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Study of periodic band gap structure of the magnetized plasma photonic crystals*

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The characteristics of the periodic band gaps of the one dimension magnetized plasma photonic crystals are studied with the piecewise linear current density recursive convolution (PLCDRC) finite-differential time-domain (FDTD) method. In frequency-domain, the transmission coefficients of electromagnetic Gaussian pulses are computed, and the effects of the periodic structure constant, plasma layer thickness and parameters of plasma on the properties of periodic band gaps of magnetized photonic crystals are analyzed. The results show that the periodic band gaps depend strongly on the plasma parameters.

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In recent years, photonic crystals (PCs) become a new important research field. The concept of PCs was proposed independently by Yablonovitch[1] and John[2] in 1987. The plasma photonic crystals (PPCs) is one kind of PCs, the idea of the PPCs was proposed by Hojo[3]. PPCs are artificially periodic array composed of alternating plasmas and dielectric materials (or vacuum). The magnetized plasma can be characterized by anisotropy, dispersion and dissipation at the same time, which makes PPCs obtain many new particular characteristics compared with conventional PCs[4,5]. So, the study of the periodic band gaps structure for magnetized plasma photonic crystals (MPPCs) has the particular practical significance.

In this paper, The piecewise linear current density recursive convolution (PLCDRC) finite-different time-domain (FDTD) method is applied to study the characteristics of one dimension homogeneous and time invariant MPPCs periodic band gaps.

The MPPCs physical model for simulation is shown in Fig.1. The one dimension MPPC is composed of alternating 6 layers of magnetized plasmas slabs and 7 layers of dielectric slabs. The relative permittivity of each dielectric slab is 7.0.

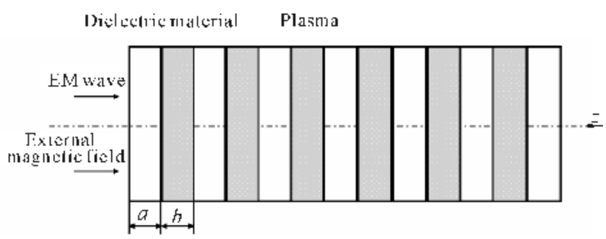

Fig.1 Physical model of one dimension MPPCs

The iterative formulas in Ref.[6] are adopted. The direction of external static magnetic field is assumed as the *z*-axis in Cartesian coordinate. The incident EM wave frequency is 0-15 GHz. *N* is the periodic structure constant, ω_p and ω_b are plasma frequency and plasma cyclotron frequency, respectively. v is plasma collision frequency. Before simulation, the values of computation parameters are assumed as follows: N=6, a=b=1 cm, $\omega_p = 8\pi\times10^9$ rad/s, $v = 3\times10^9$ rad/s, $\omega_b = 10\times10^9$ rad/s.

The value of space-step used in FDTD computation is 1 mm. According to Courant Law, the value of time-step used in computation is Δt =2 ps.The 13 cm MPPC is subdivided into 130 cells. Five cells perfectly matched layer (PML) absorbing boundaries are used to eliminate unwanted reflections. The incident EM wave used in the simulation is a Gaussian pulse as follows:

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$$E_i(t) = -A(t-6\tau)\exp(-\frac{4\pi(t-6\tau)^2}{30\tau^2}) \quad t \le 10\tau,$$

$$E_i(t) = 0 \quad t > 10\tau,$$

where τ=20, A=4.67 V/m. In order to obtain the characteristics of PBG, the electric component gotten in the time domain is transformed to the frequency domain using discrete Fourier transform (DFT) after 10 000 time steps. The electric component is composed of the right-handed circularly polarized (RCP) and left-handed circularly polarized (LCP) component. RCP and LCP transmission coefficient are combined as follows:

$$T_{RCP}(\omega) = \hat{E}_{xt}(\omega) + j \cdot \hat{E}_{yt}(\omega)$$

$$T_{LCP}(\omega) = \hat{E}_{xt}(\omega) - j \cdot \hat{E}_{yt}(\omega)$$

Fig.2 plots transmission coefficients magnitude versus frequency for LCP wave as N=1,6,16,22. Fig.2 shows that the MPPCs have the periodic band gaps as conventional PCs but the MPPCs are expected to obtain many new particular characteristics. In the following, we mainly concern with finding the influence of periodic structure constant and plasma parameters on properties of MPPCs periodic band gaps.

