Tunable resonant transmission of electromagnetic waves through a magnetized plasma

Chul-Sik Kee, Shou-Zhe Li, Kihong Kim, and H. Lim*
Department of Molecular Science and Technology, Ajou University, Suwon 442-749, Korea
(Received 11 December 2001; revised manuscript received 5 September 2002; published 21 March 2003)

We theoretically investigate the resonant transmission of circularly polarized electromagnetic waves in the electromagnetic stop band of a magnetized plasma slab using the invariant embedding method. The frequency and quality factor of the resonant mode for the right-handed (left-handed) circularly polarized wave created by inserting a dielectric layer into the plasma increase (decrease) as the magnitude of the external magnetic field increases. These phenomena are compared with the characteristics of resonant modes in metallic and dielectric Fabry-Perot resonators to show that they are due to the change of plasma reflectivity. We also discuss the damping effect due to the collisions of the constituent particles of the plasma on the resonant transmission of circularly polarized waves.

DOI: 10.1103/PhysRevE.67.036612 PACS number(s): 42.70.Qs, 41.20.Jb, 52.35.Hr

I. INTRODUCTION

Electromagnetic (EM) stop bands, the frequency ranges in which EM waves are forbidden to propagate, can be formed by multiple Bragg reflections in structures where the refractive index or the wave impedance varies periodically in space [1–3]. These stop bands are called photonic band gaps (PBGs) and the periodic structures that display PBGs are called photonic crystals [1,2]. By introducing defects into the photonic crystal and thereby breaking its periodicity locally, one can create defect levels within the PBG. EM waves with frequencies corresponding to the defect levels are allowed to propagate through a photonic crystal of finite size [4].

It is possible to create a PBG in a desired frequency range by designing a photonic crystal in an appropriate manner. The defect frequencies can also be selected by designing the shape and size of local defects. In some special cases, both the PBG and defect frequencies can be tuned by varying the dielectric permittivity ϵ or magnetic permeability μ of the constituent materials. This can be achieved by changing the temperature [5,6] or by applying an external electric [7] or a magnetic field [8]. Many interesting ideas have been proposed in improving the performance of optoelectronic and microwave devices using tunable photonic crystals [9,10].

There exist another group of EM stop bands of which formation has nothing to do with the periodicity of media. A representative example is the stop band for circularly polarized EM waves propagating parallel to the external magnetic field in a magnetized plasma [11]. The dielectric constants of a magnetized plasma for right-handed circularly polarized (RCP) and left-handed circularly polarized (LCP) waves, $\epsilon_R(\omega)$ and $\epsilon_L(\omega)$, respectively, are given by [12]

$$\epsilon_R(\omega)=1-\frac{\omega_p^2}{\omega(\omega-\omega_c+i/\tau)},$$

$$\epsilon_L(\omega)=1-\frac{\omega_p^2}{\omega(\omega+\omega_c+i/\tau)}, \qquad (1)$$

where $\omega_p(=\sqrt{4\pi n_e e^2/m}\approx 5.64\times 10^4\sqrt{n_e}$ Hz) is the plasma frequency with the electron density n_e in units of cm^{-3}, $\omega_c(=eB/mc\approx 1.76\times 10^7 B$ Hz) is the cyclotron frequency with the magnetic field B measured in Gauss, and τ is the collision time of electrons. The characteristic frequencies lie in the microwave range for common laboratory conditions [11], e.g., $\omega_p\simeq 50$ GHz for $n_e\simeq 10^{12}\ \mathrm{cm}^{-3}$ and $\omega_c\simeq$ 20 GHz for $B\simeq 10^3$ G. In a collisionless plasma with $\tau^{-1}=0$, $\epsilon_R(\omega)$ is negative for frequencies between ω_c and

$$\omega_R=\frac{\sqrt{\omega_c^2+4\omega_p^2}+\omega_c}{2} \qquad (2)$$

and $\epsilon_L(\omega)$ is negative when ω is smaller than

$$\omega_L=\frac{\sqrt{\omega_c^2+4\omega_p^2}-\omega_c}{2}. \qquad (3)$$

As is well known, EM waves incident from a vacuum are totally reflected and do not propagate in a medium if its dielectric constant is negative. Thus in the frequency range $\omega_c<\omega<\omega_L$, EM waves cannot propagate along the direction of **B** in a magnetized plasma. We will call this frequency range as the *natural* PBG. Clearly, this gap is easily tunable by an external magnetic field.

