Two-dimensional tunable metallic photonic crystals infiltrated with liquid crystals

Chul-Sik Kee and H. Lim*
Department of Molecular Science and Technology, Ajou University, Suwon 442-749, Korea

Young-Ki Ha, Jae-Eun Kim, and Hae Yong Park
Department of Physics, Korea Advanced Institute of Science and Technology, Taejon 305-701, Korea
(Received 1 March 2001; published 8 August 2001)

We have investigated the effects of liquid crystal (LC) infiltration on the photonic band gaps (PBG's) of two-dimensional (2D) arrays of metallic rods. Contrary to the LC-infiltrated dielectric photonic crystals, the infiltration of LC's into metallic arrays enlarges PBG's and creates another PBG's. The change of refractive index due to the phase transition of LC's affects both edges of PBG's so that the positions of PBG's show rather large temperature dependence near the phase transition temperature. Thus metallic arrays infiltrated with LC's can overcome the drawbacks of LC infiltration in dielectric photonic crystals, i.e., the band gap narrowing and weak tunabilty of band gap. The usefulness of LC infiltration in the implementation of 2D or 3D tunable metallic photonic crystals is also discussed.

DOI: 10.1103/PhysRevB.64.085114 PACS number(s): 42.70.Qs, 42.70.Df

I. INTRODUCTION

Over the past decade, there have been increasing interests in the properties of periodic dielectric structures that show some frequency ranges where electromagnetic (EM) waves cannot propagate in any direction, i.e., the photonic band gaps (PBG's).[1,2] Such dielectric structures showing PBG's are called as photonic crystals, PBG structures, or EM crystals. Photonic crystals can control the spontaneous emission and the propagation of EM wave.[3,4] Thus numerous applications of photonic crystals have been proposed in improving the performance of optoelectronic and microwave devices such as high-efficiency semiconductor lasers, light emitting diodes, waveguides, optical filters, high-Q resonators, antennas, frequency-selective surfaces, and amplifiers.[3,4]

The tunability of PBG's can open new appilcations of photonic crystals in the optoelectronic and microwave devices. Thus much attentions have recently been paid to the tunable photonic crystals composed of liquid crystals,[5,6] intrinsic semiconductors,[7] or ferrite materials.[8] Especially, liquid crystal (LC) is a good material for the tunable photonic crystals operating in the infrared and optical wavelength ranges because its refractive index is tunable changing the external electric field or temperature. For example, the PBG's of two-dimensional (2D) silicon (Si) photonic crystals infiltrated with LC's can be varied in the infrared frequency range by changing the temperature.[9] However, the infiltration of LC's in the void regions of dielectric photonic crystals generally decreases the band width of PBG's and, moreover, the tunable range is very narrow.[9] This is understandable if one recalls that the infiltration of LC's decreases the contrast between dielectric constant of the rods and the background one. On the other hand, metallic photonic crystals with dielectric background, the so-called metallodielectric photonic crystals, exhibit rather large PBG's due to the strong mismatch of characteristic impedance at the interface between metals and dielectric background.[10–12] Therefore, the metallic photonic crystals infiltrated with LC's may overcome the drawbacks of the dielectric photonic crystals infiltrated with liquid crystals. For example, a 2D array of silver wires infiltrated with LC's can be a good candidate for the temperature-tunable PBG structures.

In this paper, we have theoretically investigated the effects of LC infiltration on the PBG's of 2D square lattice and triangular lattice of metallic rods. Computational results show that the magnitude and position of PBG's change drastically as LC's are infiltrated in the photonic crystals. The PBG's are also rather largely dependent on the temperature near the phase transition temperature of LC's.

II. CALCULATIONS

In the calculation, the dielectric response function of metallic rods is assumed to follow a Drude-like behavior

$$\epsilon(\omega)=1-\omega_p^2/\omega(\omega+i/\tau), \tag{1}$$

where ω_p is the plasma frequency, ω the EM wave frequency, and τ the relaxation time. The absorption, which is controlled by the damping term τ^{-1}, can be rather small if $0.1\omega_p \leqslant \omega$ since $(\tau\omega_p)^{-1} \approx 10^{-2}$ for typical metals. Even if absorption cannot be completely removed and even moderate absorption slightly perturbs the photonic band structures,[13] we assumed that the Drude dielectric function is dampingless, i.e., $\tau=\infty$, restricting our investigations to the frequency region of $\omega \geqslant 0.1\omega_p$. For the in-plane propagation of EM wave in 2D photonic crystals, there are two independent polarizations of electric field **E**, s polarization (**E** parallel to rod axes), and p polaization (**E** perpendicular to rod axes). We have investigated the effect of LC infiltration on PBG's for the s-polarized wave, and then extended the discussion for the p-polarized wave. The infiltrated LC is assumed to be LC 5CB since its temperature dependence of refractive index is well known, and it undergoes a phase transition near room temperature (at 35 °C) from the nematic phase to the isotropic one.[14] Thus the variation of PBG due to the change of dielectric constant caused by the phase transition is expected to be observed near the room temperature.

