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Compton 散射对 1 维 3 元未磁化等离子体光子晶体禁带影响

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摘要： 为了研究 Compton 散射对 1 维 3 元未磁化等离子体光子晶体中 TE 波禁带影响，采用 Compton 散射模型和传输矩阵法，进行了理论分析和实验验证，取得了一些重要数据。结果表明，随着等离子体频率增大，左旋和右旋极化波禁带展宽比散射前减小 0.09GHz，禁带主频率向高频区域移动增大 0.48GHz。随着等离子体碰撞频率增大，两种极化波禁带宽度发生一定变化。随着等离子体回旋频率、填充率、光入射角和介质相对介电常数增大，左旋和右旋极化波禁带明显调谐效应。这一结果对等离子体光子晶体应用是有帮助的。

关键词： 非线性光学；禁带；传输矩阵法；等离子体光子晶体
中图分类号： O437；O53 **文献标识码：** A **doi**：10.7510/jgjs.issn.1001-3806.2013.04.022

Effect of Compton scattering on prohibited band gaps for 1-D ternary un-magnetized plasma photonic crystals

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Abstract: In order to study the effect of Compton scattering on TE wave prohibited band gaps of 1-D ternary un-magnetized plasma photonic crystals, based on the model of Compton scattering and transfer matrix method, some important data was obtained after the theoretical analysis and experimental verification. The broadening width of prohibited band gap of the left circle polarization wave and the right circle polarization wave were decreased 0.09GHz along with the increasing of plasma frequency after Compton scattering. The movement from the central frequency area of prohibited band gap to the high frequency area was increased 0.48GHz. The change of prohibited band gaps widths of the left circle polarization wave and the right circle polarization wave happened along with the increasing of plasma collision frequency. The significant tuning effect of prohibited band gaps of the left circle polarization wave and the right circle polarization wave was induced by Compton scattering along with the increasing of plasma circle frequency, filling index, light incident angle and relative dielectric constant. The result is helpful for the application of the plasma photonic crystals.

Key words: nonlinear optics; band gap; transfer matrix method; plasma photonic crystal

引 言

HOJO 等人[1]曾提出等离子体光子晶体（plasma photonic crystals, PPC）概念，因其具有许多特性，如调节等离子体参量控制光子带隙[2]、外磁场使等离子体有各向异性等[3]，成为人们研究热点[4-5]。按介质空间分布，可将 PPC 分为 1 维～3 维。虽然 2 维、3 维 PPC 比 1 维有较好特性[6]，但是 1 维 PPC 易制备，对电磁波有禁带，故研究 1 维 PPC 更具现实意义。JOHN[7]和 YABLONOVITCH[8]发现了光子禁带。SAKAI 等人[9]指出，PPC 透射波有类似光子晶子（photonic crystals, PC）带隙特性。ZHANG 等人[10-11]指出，改变等离子体温度与密度可调控禁带。LI 等人[12-13]指出，Compton 散射对 1 维 3 元磁化 PPC 带隙有影响。但未涉及 1 维 3 元未磁化情况下的 Compton 散射。作者对此进行了探索。

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1 理论分析

若等离子体中发生 Compton 散射[14]（简称散射），散射光与入射光形成的耦合光频率为[13]：

$$\omega_c = \omega\left[\frac{N\omega(1+\beta\cos\theta)(1-\beta_f\cos\theta_1{}')}{\eta^2 + \frac{\eta N\hbar\omega(1+\beta\cos\theta)}{mc^2(1-\cos\theta')^{-1}}} - 1\right] \quad (1)$$

式中,$\eta=(\gamma-\gamma_f)/|\gamma-1|$为量度散射非弹性参量;$\gamma_f=[1-(v_f/c)^2]^{-1/2}=(1-\beta_f{}^2)^{-1/2}$和$v_f$分别为电子散射前后的 Lorentz 因子和速度,N为与电子同时作用的光子数,θ为电子和光子散射前运动方向夹角,$\theta_1{}'$为实验室系中光子散射角,θ'为电子静止系中电子和光子运动方向夹角,c为真空中的光速,$h=2\pi\hbar$为普朗克常数,ω为入射光频率,m为电子静质量。设等离子体耦合频率、碰撞频率和回旋频率分别为$\omega_{c,p}=\omega_p+\Delta\omega_p$,$\nu_{c,p}=\nu_p+\Delta\nu_p$,$\omega_{c,b}=\omega_b+\Delta\omega_b$,$(\omega_p,\nu_p,\omega_b)$及$(\Delta\omega_p,\Delta\nu_p,\Delta\omega_b)$分别为散射前等离子体频率、碰撞频率、回旋频率及其相应增量。则有:

$$\omega_{c,p}{}^2 = \frac{4\pi e n_{c,e}}{mc}, \nu_{c,p} = \frac{\omega_c}{2\pi}, \omega_{c,b} = \frac{B+B_{s,//}}{me^{-1}} \quad (2)$$