From Eq. (1), one can easily see that the dielectric constant of a plasma behaves as a Drude-type dielectric function of a metal when the magnetic field is zero $(\omega_c=0)$. This fact suggests that the transmission characteristics of a dielectric layer inserted in the center of a plasma slab (Fig. 1) would be similar to that of the dielectric layer inserted between the two metal plates, i.e., a metallic Fabry-Perot (FP) resonator. In general, the reflectivity of the metal film in a metallic FP resonator influences the quality (Q) factor and the resonant frequency of the resonator. Since the variation of the dielectric constant of a plasma due to the change of external magnetic field changes the reflectivity of a plasma slab in its natural PBG, the frequency and the Q factor of a resonant mode in the dielectric layer inserted into the plasma slab can be controlled by an external magnetic field.

In this paper, we investigate theoretically, using the invariant embedding method [13], the transmission characteris-

*Email address: hanjolim@madang.ajou.ac.kr

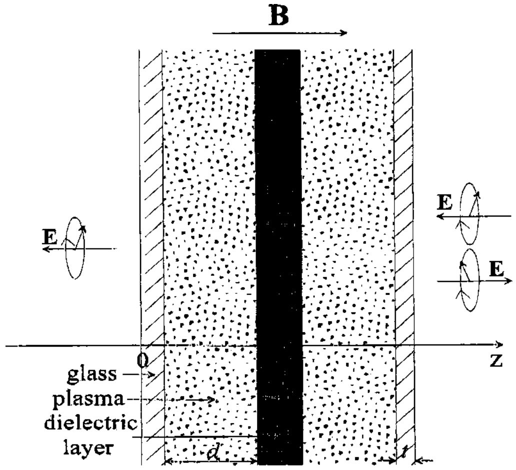

FIG. 1. Schematic drawing of a magnetized plasma slab in which an additional dielectric layer is inserted at the center. The plasma slab is assumed to be contained between two thin glasses. The circularly polarized EM waves impinge on the slab plasma from the right parallel to the applied magnetic field.

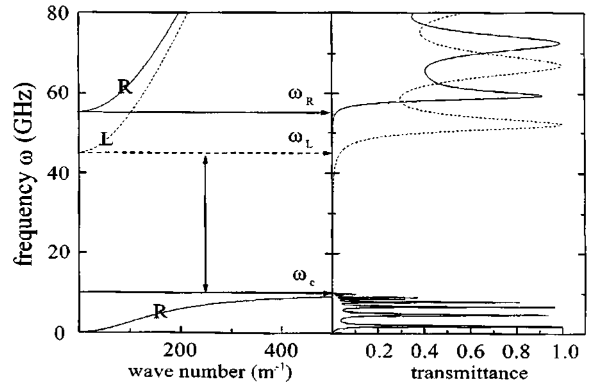

FIG. 2. Dispersion relation between ω and k (left) and the transmittance (right) of RCP (solid lines) and LCP (dashed line) EM waves propagating parallel to an external magnetic field through a magnetized plasma. The parameters used in the calculation are $\omega_c = 10$ GHz ($B \simeq 570$ G), $\omega_p = 50$ GHz ($n_e \simeq 0.79\times 10^{12}$ cm^{-3}), $\delta = 4$ mm, and $\tau^{-1} = 0$. The total thickness of the plasma and the dielectric constant of the surrounding glasses are 40 mm and 2.25, respectively. The arrows denote ω_c, ω_L, and ω_R and the capital letters R and L represent the RCP and LCP waves, respectively.

tics of the resonant modes created by inserting a dielectric layer in the center of a magnetized plasma slab. We will show that the resonant frequency and the Q factor of an RCP (LCP) wave increase (decrease) as the magnitude of the external magnetic field increases. The characteristics of the RCP and LCP resonant modes are compared with those of corresponding resonant modes in metallic and dielectric FP resonators. The damping effects due to electron collisions in the plasma on the transmission characteristics are also discussed.

