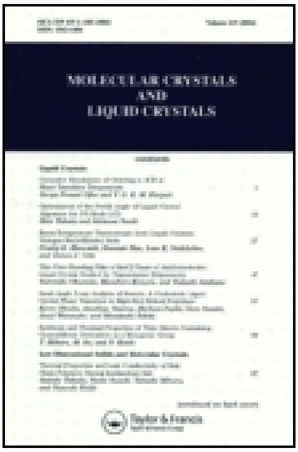


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# Light Propagation in Liquid Crystal Infiltrated Two-Dimensional Photonic Crystal at a High-Order Photonic Band

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# Light Propagation in Liquid Crystal Infiltrated Two-Dimensional Photonic Crystal at a High-Order Photonic Band

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*Light propagation into a photonic crystal infiltrated with a nematic liquid crystal is numerically investigated. At a high-order photonic band, photonic crystals generally exhibit interesting characteristics such as a negative refraction and a superprism effect. Our numerical results show that the sign of an effective refractive index of the tunable photonic crystal can be controlled at a certain frequency by changing molecular orientation. Furthermore, using a combination of positive and negative index photonic crystals, a light could be redirected 90° without a waveguide structure.*

**Keywords** Negative index material; negative refraction; optical switch; tunable photonic crystal

## 1. Introduction

Negative index materials have attracted a great deal of attention from both theoretical and experimental researches due to unconventional characteristics. Negative refractive index has not been observed in nature and has been considered unreal or imaginary idea before Pendry *et al.* reported [1]. According to their concept, subwavelength split-ring resonators that provide a negative permittivity and permeability could give rise to a negative refractive index. That is, the fabrication of the subwavelength structure allows designing even refractive index. The first metamaterial was demonstrated in microwave region, and then many researchers have been developing infrared and optical matematerials [2,3].

Photonic crystals, which are periodic optical nanostructures, also could have a negative refractive index effectively [4,5]. In 1987, photonic crystal is invented by

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Yablonovitch to achieve a low threshold laser [6]. At first stage, many researchers have mainly studied and developed photonic band gap materials to strongly confine light in a photonic crystal. This type of study is called photonic band gap engineering. Meanwhile, Kosaka *et al.* reported superprism and self-collimating phenomena in photonic crystals [7,8]. These phenomena are caused by an anomalous dispersion at a high-order photonic band. The research development based on photonic band rather than photonic band gap is called photonic band engineering. Negative refraction in a photonic crystal is also one of the photonic band engineering because the unusual light propagation occurs due to a unique frequency dispersion of a photonic band. Negative refractive index in a photonic crystal has been observed in microwave and infrared regions [9–11]. Compared with metamaterials, photonic crystals have an advantage for propagation loss because photonic crystals do not include any metal components.

Before the invention of photonic crystal, unusual light propagation in a dielectric periodic structure has been studied using a diffraction grating [12]. Not only a photonic crystal but also a diffraction grating provides complex light propagation due to folding wave vectors. Liquid crystals also show extraordinary beam propagation in which the propagation direction is determined by an ellipsoidal wave-vector surface. Recently, tunable negative refraction has been demonstrated by using nematic liquid crystal [13,14]. In the both case, an equi-frequency surface (EFS), which represents the locus in the reciprocal space of propagating wave vectors at a fixed frequency, is key for the direction of the light propagation.

In this paper, we numerically study light propagation in a liquid crystal infiltrated two-dimensional (2D) photonic crystal at a high-order photonic band. The use of a liquid crystal as photonic crystal component is widely used for tunable photonic crystal investigations. We have demonstrated tunable photonic band gaps and tunable photonic defect modes using an opal and a dielectric multilayer, respectively [15–18]. Using liquid crystal, tunable superprism effect and tunable negative refraction have also been studied [19–21]. However, they discussed only tunable refraction, not discussing tunable refractive index. They well designed an EFS in k-space to control a refractive angle, but the EFS is not a circular shape. An effective refractive index of a photonic crystal can be defined only when its EFS is a circle [4]. Here we discuss a simple configuration to obtain a circular shaped EFS and its photonic band structure, and then interface coupling of the photonic crystal is described. Further, we also numerically demonstrated control of an effective refractive index of the tunable photonic crystal.