The scalar wave equation for the s-polarized EM wave is given as

$$\nabla^2 E(\mathbf{r}) + \epsilon(\mathbf{r})\frac{\omega^2}{c^2}E(\mathbf{r}) = 0, \tag{2}$$

where c is the velocity of light. The dielectric constant $\epsilon(\mathbf{r})$ is $1-\omega_p^2/\omega^2$ in the metallic rods and it is a constant ϵ_{LC} in the liquid crystal . Hence the dielectric function is given by

$$\epsilon(\mathbf{r}) = \alpha(\mathbf{r}) - \beta(\mathbf{r})/\omega^2, \tag{3}$$

where $\alpha(\mathbf{r})=1$ and $\beta(\mathbf{r})=\omega_p^2$ in the metallic rods and $\alpha(\mathbf{r})=\epsilon_{\mathrm{LC}}$ and $\beta(\mathbf{r})=0$ in the liquid crystal. Since $\alpha(\mathbf{r})$ and $\beta(\mathbf{r})$ are periodic functions of $\mathbf{r}$, $\epsilon(\mathbf{r})$ is also a periodic function of $\mathbf{r}$. Thus, from the Bloch theorem, the electric field can be expressed as

$$E(\mathbf{r}) = \sum_{\mathbf{G}} E_{\mathbf{k}+\mathbf{G}} e^{i(\mathbf{k}+\mathbf{G})\cdot\mathbf{r}}, \tag{4}$$

where $\mathbf{k}$ is a wave vector in the irreducible Brillouin zone, and $\mathbf{G}$ is a two-dimensional reciprocal lattice vector. Substitution of Eqs. (3) and (4) into Eq. (2) gives

$$\sum_{\mathbf{G}'}\left[(\mathbf{k}+\mathbf{G})\cdot(\mathbf{k}+\mathbf{G}')\,\delta_{\mathbf{G},\mathbf{G}'} + \frac{\beta_{\mathbf{G}-\mathbf{G}'}}{c^2} - \alpha_{\mathbf{G}-\mathbf{G}'}\frac{\omega^2}{c^2}\right]E_{\mathbf{k}+\mathbf{G}'} = \mathbf{0}, \tag{5}$$

where $\beta_{\mathbf{G}-\mathbf{G}'}$ and $\alpha_{\mathbf{G}-\mathbf{G}'}$ are the Fourier transform of $\beta(\mathbf{r})$ and $\alpha(\mathbf{r})$, respectively, and $\delta_{\mathbf{G},\mathbf{G}'}$ is the Kronecker delta function. Equation (5) is a set of linear homogeneous equations for the eigenvectors $E_{\mathbf{k}+\mathbf{G}}$ and the eigenvalues $\omega(\mathbf{k})$.[15] In the calculation, 441 different $\mathbf{G}$ numbers were used for each $\mathbf{k}$ value, and 47 $\mathbf{k}$ points in the irreducible Brillouin zone were employed. These numbers are known to be sufficient enough to obtain acceptable convergence for characterizing the band structures.[15] To see the influence of LC infiltration, the photonic band structures of a square lattice of Si rods as well as those of metallic rods are investigated for comparison.

For the case of Si rods, the extraordinary refractive index of nematic phase 5CB for s-polarized wave and the refractive index of isotropic phase 5CB are taken as 1.67 and 1.55, respectively, using the measured values at the wavelength of 10.6 μm.[14] For the case of metallic rods, the above values are taken as 1.75 and 1.6, respectively, corresponding to the measured values at 488 nm. These choices were made on the consideration that, for the calculation results to be realistic, it should be assumed that the actual photonic crystals operate at rather low (high) frequency region in the case of Si (metal, silver, for example) rods so that the absorption in Si (metal) rods is negligible. Even when we use identical values for both cases, however, the calculated magnitudes of PBG would show little difference with each other since the employed dielectric constant values differ each other only slightly. We also assumed that all the nematic phase 5CB molecules are aligned parallel to the Si or metallic rods for the simplicity of calculation and the consistency with the experimental results.[9]

