第 33 卷　第 7 期　　发　光　学　报　　Vol. 33　No. 7
2012 年 7 月　　CHINESE JOURNAL OF LUMINESCENCE　　July, 2012

Article ID: 1000-7032(2012)07-0747-07

A Novel Tunable Filter Using Magnetized Plasma Defect in One-demension Photonic Crystal

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Abstract: A novel tunable filter featuring the defect mode of the TM wave from one-dimensional photonic crystals doped by magnetized plasma is investigated. Firstly, based on the continuous condition of boundary, the transfer matrix is deduced for magnetized plasma where external magnetic field is perpendicular to wave vector. Then by the transfer matrix method (TMM), we find out that the frequency of the defect mode can be modulated by plasma frequency or external magnetic field. Without changing the structure of the photonic crystal, the location of the defect mode can be modulated in a larger frequency range, and the number of the defect modes can also be controlled.

Key words: photonic crystals; magnetized plasma; transfer matrix method

CLC number: O734　　**Document code**: A　　**DOI**: 10.3788/fgxb20123307.0747

基于磁化等离子体缺陷层的一维新颖可调谐的光子晶体滤波特性

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摘要: 将磁化等离子体填充到一维光子晶体的缺陷层,构成了一种新颖可调谐的滤波器。讨论了 TM 波情况下滤波器的滤波特性,并推导了 TM 波下磁化等离子体传输矩阵。通过改进的传输矩阵方法分析得到:在不改变光子晶体结构的情况下,通过改变等离子体频率和外磁场可以实现滤波通道在光子禁带内较大带宽范围的移动,同时禁带中滤波通道出现的数目也能被等离子频率与外磁场的大小控制。

关　键　词: 光子晶体; 磁化等离子体; 传输矩阵法

1　Introduction

Since the original work of Yablonovitch[1] and John[2], photonic crystals with period modulation of the dielectric constant have attracted considerable attention. It has been proven that a photonic band gap (PBG) could be formed as a result of the interference of Bragg scattering in a periodical dielectric structure. Photonic band structures strongly depend on the geometry of the lattice and the dielectric indices of the components. Therefore, much attention has been paid to the periodic multilayered structure

收稿日期: 2012-02-29; **修订日期**: 2012-05-14
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of different materials such as dielectrics, semiconductors, liquid crystals, and metals[3-5].

Recently, this active research area has been extended to plasma photonic crystal (PPC)[6-23]. Plasma is a kind of dispersive medium. Therefore, PPCs contain more particular characteristics than the conventional PCs. Hojo H *et al.*[6] first considered the dispersion relation of the electromagnetic (EM) waves in the one dimension plasma photonic crystals (1DPPCs) and found that its band gap becomes larger with an increase of the plasma density and thickness. Li *et al.*[7] analyzed the characteristic of the EM wave propagation in the PPCs and found that the PPCs feature the structure of photonic energy band and energy gap. Shiveshwari L *et al.*[8] discussed the PBG structure of the 1DPPC in terms of plasma density, plasma width, and the number of unit cells. Liu *et al.*[9-10] adopted the finite-difference time-domain (FDTD) method to study the propagation process with Gauss pulses passing in the unmagnetized and magnetized PPCs. In time-domain, the reflection and transmission electric field of EM waves have been investigated. In frequency-domain, the reflection and transmission coefficients of the pulses through the two kinds of crystals have been computed. Guo[11-12] studied the dispersion relation of obliquely incident EM waves in 1DPPC and discussed the dependences of dispersion relation on incident angle, collision frequency, plasma-filling factor, and dielectric constant of dielectric, respectively. Qi *et al.*[13] focused on the properties of the transmission and the dispersion relation influenced by the external magnetic field, *etc.*