II. MODEL AND COMPUTATIONAL METHOD

We consider a monochromatic EM wave of frequency ω and vacuum wave number $k_0 = \omega/c$, where c is the speed of light in a vacuum, impinging normally on a layered medium lying in $0 \leqslant z \leqslant L$. Then the complex amplitude of the electric field, $E = E(z,\omega)$, satisfies the one-dimensional Helmholtz equation

$$\frac{\partial^2 E}{\partial z^2} + k_0^2 \epsilon(z,\omega) E = 0, \tag{4}$$

where the dielectric permittivity $\epsilon(z,\omega)$ is assumed to be equal to 1 for $z<0$ and $z>L$. For a plane wave of unit magnitude $E(z) = e^{ik_0(L-z)}$ incident from the right, the reflection and transmission coefficients $r = r(L,\omega)$ and $t = t(L,\omega)$ are defined by the wave function outside the medium:

$$E(z,\omega) = \begin{cases} e^{ik_0(L-z)} + r(L,\omega) e^{ik_0(z-L)}, & z>L \\ t(L,\omega) e^{-ik_0 z}, & z<0. \end{cases} \tag{5}$$

Exact differential equations satisfied by r and t can be obtained using the so-called invariant embedding method [13,14]:

$$\frac{\partial r}{\partial L} = 2ik_0 r + \frac{ik_0}{2}[\epsilon(L,\omega) - 1](1+r)^2,$$

$$\frac{\partial t}{\partial L} = ik_0 t + \frac{ik_0}{2}[\epsilon(L,\omega) - 1](1+r)t. \tag{6}$$

By solving these equations numerically with the initial conditions

$$r(L=0,\omega) = 0, \quad t(L=0,\omega) = 1, \tag{7}$$

we are able to obtain the reflectance $R = |r|^2$ and the transmittance $T = |t|^2$ as functions of L and ω for various kinds of stratified media with complex dielectric constants [14]. In the present work, we compute the transmittances of RCP and LCP waves propagating parallel to the external magnetic field $\mathbf{B} = B\mathbf{z}$ in a magnetized plasma. We used $\omega_p = 50$ GHz ($n_e = 0.79\times 10^{12}$ cm^{-3}) as the numerical value of the plasma frequency. The total width of the plasma in the z direction, $2d$, is taken as 40 mm. We also varied the thickness of plasma slab to see the influence of plasma thickness on the coupling of resonant mode with the external source. The dielectric constant and the thickness t of thin glasses that surround both sides of the plasma were taken as 2.25 and 4 mm, respectively. Another glass layer of 7 mm thickness was assumed to be inserted in the center of the plasma to create resonant modes.

III. RESULTS AND DISCUSSION

To check the validity of the invariant embedding method, we have compared in Fig. 2 the dispersion relation between ω and k obtained from Eqs. (1) and (4) for a magnetized plasma with the transmission spectra obtained by the invariant embedding method. We assumed that the plasma was lossless and $\omega_c = 10$ GHz ($B \simeq 570$ G). We can easily see