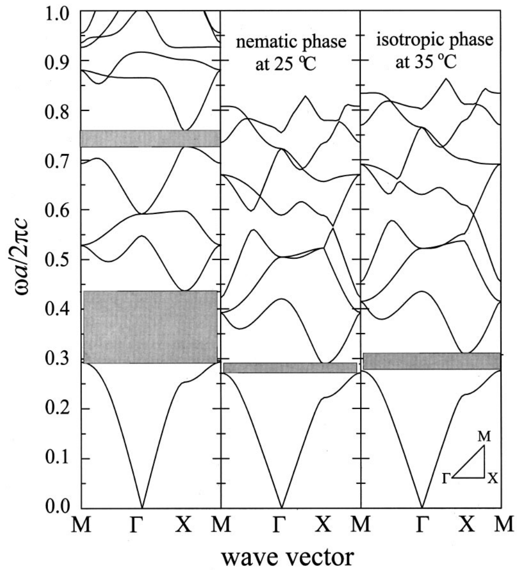

FIG. 1. Photonic band structures of the 2D square array of Si rods for the s-polarized wave in the air background (left), in the nematic phase 5CB at 25 °C (center), and in the isotropic phase 5CB at 35 °C (right). High symmetry points in the irreducible Brillouin zone of square lattice are also shown in the inset. The radius r and the dielectric constant of Si rods are taken as $r=0.2a$ and 11.7, respectively. The extraordinary refractive index of nematic phase 5CB for the s-polarized wave and the refractive index of isotropic phase 5CB are taken as 1.67 and 1.55, respectively, corresponding to the measured values at the wavelength of 10.6 μm. The frequency is normalized to $2\pi c/a$. The grey areas represent PBG's.

III. RESULTS AND DISCUSSION

Figure 1 shows the photonic band structures of 2D square array of Si rods in the air (left), in the nematic phase 5CB at 25 °C (center), and in the isotropic phase 5CB at 35 °C (right), respectively. The inset at the lower right side indicates high symmetry points in the irreducible Brillouin zone of square lattice. The radius r and the dielectric constant of Si rods are taken as $r=0.2a$ and 11.7, respectively, where a is the lattice constant. We have chosen $r=0.2a$, since the 2D square lattice of Si rods in the air shows the largest band gap for s-polarized wave around this value.[16] We notice in this figure that there are a large PBG between the first and second bands and a small one between the fourth and the fifth bands in photonic band structure of 2D square array of Si rods in the air. It is also clear that the infiltration of LC 5CB makes the second PBG disappear and the upper edge of the first PBG move down drastically with little decrease of bottom edge so that the first PBG becomes very narrow. Recently, we have shown that the center frequency (magnitude) of PBG decreases (increases) as effective refractive index (the periodic variation of characteristic impedance) of periodic structure increases.[12,17] Thus the above disappearance and

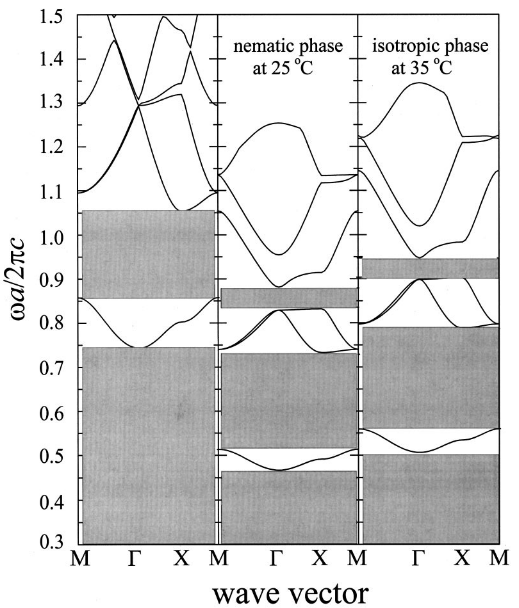

FIG. 2. Photonic band structures of the 2D square array of metallic rods for the s-polarized wave in the air (left), in the nematic phase 5CB at 25 °C (center), and in the isotropic phase at 35 °C (right). The normalized plasma frequency $\omega_p a/2\pi c$ and radius of metallic rod are taken as 1.1 and $0.45a$, respectively. The refractive indices of 5CB in each phase are takn as 1.75 and 1.6, respectively, corresponding to the measured values at 488 nm. The grey areas represent PBG's or the frequency region below cutoff. Note that the magnitude of first PBG slightly increases after the LC infiltration.

reduction of PBG's are evidently due to the decrease of the variation of characteristic impedance of the structure when LC 5CB is infiltrated. The decrease of the center frequency of first PBG after the infiltration of nematic 5CB is evidently due to the augmentation of mean refractive index. By the same token, the slight upward movement of the center frequency of the first PBG after the pahse transition of liquid crystals is due to the reduction of effective refractive index. Anyway, our results show well that the PBG's of dielectric arrays infiltrated with LC's are temperature tunable only in a narrow frequency range as observed in the recent experimental results.[9]