All the works mentioned above were devoted to investigation of the regular structures, None of them was introduced as a plasma defect in the conventional one-dimensional dielectric-air PC until Wang[14] posed the 1DPC doped by unmagnetized plasma defect layer, Zhang *et al.*[15-16] and Kong *et al.*[17] investigated the transmission characteristics of the 1DPC with magnetized plasma defects layer, where external magnetic field is parallel to wave vector. Results showed that defect modes of left-hand circular polarization and right-hand circular polarization can be controlled by external magnetic field as well as plasma parameters. In this paper, when external magnetic field is perpendicular to wave vector, we theoretically tend to investigate the dependence of the magnetized plasma defect mode of the 1DPCs composed by dielectric and air on the plasma parameters. According to the TMM, in contrast to the unmagnetized plasma defect mode, the defect mode can be modulated in a wider frequency range without altering the structure of the PCs. By varying the plasma frequency and external magnetic filed, the number of resonant frequency of defect modes can be controlled. Based on the calculated results, a multichannel transmission filter can be achieved within the PBG.

2 Theoretical Model and Formulations

Consider the periodic structure in the 1DPCs with $(AB)^N ACA (BA)^N$ shown in Fig. 1, where A and B represent two kinds of material layers, respectively, and N is the number of periods.

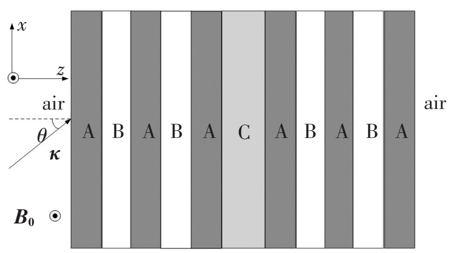

Fig. 1 Schematic of a one dimensional photonic crystal with a defect layer

The defect layer C, which generates defect modes inside the PBGs, is the magnetized plasma material. The dielectric layers are in the x-y plane, and the z direction is normal to the interface of each layer. The external magnetic filed $\boldsymbol{B}_0$ is perpendicular to wave vector $\boldsymbol{\kappa}$. Let a wave be incident from a vacuum at an angle θ onto the periodical layered structure. The relative dielectric function of dielectrics and plasma are $\boldsymbol{\varepsilon}_a$, $\boldsymbol{\varepsilon}_b$ and $\boldsymbol{\varepsilon}_c$ with thicknesses a, b and c, respectively.

When the external magnetic filed is introduced, which is perpendicular to wave vector, and the relative dielectric function of plasma is[24]:

$$\boldsymbol{\varepsilon}_c = \begin{pmatrix} \varepsilon_1 & 0 & i\varepsilon_2 \\ 0 & \varepsilon_3 & 0 \\ -i\varepsilon_2 & 0 & \varepsilon_1 \end{pmatrix}, \qquad (1)$$

Where

$$\varepsilon_1 = 1 - \frac{\omega_p^2(\omega - i\nu)}{\omega[(\omega - i\nu)^2 - \omega_c^2]}, \quad (2)$$

$$\varepsilon_2 = \frac{-\omega_p^2\omega_c}{\omega[(\omega - i\nu)^2 - \omega_c^2]}, \quad (3)$$

$$\varepsilon_3 = 1 - \frac{\omega_p^2}{\omega(\omega - i\nu)}, \quad (4)$$

ν is the collision frequency. $\omega_c = eB_0/m$ and $\omega_p = (e^2 n_e/\varepsilon_0 m)^{1/2}$ are the cyclotron frequency and the plasma frequency, respectively. n_e is plasma density. For the electric filed of the EM wave parallel to the external magnetic filed, which is denotes by $\boldsymbol{E}$ polarization, the dielectric function of plasma will not be altered by external magnetic filed. Thus, magnetized plasma is isotropic medium for TE wave. Since Wang[14] analyzed the properties of 1DPC containing unmagnetized plasma defect with $\boldsymbol{E}$ polarization in detail, thus we only consider $\boldsymbol{H}$ polarization in the following. For $\boldsymbol{H}$ polarization, due to the influence of the Lorentz force, plasma dielectric function is modulated by the external magnetic filed. Consequently, the TMM for isotropic dielectric is not suitable for our model.