式中,$n_{c,e}=n_e+\Delta n_e$为电子耦合密度,B和$B_{s,//}$分别为入射光和散射光同向磁场强度。此外,ε_i($i=1,2$)和ε_p,$\Delta\varepsilon_i$和$\Delta\varepsilon_p$分别为介质 A 和 B 及等离子体 D 的介电系数及其相应增量。a和c,b分别为介质 A 和 B 厚度和等离子体厚度,如图 1 所示。

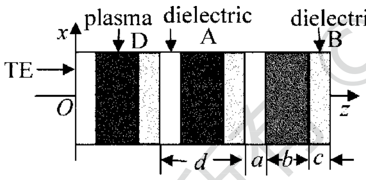

Fig. 1 Physics model

取$\omega_p=7.9\pi\times10^9$rad/s,$\Delta\omega_p=10^8$rad/s;$\nu_p=1.9\pi\times10^9$rad/s,$\Delta\nu_p=\pi\times10^8$rad/s;$\omega_b=11.9\times10^9$rad/s,$\Delta\omega_b=10^8$rad/s;$\varepsilon_1=13.8$,$\Delta\varepsilon_1=0.1$,$\varepsilon_2=3.8$,$\Delta\varepsilon_2=0.1$;$a=5$mm,$b=9$mm,$c=7$mm,周期$\alpha=20$;$\theta=0°$。模电场(transversal electric field,TE)和模磁场(transversal magnetic field,TM)电场与B和$B_{s,//}$垂直和平行,TE 波形成左旋(left-handed circularly polarized,LCP)和右旋(right-handed circularly polarized,RCP)极化波。等离子体介电系数为:

$$\varepsilon_{c,p} = \left[1 - \frac{\omega_{c,p}{}^2}{\omega(\omega - j\nu \pm \omega_b)}\right] \quad (3)$$

式中,±分别对应 LCP 波和 RCP 波。耦合光可表示为[15]:

$$\boldsymbol{M}_{c,j} = \begin{bmatrix} \cos\delta_j & -\mathrm{i}\sin\delta_j/p_j \\ -\mathrm{i}p_{c,j}\sin\delta_j & \cos\delta_j \end{bmatrix} \quad (4)$$

$$\delta_{c,j} \approx \frac{2\pi}{\lambda}n_{c,j}d_j\cos\theta_j, p_{c,j} \approx n_{c,j}\cos\theta_j \quad (5)$$

式中,$n_{c,j}=n_j+\Delta n_j$,d_j,$\theta_{c,j}=\theta_j+\Delta\theta_j$及$n_j$和$\Delta n_i$,$\theta_j$和$\Delta\theta_j$分别为$j$层介质耦合折射率、厚度、入射角及散射前折射率和入射角及其增量。推导应用了$\cos\Delta\delta_j=\cos\Delta\theta_j=1$,$\sin\Delta\delta_j=0$关系。经$\alpha$个周期后,电、磁场、透射系数分别为:

$$\begin{bmatrix} E_{c,1} \\ H_{c,1} \end{bmatrix} \approx (\boldsymbol{M}_{c,A}\boldsymbol{M}_{c,D}\boldsymbol{M}_{c,B})^{\alpha}\begin{bmatrix} E_{c,(\alpha+1)} \\ H_{c,(\alpha+1)} \end{bmatrix} = \begin{bmatrix} M_{c,11} & M_{c,12} \\ M_{c,21} & M_{c,22} \end{bmatrix}\begin{bmatrix} E_{c,(\alpha+1)} \\ H_{c,(\alpha+1)} \end{bmatrix} \quad (6)$$

$$T_c \approx \frac{2n_{c,0}}{(M_{11}+M_{12})n_0 + (M_{21}+M_{22}n_0)} \quad (7)$$