In Fig. 2, we show the photonic band structures of 2D square lattice of metallic rods in the air (left), in the nematic phase 5CB at 25 °C (center) and in the isotropic phase 5CB at 35 °C (right), respectively. The radius of metallic rods and the normalized plasma frequency $\omega_p a/2\pi c$ are taken as $0.45a$ and 1.1, respectively. We have taken these values since this case has the largest relative band gap width $\Delta\omega/\omega_{c,\mathrm{air}}$ as will be shown later. Here, $\Delta\omega$ and $\omega_{\mathrm{c},air}$ are the magnitude and the center frequency of the first PBG of 2D square array of metallic rods in the air, respectively. One can easily see that the effects of the LC infiltration in the 2D array of metallic rods are quite different from those in the 2D array of Si rods. That is, the infiltration of LC's into metallic arrays slightly enlarges the PBG between the first and second bands and creates another PBG between the third and fourth bands. In contrast to the case of Si rods, the change of refractive index due to the phase transition moves both edges of PBG's up so that the size of PBG's are kept nearly constant. Contrary to the case of Si lattice, the infiltration of LC 5CB in the metallic lattice increases the difference between the characteristic impedance of rods and the background one. This increased difference makes the magnitude of first PBG increase and the second PBG newly appear after the infiltration. On the other band, the infiltration (phase transition) of liquid crystals in the metallic photonic crystals increases (decreases) the mean refractive index as in the case of Si photonic crystals and thus decreases (increases) the center frequencies of PBG's.

The difference in the behavior of band edges of Si photonic crystals (Fig. 1) and that of metallic photonic crystals (Fig. 2) after the LC infiltration or the phase transition can be easily understood by considering the spatial distribution of the electric field of s-polarized wave in the square lattice. In the case of Si photonic crystals, the electric fields for the bottom and upper edge frequencies of the first PBG are highly concentrated in the Si rods (having high dielectric constant) and in the air, respectively.[18] Thus only the upper band edge is mainly affected by the infiltration of LC and its phase transition as in Fig. 1. In the case of metallic rods, on the contrary, electric field cannot be concentrated in the metallic rods, and thus, gap edge modes concentrate their wave energy in the air gap region. Therefore, the infiltration and/or phase transition of LC affect both frequencies of the PBG edges. If we define the tunability of the photonic crystals infiltrated with LC's as $(\omega_{c,2}-\omega_{c,1})/\omega_{c,1}$, where $\omega_{c,1}$ and $\omega_{c,2}$ are the center frequencies of the first PBG before and after the phase transition, it is calculated to be 8.1 and 4.2 % for the 2D square lattice of metallic and Si rods, respectively. Thus it is evident that the PBG of LC-infiltrated metallic photonic crystal can be more largely tunable than that of the Si photonic crystal infiltrated with LC's.

The PBG characteristics of a given photonic crystal result in its propagation direction-dependent transmission and/or reflection characteristics. Therefore, the calculation of transmission characteristics would be quite interesting in a way to predict the experimental results. We thus have calculated, using the transfer matrix method,[19] the transmission characteristics of the photonic crystal studied in Fig. 2 when the PBG structure has eight layers of metallic rods. Figures 3(a) and 3(b) show the transmission spectra for the s-polarized wave propagating along Γ-X (solid line) and Γ-M (dashed line) direction when the metallic rods are in the air (a), in the nematic phase 5CB at 25 °C (b), respectively. We can see that, for a given propagation direction, the edge frequencies of first and second transmission bands in Figs. 3(a) and 3(b) are consistent rather well with the edge frequencies of the cutoff and the first PBG in Fig. 2. We can also notice that the stop band in the frequency range between $\omega a/2\pi c = 0.84$ and 0.94 for the propagation of Γ-M direction in Fig. 3(b) is covered by the fourth band in Γ-M direction does not appear either in the transmission characteristics for the case of isotropic phase background. This absence of fourth band is believed to originate from a null coupling between the external plane wave and the fourth band in the Γ-M direction which is based on the symmetry of the wave functions for the relevant infinite lattice.[20] The influence of metal absorption on