## 2. Photonic Band Structure

We here deal with a GaAs 2D triangular lattice photonic crystal infiltrated with a nematic liquid crystal. The reason that GaAs, which has refractive index of 3.6 in infrared region, is chosen because a large index contrast is necessary in order to give rise to an effective refractive index in a photonic crystal. Since GaAs is not transparent for visible light, we assume that an infrared beam propagates into the photonic crystal. The $R/a$ ratio of the photonic crystal is 0.42, where $a$ is the lattice constant and $R$ is the radius of the holes. For light at wavelength of 1.55 μm, $a$ and $R$ are 845 nm and 355 nm, respectively.

Recently, there is a report that a dual-frequency nematic liquid crystal has a large birefringence ($\Delta n > 0.3$) in infrared region [22]. In our calculation, we examine the GaAs photonic crystal with a dual-frequency nematic liquid crystal having a large birefringence. The ordinary and extraordinary refractive indices of the liquid crystal are set to be 1.5 and 1.8, respectively. Figure 1(a) and 1(b) are the illustrations of liquid crystal molecular alignment in the photonic crystal. We assume that liquid crystal molecules align parallel to the z-direction when a low frequency electric field is applied along the *z*-direction. Due to the use of a dual-frequency nematic liquid crystal, the liquid crystal molecules should be reoriented perpendicular to the *z*-direction when a high frequency electric field is applied along the *z*-direction.

Let us consider TM mode light propagation consisting of $E_z$, $H_x$, and $H_y$. The electric field $E_z$ is affected by only the extraordinary index when the molecular directors align parallel to the *z*-direction. In contrast, the $E_z$ is affected by only the ordinary index when the molecular directors are perpendicular to the *z*-direction. In this configuration, the propagating light is not affected by both the ordinary and extraordinary indices simultaneously. Thus, we could avoid the complicated propagation owing to the optical anisotropy of the liquid crystal because the light is affected by only the ordinary or extraordinary index. This is the important key to obtain a circular shaped EFS in k-space.

Figure 2(a) shows the photonic band diagram of the structure calculated by a plane-wave method [23]. The solid and broken lines are for the ordinary and extraordinary refractive indices, respectively. At lower frequencies, there is not much difference between the solid and broken lines. However, the difference between the two lines becomes larger at higher frequencies. This is caused by the fact that the light effectively feels a larger liquid crystal domain at higher frequencies because the wavelength shortens. Therefore, the change in the refractive index can be utilized efficiently at a higher photonic band.

An effective refractive index of a photonic crystal can be defined when a photonic band forms a bell shape near the Γ point [4]. The sign of the effective index is determined by whether upward or downward direction of the bell-shaped band. An upward bell-shaped band means the photonic crystal could have positive refractive indices, while a downward bell-shaped band means that the photonic crystal could have negative refractive indices. Figure 2(b) is the enlarged diagram of Figure 2(a). The 5th band for $n_{lc} = 1.5$ and the 6th and 7th bands for $n_{lc} = 1.8$ form

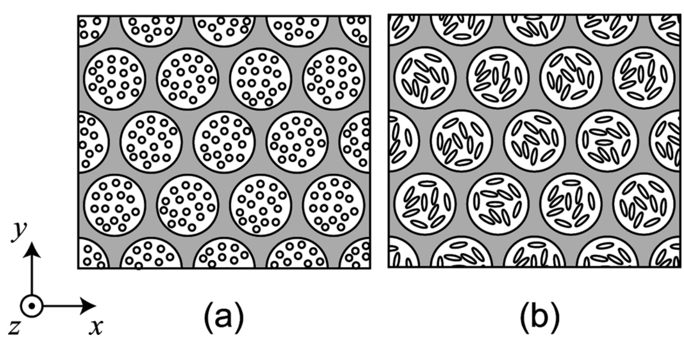


**Figure 1.** A GaAs 2D triangular lattice photonic crystal infiltrated with a dual-frequency nematic liquid crystal. (a) The liquid crystal directors are parallel to the *z*-axis when a low frequency electric field is applied along the *z*-axis. (b) The directors are perpendicular to the *z*-axis when a high frequency electric field is applied along the *z*-axis.