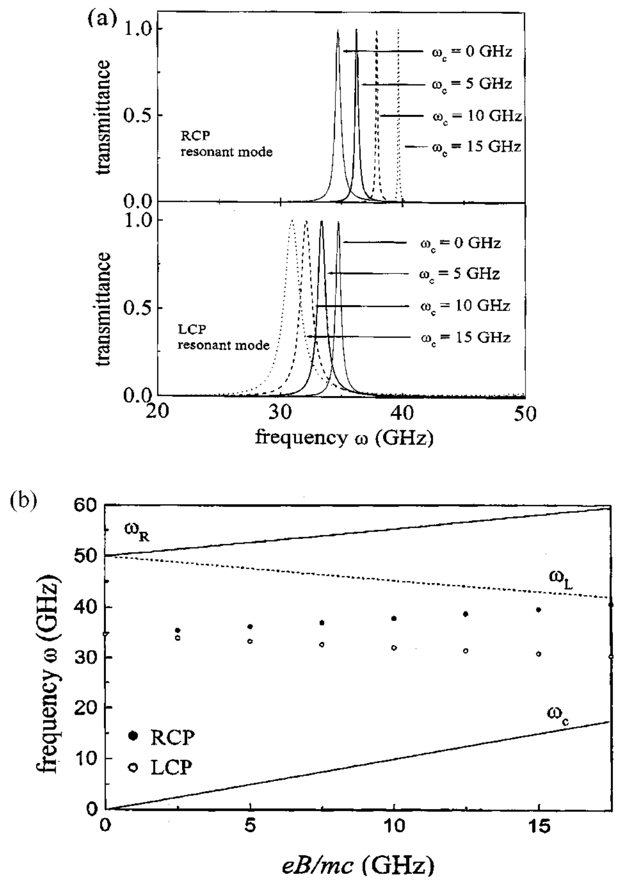

FIG. 3. (a) Calculated transmittance for RCP (top) and LCP (bottom) waves when the thickness of the central glass layer is 7 mm and $\omega_c=0$, 5 GHz (solid), 10 GHz (dashed), and 15 GHz (dotted). Other calculation parameters are identical to those employed in Fig. 2. (b) Dependence of the resonant frequencies for RCP (solid circle) and LCP (open circle) waves and the edge frequencies of the reflection band for RCP waves (solid line) and the cutoff frequency for LCP waves (dashed line) on ω_c. The natural PBG appears between the dashed line and the bottom solid line.

that the two results are fully consistent: the magnetized plasma has a common stop band for both RCP and LCP waves for the frequencies between ω_c and ω_L. The oscillatory behavior of the transmission spectra outside the natural PBG region is due to the finite thickness of the medium. The transmittance peaks (valleys) occur at the frequencies for which the thickness is equal to an even (odd) multiple of the corresponding quarter wavelengths.

In Fig. 3(a), we show the simulated transmission spectra of RCP (top) and LCP (bottom) waves propagating through a plasma slab with a glass layer of 7 mm thickness in its center (Fig. 1), for four values of the cyclotron frequency $\omega_c=0$, 5, 10, and 15 GHz. We can notice that the inserted dielectric layer creates allowed transmission modes (i.e., the resonant modes) inside the natural PBG. We also observe that the frequency and the Q factor of the RCP (LCP) resonant mode increase (decrease) as ω_c increases. In Fig. 3(b), we plot the dependence of the RCP (solid circles) and LCP (open circles) resonant frequencies on the B field. Both the edge frequencies of the reflection band (solid lines) and the resonant frequencies for the RCP wave are increasing functions of B. On the contrary, the cutoff frequency (dashed line) and the resonant frequency for the LCP wave are decreasing functions of B. A natural PBG is formed between the dashed line and the bottom solid line. The width of PBG, $\Delta\omega=\omega_L-\omega_c$, shrinks as B increases and vanishes when $\omega_c=\omega_p/\sqrt{2}$.

The behavior of the Q factor and the resonant frequency of RCP and LCP resonant modes can be understood from the dependence of the reflectivity of a plasma on B for the RCP and LCP waves. The reflectivity of a magnetized plasma for the RCP (LCP) waves increases (decreases) as B increases, since the absolute value of the negative dielectric permittivity in the frequency range of the natural PBG increases (decreases) as B increases. As mentioned above, the dielectric layer inserted into the middle of the plasma slab acts like a metallic FP resonator when $B=0$ as long as the resonant mode in the dielectric slab can couple with the external EM waves. The Q factor of a metallic FP resonator increases as the reflectivity R of the metal is increased because it is proportional to $\sqrt{R}/(1-R)$ [15]. Thus the Q factor of the resonant mode in the dielectric layer inserted into the middle of the magnetized plasma should increase as the reflectivity of plasma increases. From these, it is evident that the increase (decrease) of the Q factor of the RCP (LCP) resonant modes of the dielectric layer in the magnetized plasma with the increase of B is due to the increase (decrease) of plasma reflectivity with the increase of B.