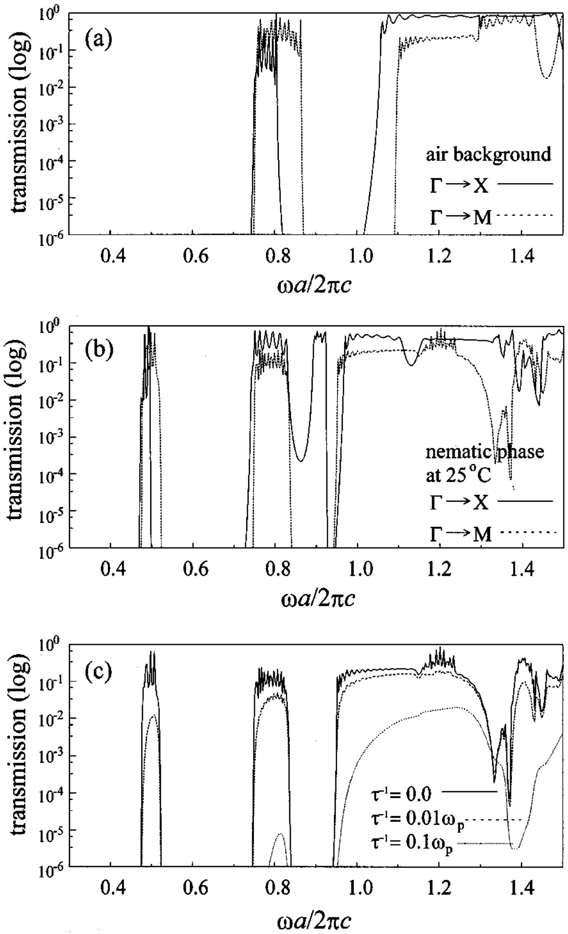

FIG. 3. Simulated transmission spectra for the *s*-polarized wave propagating along Γ-X (solid line) and Γ-M (dashed line) directions through 8 layers of metallic rods in the air (a), in the nematic phase 5CB at 25 °C (b). The spectra along the Γ-M direction through the layers of metallic rods without or with different damping terms $\tau^{-1}=0.01\omega_p$ and $\tau^{-1}=0.1\omega_p$, in the nematic phase 5CB at 25 °C (c). The employed parameters in the computation are identical as those for Fig. 2.

the transmission spectra for the *s*-polarized wave propagating along Γ-M direction when the metallic rods are in the nematic phase 5CB at 25 °C, is investigated only for the cases of $\tau^{-1}=0.01\omega_p$ and $\tau^{-1}=0.1\omega_p$ [Fig. 3(c)], since $(\tau\omega_p)^{-1}\approx 10^{-2}$ for typical metals. One can easily see that metal absorption reduces the transmission coefficients slightly but practically does not affect the edge frequencies of PBG's when $\tau^{-1}=0.01\omega_p$. Thus, even though the transmission property is perturbed rather severely by the metal absorption when $\tau^{-1}=0.1\omega_p$, it is evident that the ideal Drude dielectric function is applicable for the calculation of PBG in the case of weak absorption as previously asserted.[13]

It has already been reported that 2D triangular lattice of metallic rods in the air does not show any PBG above the cutoff frequency irrespective of the radius of metallic rods.[21] The infiltration of LC's, however, may newly create the PBG through the increased contrast between the dielectric constant of the metallic rods and the background one. To verify this conjecture, we have calculated the photonic band structures of 2D triangular metallic arrays using the same parameters as those employed in Fig. 2. Figure 4 shows the photonic band structures of 2D triangular array of metallic rods in the air (left), in the nematic phase 5CB at 25 °C (center) and in the isotropic phase 5CB at 35 °C (right), respectively. The inset at the lower left side indicates the points of high symmetry in the first Brillouin zone of triangular lattice. As can be seen in this figure, the PBG that was absent in the case of air background newly appears and varies as LC's are infiltrated and undergo a phase transition. The effects of the phase transition of LC's on the PBG are same with the case of square lattice. That is, both edges of PBG move up and the size of PBG is kept nearly constant. The tunability is calculated to be 7.1%, which is a little bit smaller than that of square lattice.

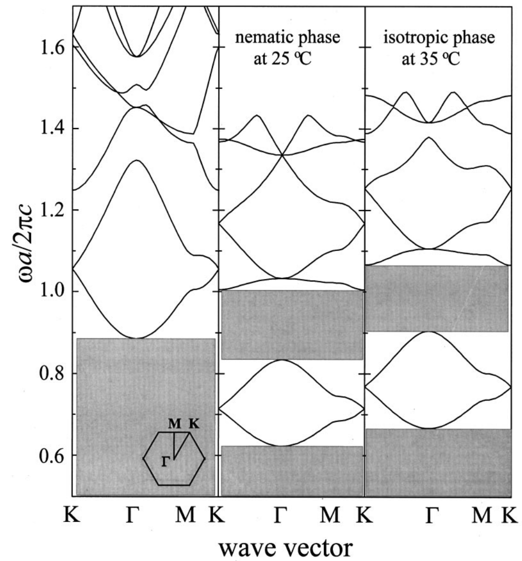

FIG. 4. Photonic band structures of 2D triangular array of metallic rods in the air (left), in the nematic phase 5CB at 25 °C (center), and in the isotropic phase 5CB at 35 °C (right), respectively. They were calculated using the same parameters as those employed in Fig. 2. Note that the PBG that is absent in the air background is newly created after the LC infiltration.