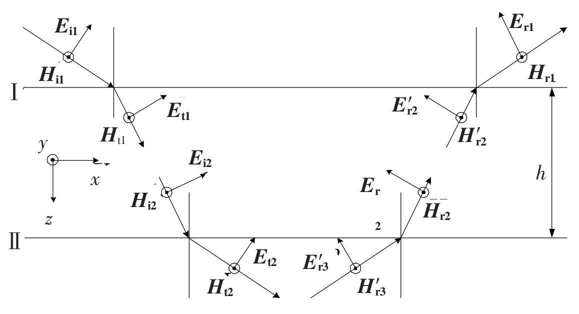

Fig. 2 Distribution of electromagnetic filed in one magnetized plasma layer

In order to obtain TMM for our model, we start from the Maxwell equation. In the case of $\boldsymbol{H}$ polarization, $\boldsymbol{E} = (E_x, 0, E_z)e^{i\omega t}$ and $\boldsymbol{H} = (0, H_y, 0)e^{i\omega t}$, thus Maxwell equation can be rewritten as

$$\frac{\partial E_z}{\partial x} - \frac{\partial E_x}{\partial z} = i\omega\mu_0\mu H_y, \quad (5)$$

$$\frac{\partial H_y}{\partial x} = i\omega\varepsilon_0\varepsilon_1 E_z + \omega\varepsilon_0\varepsilon_2 E_x, \quad (6)$$

$$\frac{\partial H_y}{\partial z} = -i\omega\varepsilon_0\varepsilon_1 E_x + \omega\varepsilon_0\varepsilon_2 E_z, \quad (7)$$

from Eq. (5), Eq. (6) and Eq. (7), we can obtain

$$\frac{\partial^2 H_y}{\partial x^2} + \frac{\partial^2 H_y}{\partial z^2} + k_{TM}^2 H_y = 0, \quad (8)$$

where $k_{TM}^2 = \varepsilon_{TM}\mu\,\omega^2/c^2$, ε_{TM} is the effective dielectric function for $\boldsymbol{H}$ polarization, which can be expressed as follows:

$$\varepsilon_{TM} = \frac{{\varepsilon_1}^2 - {\varepsilon_2}^2}{\varepsilon_1}, \quad (9)$$

when the effective dielectric function $\varepsilon_{TM} = \infty$, $\omega = \omega_H = \sqrt{\omega_p^2 + \omega_c^2}$ can be acquired, and ω_H is cyclotron resonance frequency. From $\varepsilon_{TM} = 0$, we can obtain $\omega = \omega_{R,L} = 0.5[\sqrt{4\omega_p^2 + \omega_c^2} \pm \omega_c]$. ω_R and ω_L are right cutoff frequency and left cutoff frequency, respectively.

Eq. (8) general solution is

$$\boldsymbol{H_y} = (H_+ e^{-ik_z z} + H_- e^{ik_z z})e^{i(\omega t - k_x x)}, \quad (10)$$

substituting Eq. (10) into Eq. (6) and Eq. (7), we obtain

$$\boldsymbol{E_x} = \left[\left(\frac{ik_x\varepsilon_2 + k_z\varepsilon_1}{\varepsilon_0\varepsilon_1\omega\varepsilon_{TM}}\right)H_+ e^{-ik_z z} + \left(\frac{ik_x\varepsilon_2 - k_z\varepsilon_1}{\varepsilon_0\varepsilon_1\omega\varepsilon_{TM}}\right)H_- e^{ik_z z}\right]e^{i(\omega t - k_x x)}, \quad (11)$$

$$\text{where } k_z = \begin{cases} \sqrt{{k_0}^2\varepsilon_{TM}\mu - {k_x}^2} & {k_x}^2 < {k_0}^2\varepsilon_{TM}\mu \\ -i\sqrt{{k_x}^2 - {k_0}^2\varepsilon_{TM}\mu} & {k_x}^2 > {k_0}^2\varepsilon_{TM}\mu \end{cases}$$