This behavior of Q factor discussed in the precedent paragraph suggests that the movement of resonant peaks would also be related to the change of plasma reflectivity. This conjecture can be clarified by investigating the change of transmission peaks in a dielectric FP resonator consisting of two parallel dielectric mirrors. These mirrors, the so-called distributed Bragg reflectors (DBRs), are quarter-wave stacks of alternating dielectric materials with different refractive indices n_1 and n_2 ($n_1<n_2$). As n_1 decreases, the reflectance of DBR increases, and so does the Q factor of a dielectric FP resonator. The central dielectric medium between the two DBR mirrors corresponds to a defect in view of one-dimensional (1D) photonic crystals. And the resonant mode formed inside the FP resonator corresponds to the defect mode formed in the reflection band of the DBRs. The resonant transmission due to the central defect between two identical 1D photonic crystals has been attributed to the resonant tunneling of EM waves through the optical barriers [16]. The EM wave whose frequency lies within the photonic band gap is evanescent in the photonic crystal, as the EM wave is evanescent in the optical barrier [17,18]. Hence, for the resonant mode, a dielectric FP resonator can be regarded as an optical system consisting of a central resonator and the surrounding barriers [15], as the dielectric layer inserted in a magnetized plasma slab can. Thus even if the reflection mechanism of the magnetized plasma is different from that of the DBR, the cavity surrounded by the magnetized plasma and the cavity surrounded by the DBR are expected to behave similarly.

To confirm these ideas, we have simulated the transmittance of a dielectric FP resonator using the invariant embedding method. Assuming that the DBR consists of MgF_2 (n_1

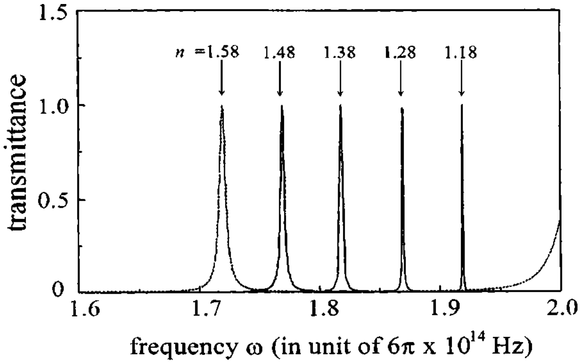

FIG. 4. Variation of the resonant transmittance of a FP resonator for different n_1 values, 1.18, 1.28, 1.38, 1.48, and 1.58. The DBRs of the FP resonator are assumed to be composed of five periods of alternating layers with $d_1=550$ nm/(4×1.38), $n_2=2.34$, and $n_2d_2=550$ nm/4. The refractive index and the length of the central dielectric medium between the two dielectric mirrors are assumed to be $n_d=2$ and $d_d=550$ nm/$(2n_d)$, respectively. When $n_1=1.38$, the dielectric mirror becomes a quarter-wave stack DBR and the wavelength of the resonant mode is matched at the center of the reflection band of the mirror, i.e., at 550 nm.

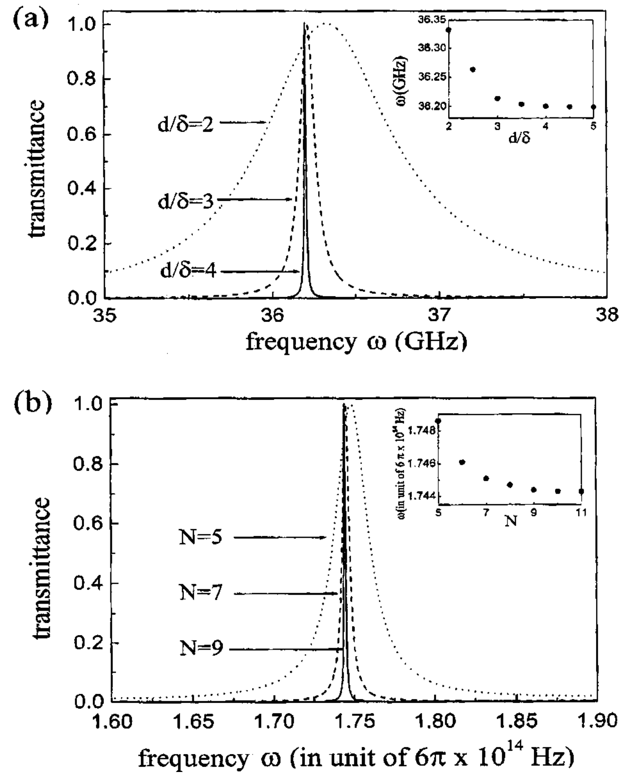

FIG. 5. (a) Variation of the resonant transmittance of the EM waves through the magnetized plasma slab for RCP waves when the thickness of the magnetized plasma $d=2\delta$, 3δ, and 4δ and $\omega_c=5$ GHz and $\omega_p=50$ GHz, where δ is the penetration depth of the magnetized plasma. The inset shows the dependence of resonant frequency on *d*. Note that the resonant frequency (*Q* factor) of resonant mode decreases (increases) as *d* increases. (b) Variation of the resonant transmittance of the FP resonator with $n_1=1.58$ shown in Fig. 4 when the number of the period of dielectric stack $N=5$, 7, and 9. The inset shows the dependence of resonant frequency on *N*. Note that the *Q* factor (resonant frequency) of resonant mode increases (decreases) as *N* increases.