Figure 5 shows the variation of PBG edge frequencies due to the change of the refractive index of LC's for the photonic crystals studied in Figs. 2 and 4. For the calculations, the experimental data of 5CB at a wavelength 488 nm (Ref. 14) were employed. One can notice that edge frequencies increase slowly at the temperatures far below the phase transition temperature and then increase steeply near the phase transition temperature. Thus the steep increase is evidently due to the sharp decrease of the refractive index near the phase transition temperature. Thus the abrupt changes of PBG's around the transition temperature can be employed for the measurement of the phase transition temperature of some LC's as already reported.[6] Judging by our computational results, either square or triangular 2D lattice of metallic rods would be conveniently employed in this measurement.

We have also calculated the dependence of the relative band gap width $\Delta\omega/\omega_c$ on the radius of metallic rods for the

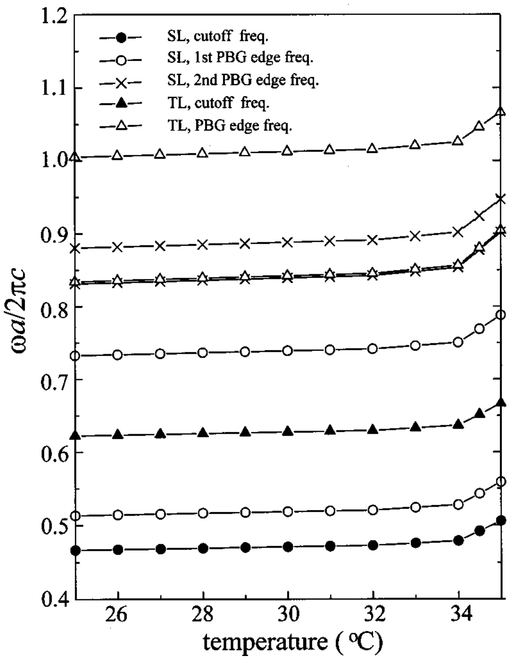

FIG. 5. Dependence of PBG edge frequencies and the cutoff frequencies on the temperature between 25 °C and 35 °C. SL and TL are the abbreviations of a square lattice and a triangular lattice, respectively. Note that the edge or cutoff frequency increases sharply only one or two degree below the phase transition temperature.

first PBG of square lattice [Fig. 6(a)] and the newly appeared PBG of triangular lattice after LC infiltration [Fig. 6(b)], respectively. One can see that the relative band gap width of square lattice after the LC infiltration is always larger than that in the air background. The former increases almost linearly with the increase of radius, while latter reaches a maximum around $r=0.45a$ and then decreases as reported earlier.[21] The maximum value of $\Delta\omega/\omega_c$ obtainable from the LC infiltrated square lattice is about two times larger than

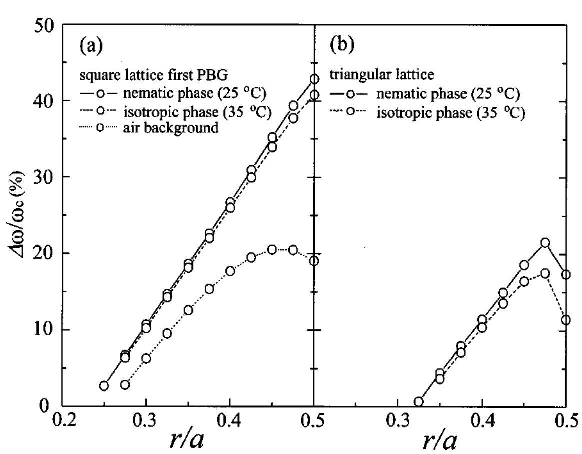

FIG. 6. Dependence of the relative band gap widths $\Delta\omega/\omega_c$ on the radius of metallic rods for the first PBG of square lattice (a) and the PBG of triangular lattice infiltrated with LC's (b). Note that the maximum variation of $\Delta\omega/\omega_c$ caused by the phase transition is larger in triangular lattice than in square lattice.

that obtainable from the square lattice in the air background. Moreover, the infiltration of LC's gives rise to the PBG in a smaller radius of metallic rods. In the case of triangular lattice infiltrated with LC's, the PBG begins to appear around $r=0.325a$ and the value of $\Delta\omega/\omega_c$ shows similar dependence on the radius r with that of square lattice in the air background. For both lattices, the value of $\Delta\omega/\omega_c$ decrease a little bit after the phase transition, since the phase transition makes both edges of PBG's move up keeping the size of PBG's nearly constant (Figs. 2 and 4). We can see in this figure that the change of $\Delta\omega/\omega_c$ due to the phase transition is larger in triangular lattice than in square lattice. We have verified that this is because the variation of ω_c of triangular lattice is larger than that of square lattice. However, ω_c of triangular lattice is higher than that of the first PBG of square lattice (see Figs. 2 and 4), and the relative variation of ω_c corresponding to the tunabilty is calculated to be larger in square lattice than in triangular lattice. Therefore,we can conclude that LC-infiltrated square lattice gives larger relative band gap width and tunabilty than the triangular lattice.