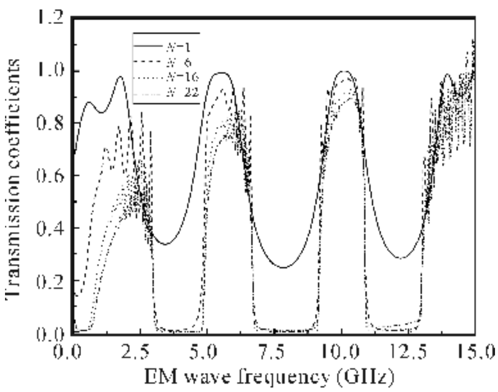

Fig.2 Transmission coefficients magnitude versus frequency for LCP wave as *N*=1,6,16, 22

Fig.3 plots transmission coefficients magnitude versus frequency for RCP wave as N=1,6,16,22. Fig.2 and Fig.3 show that MPPCs which are composed of a single plasma slab and dielectric slab haven't periodic PBGs as LCP and RCP wave propagating through the MPPCs, the PBGs have been broadened and the center of PBGs moves to high-frequency stage slightly for increasing N. However, when the N increases enough, the PBGs will be not broadened but the maximum values of transmission coefficients decrease. Physically, it can be explained on the basis that the plasma is a kind of dissipative medium which can absorb the most of EM wave energy. This result can be understood in terms of the simple model of a plasma electron oscillated by EM wave and impeded by collisions with background atoms. As increasing N, the numbers of plasma electron also increase so that more EM wave energy is absorbed. Therefore, the PBGs can't be broadened only by increasing N but MPPCs have periodic band gaps with N increasing.

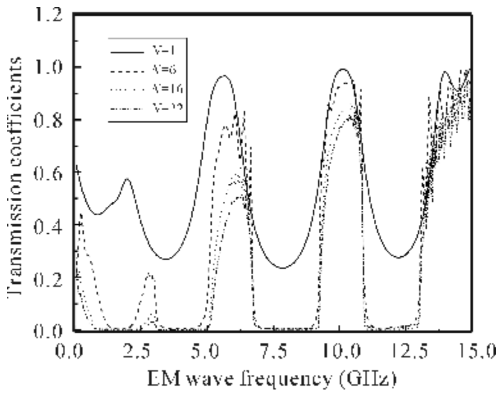

Fig.3 Transmission coefficients magnitude versus frequency for RCP wave as *N*=1,6,16, 22

Fig.4 plots transmission coefficients versus frequency for LCP wave as b=10 to 40 mm. Fig.5 plots transmission coefficients magnitude versus frequency for RCP wave as b=10 to 40 mm. Fig.4 and Fig.5 show that MPPCs have no periodic band gaps and the PBGs are broadened with increasing values of the plasma thickness as LCP and RCP wave propagating through the MPPCs. With high value of the plasma slab thickness and incident EM wave with low frequency, the MPPCs have no periodical PBGs. Unless the value of the plasma slab thickness is low and incident EM wave frequency is high , the MPPCs will have the periodic PBGs. It is seen that incident LCP and RCP wave are reflected totally

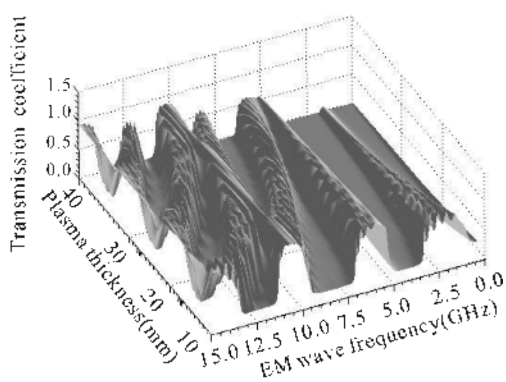

Fig.4 Transmission coefficient versus frequency for LCP wave as *b*=10 to 40 mm

as the incident EM wave frequency is 3.0 GHz and the plasma slab thickness is 40 mm. Therefore, we can change the value of the plasma slab thickness to get the optimal PBGs according to the incident EM wave frequency.