and $k_x = k_0\sin\theta$. Fig. 2 gives the distribution of the electric and magnetic fields in the single layer with $\boldsymbol{H}$ polarization. At the boundary Ⅰ, the tangential components of both $\boldsymbol{E}$ and $\boldsymbol{H}$ should be continuous. Thus, this leads to the following equations,

$$H_{\mathrm{I}} = H_{i1} + H_{r1} = H_{t1} + H'_{r2} = H_{t1y} + H'_{r2y}, \quad (12)$$

$$E_{\mathrm{I}} = E_{i1x} + E_{r1x} = E_{t1x} + E'_{r2x}, \quad (13)$$

from Eq. (10), Eq. (11), Eq. (12) and Eq. (13) above, we can obtain

$$\begin{pmatrix} E_{\mathrm{I}} \\ H_{\mathrm{I}} \end{pmatrix} = \begin{pmatrix} \frac{ik_x\varepsilon_2 + k_z\varepsilon_1}{\varepsilon_0\varepsilon_1\omega\varepsilon_{TM}} & \frac{ik_x\varepsilon_2 - k_z\varepsilon_1}{\varepsilon_0\varepsilon_1\omega\varepsilon_{TM}} \\ 1 & 1 \end{pmatrix}\begin{pmatrix} H_{t1y} \\ H'_{r2y} \end{pmatrix}, \quad (14)$$

in a similar way at the boundary Ⅱ

$$\begin{pmatrix} E_{\mathrm{II}} \\ H_{\mathrm{II}} \end{pmatrix} = \begin{pmatrix} \frac{ik_x\varepsilon_2 + k_z\varepsilon_1}{\varepsilon_0\varepsilon_1\omega\varepsilon_{TM}} & \frac{ik_x\varepsilon_2 - k_z\varepsilon_1}{\varepsilon_0\varepsilon_1\omega\varepsilon_{TM}} \\ 1 & 1 \end{pmatrix}\begin{pmatrix} H_{i2y} \\ H_{r2y} \end{pmatrix}, \quad (15)$$

And, the relation of magnetic filed between boundary Ⅰ and Ⅱ in the dielectric material can be given by

$$\begin{pmatrix} H_{i2y} \\ H_{r2y} \end{pmatrix} = \begin{pmatrix} e^{-ik_z h} & 0 \\ 0 & e^{ik_z h} \end{pmatrix} \begin{pmatrix} H_{t1y} \\ H'_{r2y} \end{pmatrix}, \quad (16)$$

according to Eq. (14), Eq. (15) and Eq. (16), the electric and magnetic fields in the two interfaces of one layer can be correlated by

$$\begin{pmatrix} E_{\mathrm{I}} \\ H_{\mathrm{I}} \end{pmatrix} = \boldsymbol{M}_{\mathbf{c}} \begin{pmatrix} E_{\mathrm{II}} \\ H_{\mathrm{II}} \end{pmatrix}, \quad (17)$$

where $\boldsymbol{M}_{\mathbf{c}}$ for our model is

$$\boldsymbol{M}_{\mathbf{c}} = \begin{pmatrix} \cos k_z h - \dfrac{k_x \varepsilon_2}{k_z \varepsilon_1} \sin k_z h & \dfrac{ik_z}{\omega \varepsilon_0 \varepsilon_{\mathrm{TM}}} \left[1 + \left(\dfrac{k_x \varepsilon_2}{k_z \varepsilon_1} \right)^2 \right] \sin k_z h \\ \dfrac{i\omega \varepsilon_0 \varepsilon_{\mathrm{TM}}}{k_z} \sin k_z h & \cos k_z h + \dfrac{k_x \varepsilon_2}{k_z \varepsilon_1} \sin k_z h \end{pmatrix}, \quad (18)$$

likewise, transfer matrix $\boldsymbol{M}_{\mathbf{a}}$ and $\boldsymbol{M}_{\mathbf{b}}$ for dielectric layer can be written as