Now, it would be worth discussing the effects of LC infiltration on the PBG's of 2D lattices of metallic rods for the p-polarized wave. The existence of large PBG's due to the strong mismatch between the characteristic impedance of metallic rods and that of dielectric background does not depend on polarization of the EM wave, even if the PBG for the p-polarized wave is smaller than that of the s-polarized wave.[22] The infiltration of LC's increases the mismatch of characteristic impedance and the effective refractive index for the p-polarized wave as well as the s-polarized wave. Thus, for the p-polarized wave, the LC infiltration is expected to reduce the center frequency of PBG's at least without any reduction of PBG magnitude. Moreover, the electric field of the p-polarized wave cannot be concentrated in the metallic rods, and thus, PBG edge modes concentrate their wave energy in the dielectric background. Therefore, the infiltration and/or phase transition of LC's will affect both edge frequencies of PBG, as the case of s-polarized wave. But, the effects of the phase transition of LC's on the PBG's for the p-polarized wave will be different from those for the s-polarized wave because of the anisotropicity of LC's. When all the nematic phase LC molecules are aligned parallel in one direction, its refractive indices are extraordinary and ordinary, for the s- and p-polarized waves, respectively. In many LC's, the ordinary refractive index of nematic phase is smaller than that of isotropic phase, while the extraordinary one of nematic phase is larger than that of isotropic phase. In the case of 5CB at the wavelength of 10.6 μm, for example, the extraordinary (ordinary) refractive index of nematic phase is 1.67 (1.50), and the refractive index of isotropic phase is 1.55. Thus, contrary to the case for the s-polarized wave, the change of refractive index by the phase transition would move both edges of PBG's down for the p-polarized wave.

Some of our results can be applied to the three-dimensional (3D) metallic arrays infiltrated with LC's. It has been reported that any periodic structure composed of metallic or metal-coated spheres can exhibit complete PBG's in optical frequencies when the filling fraction of the spheres exceeds a threshold.[23,24] Thus a 3D lattice of metallic spheres, for example face-centered cubic (fcc) structures of nanosize silver spheres, infiltrated with LC's is a good candidate for a tunable complete PBG structure in optical range, since colloidal systems of microspheres crystallize with a fcc structure and monodisperse silver colloids of several hundred nanometer radius can be easily produced.[25] On the other hand, the fact that the dielectric response of 2D and 3D artificial structures composed of thin metal wires can show the Drude-like behavior in the GHz frequencies[26,27] suggests that the infiltration of LC's into these structures would enlarge the PBG's and make them tunable by changing the temperature. The dielectric function of practical metals, silver for example, deviates from the ideal Drude dielectric function particularly in the proximity of the zero crossing of real ϵ (328 nm for silver) because of the contribution of bound *d* electrons to the dielectric function. This deviation affects the photonic band structures of the metallodielectric photonic crystals in the proximity of the zero crossing of real ϵ.[22,24] But, the effects of dielectric background on the magnitude and center frequency of PBG's of the array of real silver rods[22] are identical with those of the array of silver rods with ideal Drude dielectric function. Another interesting example showing temperature dependent PBG's can be sought in a 2D array of semiconducting rods embedded in dielectrics. For example, the dielectric constant of intrinsic InSb can be modeled by a Drude-like dielectric function in THz frequency range with a temperature-dependent plasma frequency, which is caused by the temperature dependence of free carrier concentration.[7] Based on this fact, Halevi *et al.* have recently suggested a tunable 2D photonic crystal based on the array of InSb rods in air.[7] However, the suggested relative PBG widths were rather narrow at the room temperature. We have verified from the band calculations that the infiltration of LC's in the suggested InSb photonic crystals, reduces the magnitude and tunable range of PBG's even more (not shown here). This is evidently due to the decrease of the contrast between the dielectric constant of InSb rods and the background one after the infiltration of LC's. We can thus conclude, from this result and the results in Fig. 1, that the infiltration of LC's in the dielectric photonic crystals and semiconducting photonic crystals generally reduces the PBG and its tunability. Therefore, the infiltration of LC's for the implementation of tunable photonic crystals surely has greatest merit in the case of metallic photonic crystals.