式中,$E(H)_{c,1}=E(H)_1+\Delta E(H)_1$,$\boldsymbol{M}_{c,A(D,B)}=\boldsymbol{M}_{A(D,B)}+\Delta\boldsymbol{M}_{A(D,B)}$,$M_{c,11(12)}=M_{11(12)}+\Delta M_{11(12)}$,$M_{c,21(22)}=M_{21(22)}+\Delta M_{21(22)}$,$n_{c,0}=n_0+\Delta n_0$,$E(H)_{c,(\alpha+1)}=E(H)_{\alpha+1}+\Delta E(H)_{\alpha+1}$。$E(H)_1$和$n_0$,$\Delta E(H)_1$和$\Delta n_0$分别为散射前电场(磁场)、空气折射率及其相应增量。左旋和右旋极化波的透射频谱如图 2 所示,与参考文献[10]比较可知,位置未变的高频禁带变窄,低频禁带向高频移动。

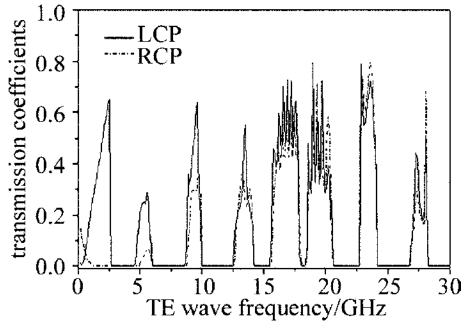

Fig. 2 Transmission spectum of LCP and RCP

2 数值模拟

2.1 等离子体频率对禁带影响

$\omega_{c,p}=1$GHz~25GHz 的 LCP 和 RCP 透射频谱如图 3 所示。与参考文献[10]比较可知,随着$\omega_{c,p}$增大,两禁带展宽减小约 0.1GHz,禁带频率向高频移动约增大 0.45GHz。这是因为$\omega_{c,p}$越大,极化电子和等离子体吸收光越多,光衰减效应增大而减小了禁带拓展效应;$\omega_{c,p}>>\omega$,光被截止;$\omega<10$GHz,透射率峰值几乎减至为 0。

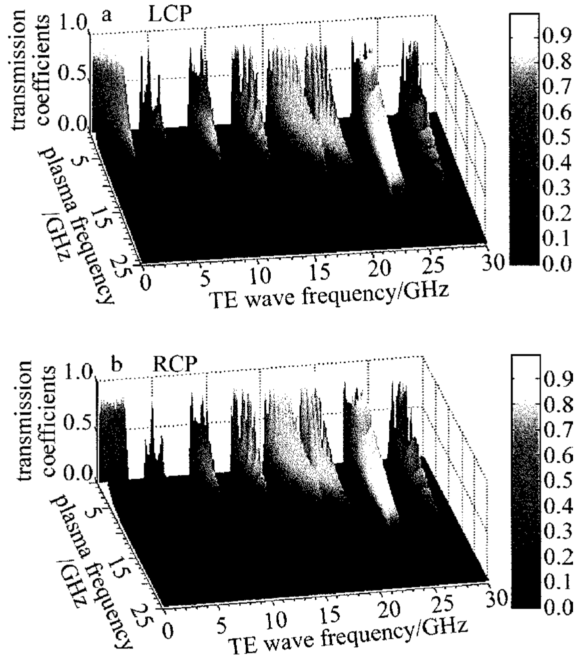

Fig. 3　Transmission spectrum when $\omega_{c,p}$ = 1GHz ~ 25GHz

2.2　等离子体碰撞频率对禁带影响

$\nu_{c,p}$ = 0.1GHz ~ 85GHz 的 LCP 和 RCP 透射频谱如图 4 所示。与参考文献[10]比较可知，随着 $\nu_{c,p}$ 增大，透射率峰值先迅速减小后再逐渐增大。这是因为 $\nu_{c,p}$ 增大，电子未完全极化与中性离子碰撞而降低吸收的缘故。