$$\boldsymbol{M}_i = \begin{pmatrix} \cos k_{iz} h & \dfrac{ik_{iz}}{\omega \varepsilon_0 \varepsilon_i} \sin k_{iz} h \\ \dfrac{i\omega \varepsilon_0 \varepsilon_i}{k_{iz}} \sin k_{iz} h & \cos k_{iz} h \end{pmatrix}, \quad (19)$$

where $k_{iz} = k_0 \sqrt{\varepsilon_i \mu - \sin\theta^2}$, $i = a, b$. Therefore, when there are $2N+3$ layers with defect modes for PPC, the transfer matrix at the input and output boundary can be expressed as follows:

$$\boldsymbol{M} = (\boldsymbol{M}_{\mathbf{a}} \boldsymbol{M}_{\mathbf{b}})^N \boldsymbol{M}_{\mathbf{a}} \boldsymbol{M}_{\mathbf{c}} \boldsymbol{M}_{\mathbf{a}} (\boldsymbol{M}_{\mathbf{a}} \boldsymbol{M}_{\mathbf{b}})^N, \quad (20)$$

if we denote by m_{ij}, with $i, j = 1, 2$, the elements of the matrix $\boldsymbol{M}$, expressions for the amplitude reflection and transmission coefficients (r and t) are readily derived up to a phase factor,

$$r = \frac{m_{11}\eta_0 + m_{12}\eta_0\eta_{n+1} - m_{21} - m_{22}\eta_0}{m_{11}\eta_0 + m_{12}\eta_0\eta_{n+1} + m_{21} + m_{22}\eta_0}, \quad (21)$$

$$t = \frac{2\eta_0}{m_{11}\eta_0 + m_{12}\eta_0\eta_{n+1} + m_{21} + m_{22}\eta_0}, \quad (22)$$

where $\eta_0 = \eta_{n+1} = \sqrt{\varepsilon_0/\mu_0}/\cos\theta$ for the vacuum of the space before the incident end and the space after the exit end. Moreover, the reflectance R and transmittance T are given by

$$R = |r|^2, \ T = |t|^2. \quad (23)$$

3 Results and Discussion

3.1 Calculation Results and Analysis

In order to design a photonic crystal with a wide band gap and a tunable defect mode in a wider frequency range, we choose the structure parameters as follows: $N=2$, $\varepsilon_a = 4 (n_a = 2)$, $a = 7.4$ mm, $\varepsilon_b = 1 (n_b = 1)$, and $b = 14.8$ mm. The layers A and B refer to SiO_2 and air, respectively. Because of $n_a a = n_b b = \lambda_0/4$, the PC structure can be considered as a quarter-wave stack with basic frequency $f_0 = c/2(n_a a + n_b b) = 5.068$ GHz. Obviously, a photonic band gap could be formed as a result of the interference of Bragg scattering in a periodical dielectric. Adding another air layer in the middle of the structure, then two air layers will act as a half-wave defect layer C, which will open up a narrow transmission window at λ_0 in the middle of its reflecting band. When there are external magnetic filed and RF power in defect layer C, layer C becomes magnetized plasma which is an ionized gas. Plasma is dispersive medium and its equivalent refractive index is related to the plasma frequency and external magnetic filed, so it is feasible to shift the syntonic frequency of plasma defect by changing plasma parameters. Subsequently, we investigate how defect modes vary with external magnetic filed and plasma frequency.

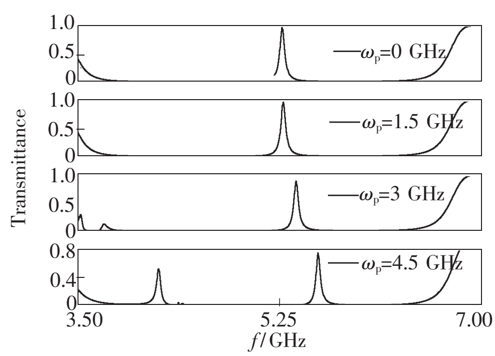

Fig. 3 Transmittance of the 1DPC doped by magnetized plasma layers with different plasma frequency