IV. CONCLUSION

We have studied, from the photonic band calculation, the effects of LC infiltration on the PBG's of two-dimensional square and triangular lattices of metallic rods. The infiltration of LC's into the square lattice enlarges the PBG that already exists in the air background and creates another higher-order PBG. The infiltration of LC's in the triangular lattice creates a gap between the second and third bands for $r \geqslant 0.325a$, while the lattice in the air background does not show any PBG irrespective of the value of radius. The change of refractive index caused by the phase transition of LC's moves both edges of PBG's up and reduces the value of $\Delta\omega/\omega_c$ for the *s*-polarized wave. PBG position changes largely just near the phase transition temperature of LC's for the *s*-polarized wave. For *p*-polarized wave, these changes due to the phase transition of LC's are expected to be in the opposite direction with those for the *s*-polarized wave. The tunability of PBG by the change of temperature is larger in square lattice than in triangular lattice, even if the variation of PBG position due to the phase transition of LC's is larger in triangular lattice. Our results show also that the PBG's of LC-infiltrated metallic photonic crystals are more easily tunable than those of dielectric photonic crystal infiltrated with LC's. We have also discussed the usefulness of LC infiltration in the implementation of 2D or 3D tunable metallic photonic crystals.

ACKNOWLEDGMENTS

Parts of this work were financially supported by the KOSEF through QSRC of Dongguk University (QSRC-00-II-1-1) and the Cooperative Research Program (2000-042-D00054) of the Korean Research Foundation.

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

[1] E. Yablonovitch, Phys. Rev. Lett. **58**, 2059 (1987).
[2] S. John, Phys. Rev. Lett. **58**, 2486 (1987).
[3] See, for example, J. Lightwave. Technol. **11** (1999).
[4] See, for example, IEEE Trans. Microwave Theory Tech. **47** (1999).
[5] K. Busch and S. John, Phys. Rev. Lett. **83**, 967 (1999).
[6] K. Yoshino, Y. Shimoda, Y. Kawagishi, K. Nakayama, and M. Ozaki, Appl. Phys. Lett. **75**, 932 (1999).
[7] P. Halevi and F. Ramos-Mendieta, Phys. Rev. Lett. **85**, 1875 (2000).
[8] C.-S. Kee, J.-E. Kim, H.Y. Park, I. Park, and H. Lim, Phys. Rev. B **61**, 15 523 (2000).
[9] S.W. Leonard, J.P. Mondia, N.M. van Driel, O. Toder, and S. John, Phys. Rev. B **61**, R2389 (2000).
[10] E.R. Brown and O.B. McMahon, Appl. Phys. Lett. **67**, 2138 (1995).
[11] D.F. Sievenpiper, E. Yablonovitch, J.N. Winn, S. Fan, P.R. Villeneuve, and J.D. Joannopoulos, Phys. Rev. Lett. **80**, 2829 (1998).
[12] 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).
[13] V. Kuzmiak and A.A. Maradudin, Phys. Rev. B **55**, 7427 (1997).
[14] I.-C. Khoo, *Liquid Crystals*, 1st ed. (John Wiley & Sons, New York, 1995), p. 51.
[15] M.S. Kushwaha, P. Halevi, L. Dobrzynski, and B. Djafari-Rouhani, Phys. Rev. Lett. **71**, 2022 (1993).
[16] A. Mekis, S. Fan, and J.D. Joannopoulos, Phys. Rev. Lett. **58**, 4809 (1998).
[17] C.-S. Kee, J.-E. Kim, H.Y. Park, and H. Lim, IEEE Trans. Microwave Theory Tech. **47**, 2148 (1999).
[18] J.D. Joannopoulos, R.D. Meade, and J.N. Winn, *Photonic Crystals: Molding the Flow of Light* (Princeton University Press, Princeton,1995), p. 42.
[19] J.B. Pendry and A. MacKinnon, Phys. Rev. Lett. **69**, 2772 (1992).
[20] W.M. Robertson, G. Arjavalingam, R.D. Meade, K.D. Brommer,

A.M. Rappe, and J.D. Joannopoulos, Phys. Rev. Lett. **68**, 2023 (1992).
[21] V. Kuzmiak, A.A. Maradudin, and F. Pincemin, Phys. Rev. B **50**, 16 835 (1994).
[22] H. van der Lem and A. Moroz, J. Opt. A **2**, 395 (2000).
[23] W.Y. Zhang, X.Y. Lei, Z.L. Wang, D.G. Zheng, W.Y. Tam, C.T. Chan, and Ping Sheng, Phys. Rev. Lett. **84**, 2853 (2000).
[24] A. Moroz, Phys. Rev. Lett. **83**, 5274 (1999).
[25] D.V. Goia and E. Matijecic, New J. Chem. **146**, 139 (1999).
[26] J.B. Pendry, A.J. Holden, W.J. Stewart, and I. Youngs, Phys. Rev. Lett. **76**, 4773 (1996).
[27] D.R. Smith, D.C. Vier, W. Padilla, S.C. Nemat-Nasser, and S. Schultz, Appl. Phys. Lett. **75**, 1425 (1999).