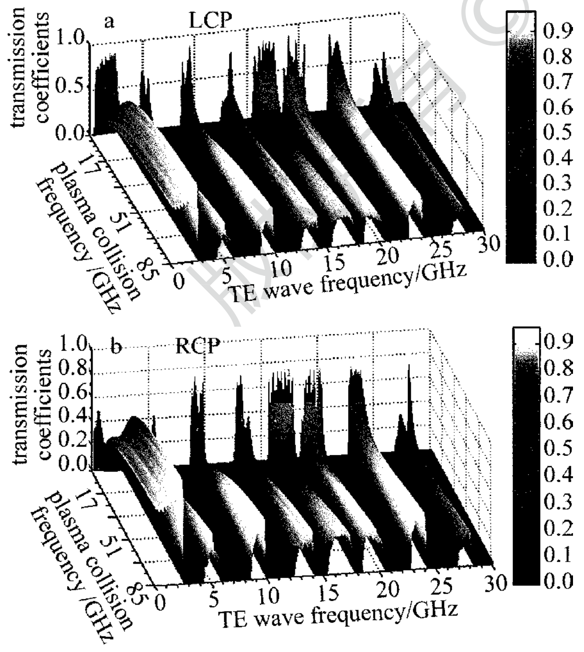

Fig. 4　Transmission spectrum when $\nu_{c,p}$ = 0.1GHz ~ 85GHz

2.3　等离子体回旋频率对禁带影响

$\omega_{c,b}$ = 0.1GHz ~ 40GHz 的 LCP 和 RCP 透射频谱如图 5 所示。由 $(\omega_{c,p}^{2} + \omega_{c,b}^{2})^{1/2} \mp \omega_{c,b}/2$[15] 可知，随着 $\omega_{c,b}$ 增大，RCP 上截止频率近似线性增大，

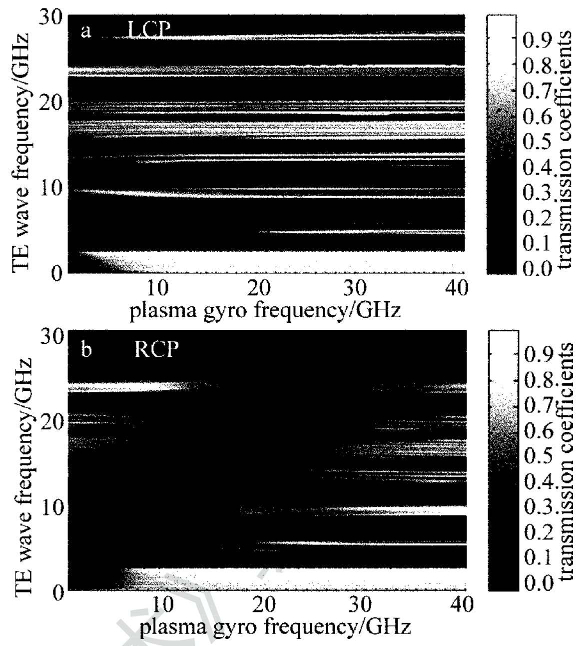

Fig. 5　Transmission spectrum when $\omega_{c,b}$ = 0.1GHz ~ 40GHz

LCP 最大值不超过 0.6GHz，即禁带宽在小于该区受影响明显，RCP 出现全禁止带，使透射率峰值先减小然后趋于 0 而后增大。$\omega_{c,b}$ 较小时，RCP 禁带才呈现周期性。

2.4　填充率、入射角和介电常数对禁带影响

填充率 $f = b/d$ = 0.01 ~ 0.95 的 LCP 和 RCP 透射频谱如 6 图所示。与参考文献[10]比较可知，禁带低频区展宽，透射率峰值减小直至消失。高频区新模式形成窄禁带数目增加，透射率峰值逐渐减小。