3.1.1 Influence of plasma frequency

When external magnetic filed is perpendicular to wave vector, plasma is isotropic for TE wave and anisotropic for TM wave. Thus, there is different transmission characteristic at normal incidence for the two polarizations. Here, we only consider the TM wave normal incident to 1DPC and focus on the first band gap near λ_0 ($\lambda_0 = 5.068$ GHz). The parameters are $N = 2$, $\theta = 0$, $\omega_c = 2$ GHz, $\nu = 0.01$ GHz, and $c = 0.5\lambda_0$. As shown in Fig. 3, the transmission spectrum of tunable defect mode with different plasma frequency can be acquired. When the plasma frequency ω_p equals to zero, the defect layer corresponds to the air layer, the defect mode presents itself at the basic frequency $f_0 = 5.068$ GHz. With the increase of plasma frequency, resonant frequency of plasma defect move to the higher frequencies region. According to Fig. 4 which gives the relation between the real part $\mathrm{Re}(\varepsilon_{TM})$ of ε_{TM} and external magnetic field, with the increase of plasma density, the refractive index of defect layer decreases between 3.5 GHz and 6.6 GHz. As a result of the decreased optical width of the defect layer, the resonant EM wave frequency rises. In Fig. 4, because an external magnetic field is introduced, the corresponding magnitude of $\mathrm{Re}(\varepsilon_{TM})$ has two peaks. This phenomenon is awoken by the Lorentz force. When EM wave frequency is in the range of $\omega_L < \omega < \omega_H$ and $\omega > \omega_R$, the effective dielectric function is greater than zero. While if EM wave frequency is in the range $\omega_H < \omega < \omega_R$ and $\omega < \omega_L$, the effective dielectric function is less than zero. Therefore, there are two pass bands and two stop bands for magnetized plasma layer, which may generate more than one defect modes in PBG, as shown in Fig. 3 and Fig. 5. Obviously, by adjusting the plasma frequency, the number of the defect modes can be effectively controlled. In Fig. 5, as the plasma frequency swells from 3 GHz to 5.83 GHz, there are three defect

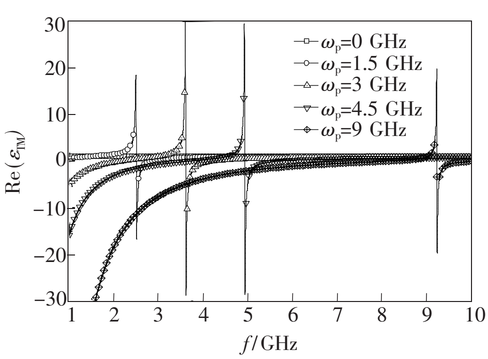

Fig. 4　The real part of ε_{TM} *vs* plasma frequency

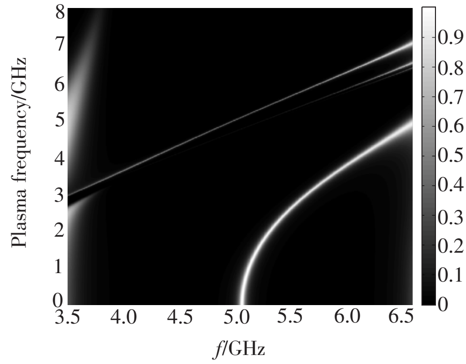

Fig. 5　Transmittance of the finite structure $(AB)^2ACA(BA)^2$ obtained by TMM. The result is consistent with that of Fig. 3.

modes. However, there are only two ones between 5.83 GHz and 7.77 GHz. From Fig. 4 and Fig. 5, when the plasma density rises up to a higher value, the cutoff frequency of the plasma excels the edge of the band gap, there will be no defected mode in the gap.

Plasma frequency is a function of the plasma density, and plasma density can be changed by controlling the applied RF power in discharge plasma[25]. Therefore, according to Eq. (2), Eq. (3), Eq. (4) and Eq. (9), varying the applied power in the 1DPPC can change refractive index of plasma, so that the transmission property of multichannel filter can be adjusted without changing the structure of the photonic crystal. Thus plasma frequency is a very important parameter for designing filters.