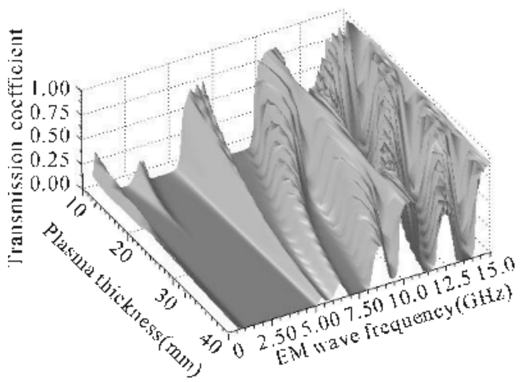

Fig.5 Transmission coefficient versus frequency for RCP wave as *b*=10 to 40 mm

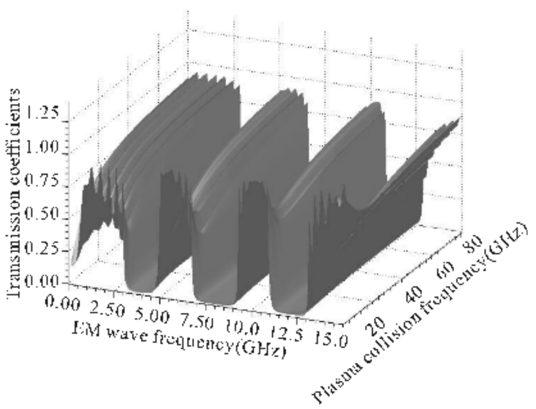

Fig.6 Transmission coefficient versus frequency for LCP wave as *ν* =0.1 to 80 GHz

Fig.6 plots transmission coefficient versus frequency for LCP wave as ν =0.1 to 80 GHz. Fig.7 plots transmission coefficient versus frequency for RCP wave as ν =0.1 to 80 GHz. Fig.6 and Fig.7 show that MPPCs have periodic band gap structures and the widths of the PBGs are always invariable with varying plasma collision frequency as LCP and RCP wave propagation through the MPPCs. If the value of plasma collision frequency is greater or smaller, the peak values of transmissivity decrement for LCP and RCP wave are low. This can be explained by plasma collision. If the value of plasma collision frequency is low, the times of collision between plasma electrons and neutral corpuscles decrease. Obviously, the impeded energy decreases. If the value of plasma collision frequency is near to zero, the plasma is a zero-loss medium. If the value of plasma collision frequency is high, the plasma electrons come into collision with neutral corpuscles frequently so that the number of plasma electrons which are polarized by EM wave decreases. The plasma electrons do not accelerate sufficiently by EM wave before collision with neutral corpuscles. Fig.6 and Fig.7 also show that the peak values of transmission coefficients for LCP and RCP wave decrease for increasing plasma collision frequency. As the peak values of transmission coefficients reach minimum, the peak values of transmissivity will increase slowly. If the value of plasma collision frequency increases enough, the peak values of transmissivity do hardly increase. This can be explained by relationship between attenuation coefficient and plasma collision frequency[7]. If the values of the plasma collision frequency and incident wave frequency are low, the attenuation coefficient is high and vice versa.