$=1.38$)/ZnS ($n_2=2.35$) stacks, we take $n_2=2.35$ and choose $n_1=1.18$, 1.28, 1.38, 1.48, and 1.58. The refractive index and the length of the central dielectric layer between two mirrors are taken as $n_d=2$ and $d_d=550$ nm/$(2n_d)$, respectively. Each dielectric mirror is assumed to consist of five periods of dielectric materials with $d_1=550$ nm/(4×1.38) and $d_2=550$ nm/$(4n_2)$. It becomes a perfect quarter-wave stack only when $n_1=1.38$ and the resonant wavelength is matched at 550 nm. The simulated transmission spectra are shown in Fig. 4. As expected, we find that the resonant mode becomes sharper and shifts to higher frequencies as n_1 decreases. One can easily verify that this variation of resonant frequency ω_{re} is due to the fact that each ω_{re} satisfies the relation $\phi-n_dd_d\omega_{\mathrm{re}}/c=m\pi$ (*m* is integer), where ϕ is the phase shift due to the reflection by the dielectric mirror. From the close analogy between this behavior and that of the resonant mode formed in a magnetized plasma (Fig. 3), we can see that the above phase relation also governs the resonant frequency in the magnetized plasma.

The analogy between the dielectric layer inserted in a magnetized plasma slab and the dielectric FP resonator can be also verified by comparing the dependence of resonant transmission of EM wave in the former on the thickness of magnetized plasma slab *d* with the dependence in the latter on the number of the period of dielectric mirror *N*. Figure 5(a) shows the resonant transmission of the magnetized plasma slab for RCP wave when $d=2\delta$, 3δ, and 4δ, where δ is the penetration depth of magnetized plasma, which is ≈ 8 mm at $\omega=36$ GHz when $\omega_p=50$ GHz and $\omega_c=5$ GHz. The inset shows the dependence of resonant frequency on *d*. One can see that the *Q* factor (resonant frequency) of resonant mode increases (decreases) as *d* increases. This behavior is originated from the change of the reflection of the EM wave by the magnetized plasma slab with the increase of *d*. In general, the reflectance of the magnetized plasma increases as the thickness of the magnetized plasma increases and thus, the *Q* factor of resonant mode increases as *d* increases. The phase shift for the EM waves whose frequency falls within the natural PBG of the magnetized plasma decreases as *d* increases. Hence, the resonant frequency satisfying the condition $\phi-n_dd_d\omega_{\mathrm{re}}/c=m\pi$ shifts to the lower frequency as *d* increases. Thus, the decrease of resonant frequency is evidently due to the change of ϕ by the increase of *d*. One can see that the increase of *Q* factor and the decrease of the resonant frequency are nearly saturated when *d* is larger than 4δ. This is clearly due to the fact that the reflection of the EM waves whose frequency falls within the natural PBG by the magnetized plasma slab is nearly unchanged when the magnetized plasma is much thicker than the penetration depth of the plasma. The dependence of resonant transmission of dielectric FP resonator with $n_1=1.58$ (Fig. 4) on the number of the period of the dielectric mirror is shown in Fig. 5(b). As *N* increases, the *Q* factor of resonant mode increases and the resonant frequency decreases. The inset shows the dependence of resonant frequency on *N*. One can easily notice that the dependence in Fig. 5(b) is very similar to that in Fig. 5(a). This close simi-

