [17,18]. The negative value of ε is a natural property of metals or plasmas and can therefore be incorporated into the metamaterials by simple metallic such as metallic rods or microplasmas, the negative value of μ has to be gained using a resonance [19–21]. But this double resonance scheme faces limitations because the design and fabrication can be complicated. Fortunately, it has shown that this interesting phenomenon NR may also occur in PCs [22–28]. These areas sound very interesting, but have not been examined in plasma PCs. So it is of great theoretical significance for studying the NR in plasma PCs, as plasma PCs are a novel and innovative periodic structures which are very different from the conventional PCs. Motived by it, in the present paper, we theoretically explore the NR in one-dimensional plasma PCs in the whole frequency regions: both in $\omega < \omega_p$ and

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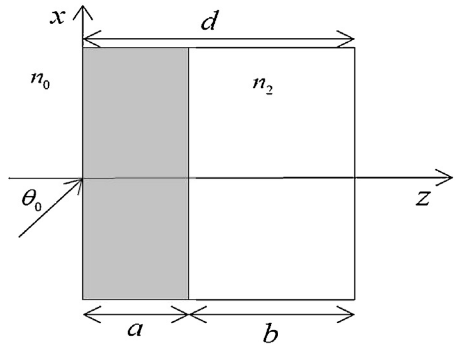

Fig. 1. One period of one-dimensional structure consisting alternate plasma layer (shaded region) and dielectric materials n_2.

$\omega > \omega_p$, here ω is the frequency of incidence and ω_p the plasma frequency.

The paper is organized as follows. The model and corresponding analytical formulas, are introduced in Section 2. Numerical results are presented and discussed in Section 3. Finally, conclusions are given in Section 4.

2. Model and formulations

For simplicity, we only consider the TE-polarized case. We start with the Maxwell equation, which corresponds to TE-polarized electric field of an EM wave propagating along the z-axis, given by

$$\frac{d^2E(z)}{dz^2} + \left[\frac{\omega^2}{c^2}\varepsilon(z) - \beta^2\right]E(z) = 0. \tag{1}$$

where $\beta = (\omega/c)\varepsilon_i(z)\sin\theta_i$ is the propagation constant, where θ_i is the angle of TE incidence with the subscript $i = p, d$ denotes plasma and dielectric materials, and c the velocity of light in the free space. $\varepsilon(z)$ in Eq. (1) is permittivity of the constructed plasma PC given by

$$\varepsilon(\omega, z) = \begin{cases} \varepsilon_p = 1 - \dfrac{\omega_p^2}{\omega^2}, & 0 < z < a \\ \varepsilon_d. & a < z < d \end{cases} \tag{2}$$

with

$$\varepsilon(\omega, z) = \varepsilon(\omega, z \pm d). \tag{3}$$

where ε_p and ε_d being the dielectric constant of the plasma and dielectric layer, respectively. $d = a + b$ is the period of the plasma PC with a and b being the widths of layers. The schematic view of TE wave propagation in one-dimensional plasma dielectric PC is shown in Fig. 1.

In this work, we are aiming at the NR in plasma PCs. In a PC only group velocity V_g has a proper meaning and it governs the energy flow of a EM waves beam. The Bloch wave vector in a PC is given by $k = \beta\hat{x} + K\hat{z}$. So the group velocity V_g in a PC can be expressed as below [29,30]

$$V_g = V_{gx}\hat{x} + V_{gz}\hat{z}. \tag{4}$$

where V_{gx} and V_{gz} are the components of the group velocity in the $x-$ and $z-$axis respectively, and these two components are given by

$$V_{gx} = \frac{\partial\omega}{\partial\beta} = -\frac{\partial K(\omega, \beta)/\partial\beta|_{const(\omega)}}{\partial K(\omega, \beta)/\partial\omega|_{const(\beta)}}, \tag{5}$$

and

$$V_{gz} = \left(\frac{dK}{d\omega}\right)^{-1}. \tag{6}$$

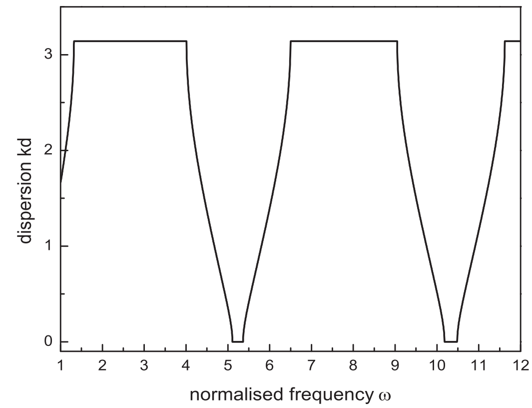

Fig. 2. Dispersion vs. normalised frequency ω for the oblique incidence ($\theta_0 = \pi/4$) with $n_0 = 1$, $n_b = 4.2$, $a = 0.85d$, and $b = 0.15d$, at $\omega_p < \omega$.

here, K is the effective propagation constant of TE waves propagating in one-dimensional plasma PCs, which can be derived by using the transfer matrix method and can be written as a function of ω and β [7]

$$K(\omega, \beta) = \frac{1}{d}\cos^{-1}\left[\cosh k_{px}a\cos k_{dx}b + \frac{1}{2}\left(\frac{k_{px}}{k_{dx}} - \frac{k_{dx}}{k_{px}}\right)\sinh k_{px}a\sin k_{dx}b\right], \tag{7}$$

for $\omega < \omega_p$ and

$$K(\omega, \beta) = \frac{1}{d}\cos^{-1}\left[\cos k'_{px}a\cos k_{dx}b - \frac{1}{2}\left(\frac{k'_{px}}{k_{dx}} + \frac{k_{dx}}{k'_{px}}\right)\sin k'_{px}a\ \sin k_{dx}b\right]. \tag{8}$$

for $\omega > \omega_p$, where

$$k_{dx} = \left[\left(\frac{\omega}{c}\right)^2\varepsilon_d - \beta^2\right]^{1/2}, k_{px} = \left[\left(\frac{\omega}{c}\right)^2(-\varepsilon_p) - \beta^2\right]^{1/2}, \text{ and } k'_{px} = \left[\left(\frac{\omega}{c}\right)^2(\varepsilon_p) - \beta^2\right]^{1/2}.$$

In a follow up, we numerically investigate the x component of group velocity V_{gx} of TE waves propagation in one-dimensional plasma PCs by using the Eqs. (9) and (10) which shown in Appendix A. And with the help of the group velocity V_{gx}, we explore the NR in one-dimensional plasma PCs.

3. Results and discussion

In this section, we calculate the group velocity by using Eq. (5) and related equations. For the numerical calculations, we have taken $n_0 = 1$, $n_2 = \sqrt{\varepsilon_d} = 4.2$, $a = 0.85d$, $b = 0.15d$ for the oblique incidence case of $\theta_0 = \pi/4$. Here, we introduce the dimensionless variable $\omega d/c$ which is normalized to 1 at $\omega = \omega_p$.

Figs. 2–5 depict the dispersions in the different frequency regions, $\omega_p < \omega$ and $\omega_p > \omega$, respectively. From these two figures, we can see that the dispersions become photonic band structures with frequency gaps, and cut-off frequency exists. It is noticeable that the bandwidth of odd number band gap is wide, but the bandwidth of even number band gap is narrow. Moreover, we can conclude that the results obtained here is valid for arbitrary wavelengths because the lattice constant d is arbitrary in our model. The properties of the band gap structures can be tuned by external parameters,