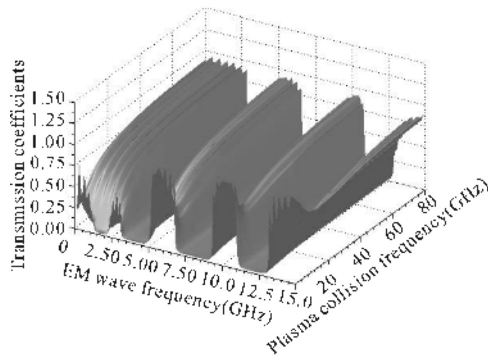

Fig.7 Transmission coefficient versus frequency for RCP wave as *ν* =0.1 to 80 GHz

Fig.8 plots transmission coefficients magnitude versus frequency for LCP wave as ω_b =1 to 40 GHz. Fig.9 plots transmission coefficients magnitude versus frequency for RCP wave as ω_b =1 to 40 GHz. Fig.8 shows that the MPPCs have periodic band gaps structure and the width of PBGs is almost invariable with varying plasma cyclotron frequency as LCP wave propagating through the MPPCs. Fig.9 shows that MPPCs have periodic band gaps structure only the value of plasma cyclotron frequency is smaller or greater and the widthes of PBGs are variable with varying plasma collision frequency as RCP wave propagating through the MPPCs. As the value of plasma cyclotron frequency is greater, the width of PBGs tends to a constant. Fig.8 also shows that the peak values of transmissivity for LCP wave will tend to a constant with increasing plasma cyclotron frequency. Fig.9 also shows that the MPPCs have a diagonal forbidden band and the peak values of transmissivity for RCP wave will tend to a constant with greater value of plasma cyclotron frequency. This can be explained by that both LCP and RCP wave have two pass bands [11] and one forbidden band[11]. The forbidden band for LCP wave is given by: $\omega_b < \omega_L < \omega_c$,where $\omega_c = \sqrt{\omega_p^2 + \omega_b^2/4} - \omega_b/2$, The forbidden band for RCP wave is given by: $\omega_b<\omega_L<\omega_c^1$, where $\omega_c^1=\sqrt{\omega_p^2+\omega_b^2/4}+\omega_b/2$. Therefore, the incident EM wave energy is absorbed obviously (the peak values of transmissivity decrease) by the magnetized plasmas only the incident EM wave frequency is greater than the plasma cyclotron frequency. If the incident EM wave frequency is less than the plasma cyclotron frequency, the incident EM wave frequency is in pass band so that the incident EM wave energy is hardly absorbed (the peak values of transmissivity reach a constant) and the PBGs are periodic at the same time. Because the maximum of the LCP wave cut-off frequency does not exceed 3.5 GHz, the plasma cyclotron frequency has a little influence on the low-frequency stage of PBGs and the MPPCs have periodic PBGs. The value of the RCP wave cut-off frequency linearly increases with increasing plasma cyclotron frequency so that the MPPCs have not the periodic PBGs and the PBGs are broadened. Consequently, the MPPCs have the periodic PBGs and the PBGs can't be broadened by changing plasma cyclotron frequency as LCP wave propagating through the MPPCs. But we can control the width of the PBGs by changing plasma cyclotron frequency as RCP wave propagating through the MPPCs.

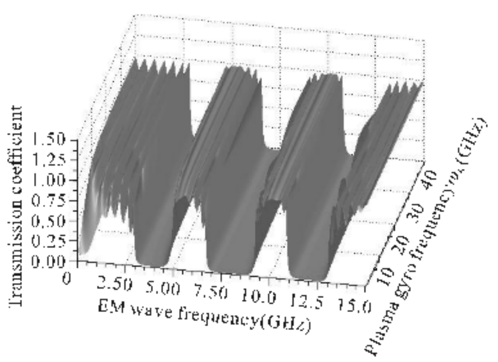

Fig.8 Transmission coefficients versus frequency for LCP wave as ω_b=1 to 40 GHz

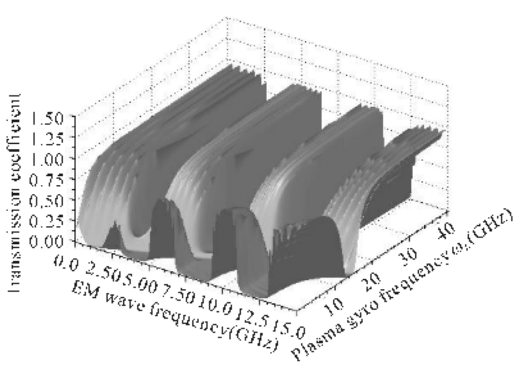

Fig.9 Transmission coefficients versus frequency for RCP wave as ω_b = 1 to 40 GHz