3.3.2　Influence of external magnetic filed

Based on $N = 2$, $\theta = 0$, $\omega_p = 2$ GHz, $\nu = 0.01$ GHz and $c = 0.5\lambda_0$ for different external magnetic field, the transmittance spectrum is shown in Fig. 6. When $\omega_c = 0$, it is clear that the peak transmittance inside the band gap appears at $\omega > 5.068$ GHz, about 5.274 GHz. With the increase of the external magnetic field, the position of the defect mode moves to the higher frequency of EM waves. This is because optical width of the defect layer decreases as EM waves varying from 3.5 GHz to 6.6 GHz, as shown in Fig. 7. As a result of the effect of external magnetic filed, there are more pass bands and stop bands for magnetized plasma layer one. Thus more than one resonant frequency inside the band gap can be acquired. From Fig. 7, with the increase of external magnetic filed, the corresponding magnitude of Re(ε_{TM}) is approximately approaches 1 between 3.5 GHz and 6.6 GHz. Consequently, when external magnetic filed becomes larger in the plasma defect layer C, the layer C can be considered as the air. The defect mode appears at near λ_0 (λ_0 = 5.068 GHz) as shown in Fig. 8.

Compared with the 1DPC doped by unmagnetized plasma layer, the magnetized plasma layer can

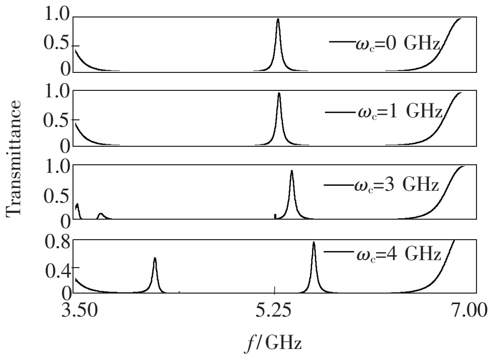

Fig. 6 Transmittance of the 1DPC doped by magnetized plasma layers with external magnetic field

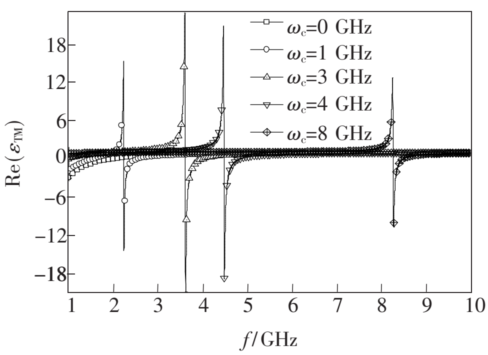

Fig. 7 The real part of ε_{TM} *vs.* external magnetic filed

modulate location and the number of the defect modes in a larger frequency range by changing the external magnetic field without varying the structure of the filter. This advantage is much outstanding in designing the given filter.

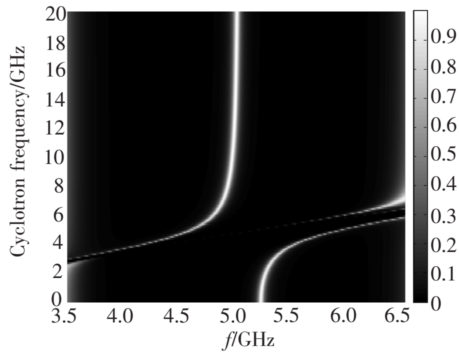

Fig. 8 Transmittance of the finite structure $(AB)^2ACA(BA)^2$ obtained by TMM. The result is consistent with that of Fig. 6

4 Conclusion

In conclusion, we have demonstrated the possibility of making a tunable filter from 1DPCs doped by magnetized plasma, which features the defect mode of the TM wave. Compared with those doped by normal material or unmagnified plasma, 1DPC doped by magnetized plasma layer can modulate the location and the number of defect mode by plasma frequency or external magnetic field without changing the structure of the filter. These unusual transmission properties may provide a new means of controlling signal in future microwave device.

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