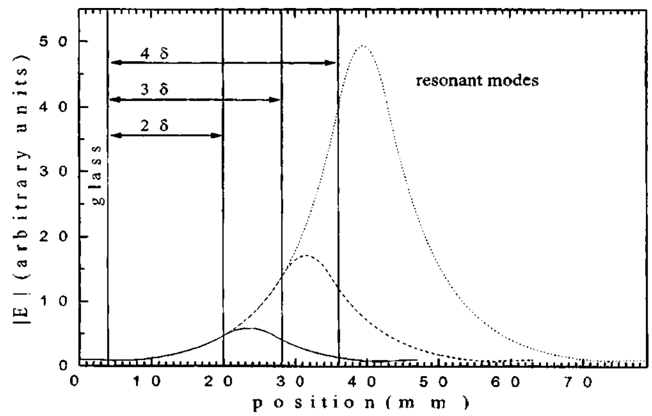

FIG. 6. Amplitude of electric field inside the plasma slab at the resonant frequencies for RCP wave when $d=2\delta$, 3δ, and 4δ and $\omega_c=5$ GHz and $\omega_p=50$ GHz. Note that the coupling between the resonant mode and the external source is maintained to show the resonant transmission, even if the thickness of magnetized plasma slab d is much larger than the penetration depth of the magnetized plasma δ.

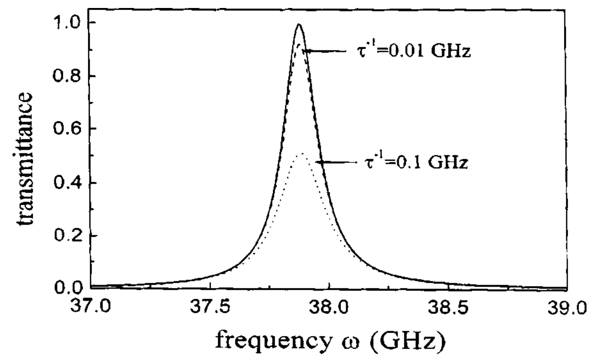

FIG. 7. Resonant transmittance of RCP waves without (solid line) and with the damping term $\tau^{-1}=0.01$ GHz (dashed line) and 0.1 GHz (dotted line) when $\omega_c=10$ GHz. Other calculation parameters are identical to those employed in Fig. 3. The transmittance is slightly reduced when $\tau^{-1}=0.01$ GHz and rather severely when $\tau^{-1}=0.1$ GHz. Note that the mode frequency is not changed.

larity is evidently due to the fact that the reflectance of dielectric mirror (the phase shift of reflected EM waves) increases (decreases) as N increases. One can see in Fig. 5(a) that the resonant transmission is persistent even when the plasma slab is much thicker than the penetration depth as the transmission via a defect mode does in a finite-size photonic crystal [Fig. 5(b)]. As d increases, the intensity of external EM wave reaching the inserted dielectric layer decays exponentially. For example, when $d=5\delta$, it is $\approx 0.6\%$. But, the intensity of resonant mode confined in the dielectric layer increases rapidly as d is increased, and the coupling between the resonant mode and the external EM wave can be maintained to show the resonant transmission, even when d is much larger than δ. The amplitude of electric field inside the plasma slab at the resonant frequencies for RCP wave when $d=2\delta$, 3δ, and 4δ (Fig. 6) clearly demonstrates that this argument is correct. Thus it is clear that the coupling between the defect mode and the external EM wave appears similar in the two systems even though their reflection mechanisms are different from each other. It would be worth emphasizing the difference between the resonant transmission of EM waves in the magnetized plasma with an inserted dielectric layer and that in dielectric FP resonator. Especially, the resonant transmission characteristics in the FP resonator composed of the quarter-wavelength stacks and the central half-wavelength dielectric layer are quite different from those in the magnetized plasma slab. When the number of the period of the quarter-wavelength stacks increases, the Q factor of resonant mode increases but the resonant frequency does not change. This is because the resonant mode has nodes at two interfaces between the central half-wavelength dielectric layer and the quarter-wavelength stacks. Thus the phase shift due to the reflection is always zero regardless of the number of the period of the quarter-wavelength stacks. Therefore, the resonant frequency of the FP resonator composed of the quarter-wavelength stacks and the central half-wavelength dielectric layer does not change. In the magnetized plasma with an inserted dielectric layer, the EM wave of resonant mode never has a node at the interface between the plasma and the dielectric layer, since the EM wave always penetrates inside the plasma. Thus, the phase shift due to the reflection is affected by the thickness of the plasma slab and the external magnetic field and the resonant frequency is changed by them.