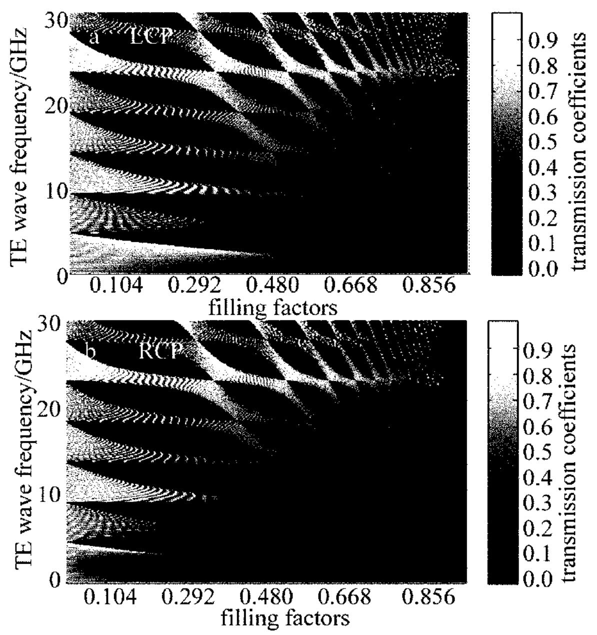

Fig. 6　Transmission spectrum when f = 0.01 ~ 0.95

入射角 θ 分别为 0° ~ 89°的 LCP 和 RCP 透射频谱如图 7 所示。与参考文献[10]比较知，ω < 15GHz，

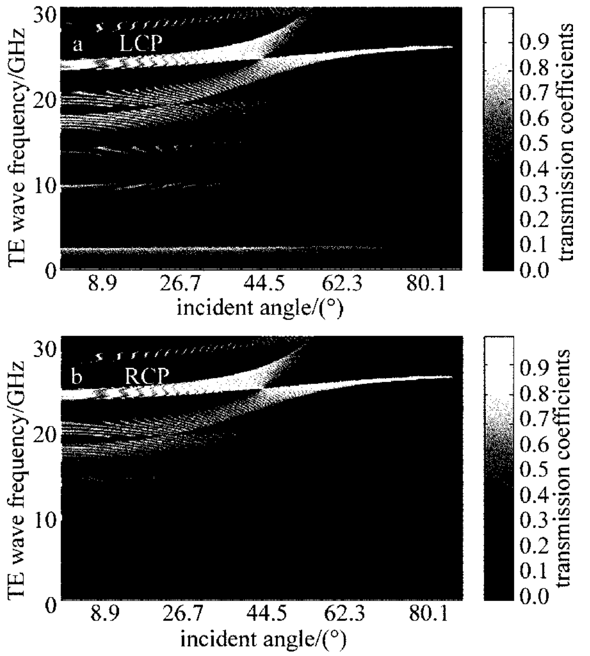

Fig. 7 Transmission spectrum when $\theta = 0° \sim 89°$

禁带宽随 θ 增大而增大，透射率峰值逐渐减小；$\omega >$ 15GHz，禁带宽随 θ 增大先减小后增大，透射率峰值逐渐减小。

介电常数比 $p_c = \varepsilon_{c,1}/\varepsilon_{c,2} = 0.26 \sim 6$ 的 LCP 和 RCP 透射频谱如图 8 所示。与参考文献[10]比较可知，随着 p_c 增大，两禁带宽（或数目）变宽（或增多），透射率峰值逐渐减小。这使得该 PPC 不引入缺陷即可实现多模滤波。

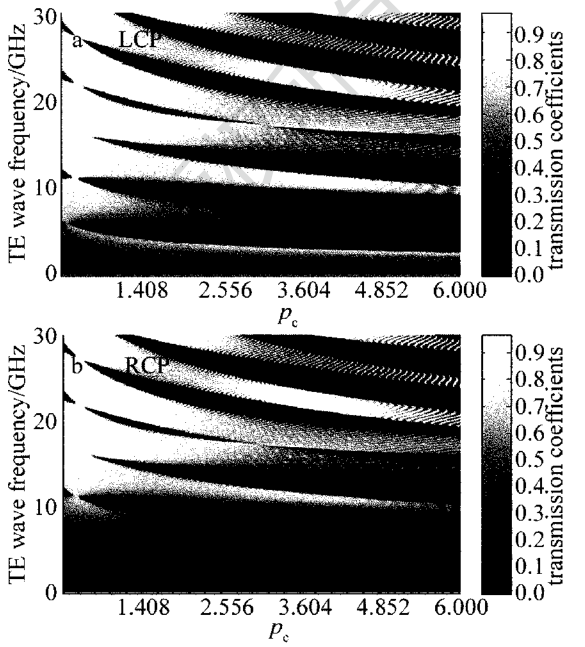

Fig. 8 Transmission spectrum when $p_c = 0.26 \sim 6$

3 结 论

随着 $\omega_{c,p}$ 增大，散射使 LCP 和 RCP 的禁带展宽减小 0.09GHz，禁带中心频率向高频区域移动增大 0.48GHz。随着 $\nu_{c,p}$，f，θ 和 p_c 增大，散射对两禁带宽有一定且明显的调谐作用。

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