Fig.10 plots transmission coefficients magnitude versus frequency for LCP wave as ω_p =1 to 25 GHz. Fig.11 plots transmission coefficients magnitude versus frequency for RCP wave as ω_p =1 to 25 GHz.

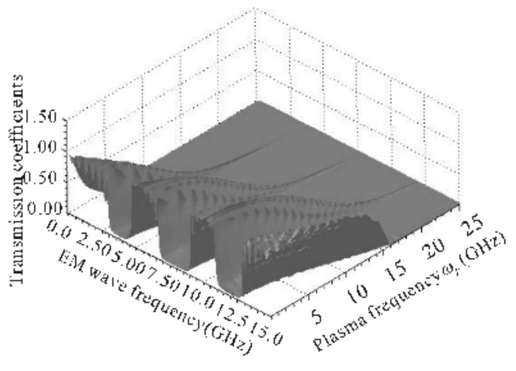

Fig.10 Transmission coefficients versus frequency for LCP wave as ω_p =1 to 25 GHz

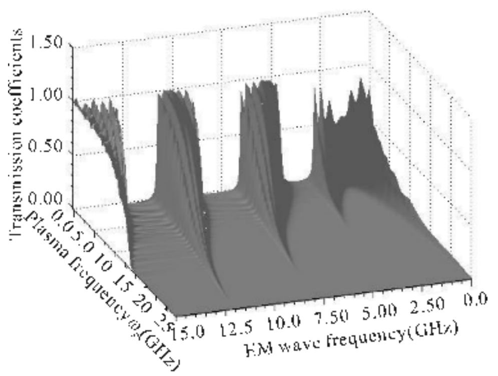

Fig.11 Transmission coefficients versus frequency for LCP wave as ω_p = 1 to 25 GHz

Fig.10 and Fig.11 show that the MPPCs have the periodic PBGs only plasma frequency is smaller as LCP and RCP wave propagation through the MPPCs. If the value of plasma frequency is greater, the MPPCs haven't the periodic PBGs but the widthes of PBGs are broadened. It is obviously that the incident EM is totally reflected as ω_p is 21 GHz. Fig.10 and Fig.11 also show that the peak values of transmissivity for LCP or RCP wave decrease sharply with the increasing plasma frequency.We can control the PBGs by changing plasma collision but the MPPCs maybe have not the periodic PBGs.

In summary, the PLCDRC-FDTD method is applied to simulate one dimension homogeneous and time invariant MPPCs . The results show theoretically that the MPPCs can lead to the PBGs which are analogous to the conventional PCs as LCP and RCP wave propagation through the MPPCs.

The width of the PBGs can be broadened by changing the plasma thickness and plasma frequency but the MPPCs have not the periodic PBGs. Changing the periodic structure constant and plasma collision frequency can not broaden the width of PBGs but the MPPCs have the periodic PBGs. If the incident LCP or RCP wave frequency are far less than the plasma frequency and plasma collision frequency , the decrements of LCP and RCP wave increase sharply then decrease slowly and reach a constant finally. Therefore, the MPPCs have the same periodic PBGs even the plasma frequency and plasma collision frequency change in a large frequency range. Changing the plasma cyclotron frequency, the width of PBGs can not be broadened and the MPPCs have the periodic PBGs as LCP wave propagation through the MPPCs but as RCP wave propagation through the MPPCs, the PBGs can be broadened and the MPPCs have not the periodic PBGs.

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