The damping effects due to electron collisions in the plasma can be taken into account by considering the cases with a finite τ. For a typical laboratory plasma with the electron density $n_e \simeq 10^{12}$ cm^{-3}, the collision frequency τ^{-1} has a value between 0.01 and 1 GHz [19]. In Fig. 7, we show the resonant transmittance of an RCP EM wave for $\tau^{-1}=0$, 0.01, and 0.1 GHz and $\omega_c=10$ GHz. We find that the damping reduces the resonant transmission slightly when $\tau^{-1}=0.01$ GHz, but rather severely when $\tau^{-1}=0.1$ GHz. We also find that the damping does not practically affect the frequency of the resonant mode even when it reduces the size of the transmittance. Recently, two of us have shown that a slight absorption in a two-dimensional photonic crystal does not practically affect the PBG edge frequencies [20]. It appears that the absorption or damping in a photonic crystal does not change the defect mode frequency as well as the PBG edge frequencies.

IV. CONCLUSION

In conclusion, we have shown that the introduction of a dielectric layer in a magnetized plasma gives rise to the resonant transmission of circularly polarized EM waves in the EM stop band, when the applied magnetic field is parallel to the propagation direction of the waves. It is shown that the resonant frequency can be easily tuned by an external magnetic field. The Q factor and the frequency of the resonant mode increase (decrease) for the RCP (LCP) wave as the magnetic field is increased. The damping effects due to electron collisions have also been discussed.

ACKNOWLEDGMENTS

This work has been supported by the ABRL Program of KOSEF and the Ministry of Commerce, Industry and Energy (Grant No. A18-02-01).

[1] E. Yablonovitch, Phys. Rev. Lett. **58**, 2059 (1987).
[2] S. John, Phys. Rev. Lett. **58**, 2486 (1987).
[3] C.-S. Kee, J.-E. Kim, H.Y. Park, S.J. Kim, H.C. Song, Y.S. Kwon, N.H. Myung, S.Y. Shin, and H. Lim, Phys. Rev. E **59**, 4695 (1999).
[4] E. Yablonovitch, T.J. Gmitter, R.D. Meade, A.M. Rappe, K.D. Brommer, and J.D. Joannopoulos, Phys. Rev. Lett. **67**, 3380 (1991).
[5] K. Yoshino, Y. Shimoda, Y. Kawagishi, K. Nakayama, and M. Ozaki, Appl. Phys. Lett. **75**, 932 (1999).
[6] P. Halevi and F. Ramos-Mendieta, Phys. Rev. Lett. **85**, 1875 (2000).
[7] K. Busch and S. John, Phys. Rev. Lett. **83**, 967 (1999).
[8] C.-S. Kee, J.-E. Kim, H.Y. Park, I. Park, and H. Lim, Phys. Rev. B **61**, 15 523 (2000).
[9] See, for example, J. Lightwave Technol. **11** (1999).
[10] See, for example, IEEE Trans. Microwave Theory Tech. **47** (1999).
[11] N.A. Krall and A.W. Trivelpiece, *Principle of Plasma Physics* (McGraw-Hill, NewYork, 1973), Chap. 4.
[12] P.M. Platzman and P. A. Wolff, *Waves and Interactions in Solid State Plasmas* (Academic Press, New York, 1973), p. 134.
[13] V.I. Klyatskin, Prog. Opt. **33**, 1 (1994).
[14] K. Kim, Phys. Rev. B **58**, 6153 (1998).
[15] P. Yeh, *Optical Waves in Layered Media* (Wiley, New York, 1988), Chaps. 6 and 7.
[16] S.Y. Lin, V.M. Hietala, and S.K. Lyo, Appl. Phys. Lett. **68**, 3233 (1996).
[17] T. Suzuki and P.K.L. Yu, J. Opt. Soc. Am. B **12**, 804 (1995).
[18] E. Yablonovitch, http://www.ee.ucla.edu/labs/photon. There are excellent pictures showing how the waves whose frequency fall within the photonic band gaps evanesce in photonic crystals.
[19] G.G. Borg, J.H. Harris, D.G. Miljak, and N.M. Martin, Appl. Phys. Lett. **74**, 3272 (1999).
[20] C.-S. Kee, H. Lim, Y.-K. Ha, J.-E. Kim, and H.Y. Park, Phys. Rev. B **64**, 085114 (2001).