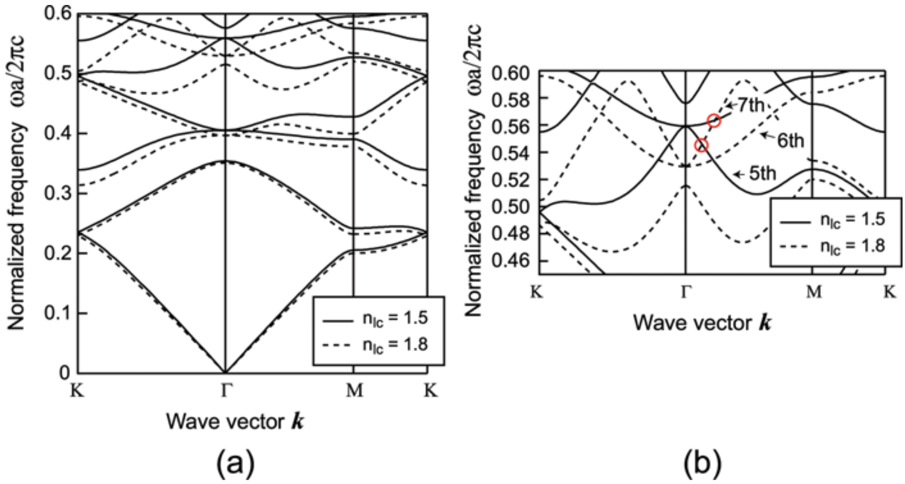


**Figure 2.** Photonic band diagram of the tunable photonic crystal calculated by a plane-wave method. (b) is the enlarged diagram of Figure 2(a). (Figure appears in color online.)

a bell shape near the Γ point. The effective refractive index of the photonic crystal is determined by $|n_{\mathrm{eff}}| = ck/\omega$ that is definable when an EFS is circular. Figure 3 shows the EFS of the 5th band for $n_{\mathrm{lc}} = 1.5$. The EFS corresponds to a contour plot of the photonic band, and a hexagon represents the first Brillouin zone. It is clear that the contours become circular above the normalized frequency $\omega a/2\pi c$ of 0.52 at the center. These calculations indicate that the photonic crystal could have an effective refractive index between 0.52 and 0.55. Here we again emphasize that the effective index is determined by $|n_{\mathrm{eff}}| = ck/\omega$. Note that there are some intersection points in Figure 2(b). The marked intersections mean that the both bands for $n_{\mathrm{lc}} = 1.5$ and $n_{\mathrm{lc}} = 1.8$ have the same $k$ and $\omega$. That is, the photonic crystal with $n_{\mathrm{lc}} = 1.5$ and $n_{\mathrm{lc}} = 1.8$ have the same $|n_{\mathrm{eff}}|$ under the conditions. In contrast, the sign of the effective index is not same because the directions of the bell-shaped bands are opposite between $n_{\mathrm{lc}} = 1.5$ and $n_{\mathrm{lc}} = 1.8$. Therefore, the tunable photonic crystal can change in the sign of the effective refractive index by using the liquid crystal.

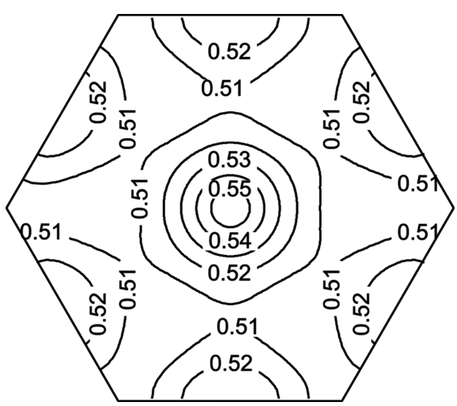


**Figure 3.** EFS of the 5th band for $n_{\mathrm{lc}} = 1.5$.

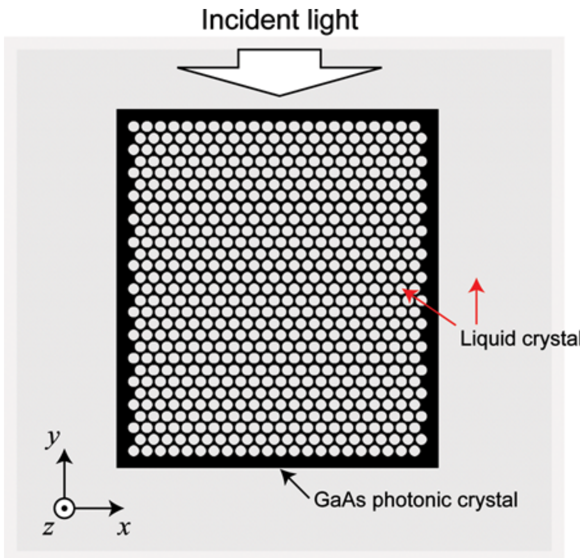


**Figure 4.** Structure of the tunable photonic crystal for FDTD simulation. (Figure appears in color online.)



## 3. Light Coupling at High-Order Band

Finite-difference time-domain (FDTD) simulation is performed to investigate light propagation into the tunable photonic crystal described in Section 2. The FDTD method is a popular computational electrodynamics modeling technique based on the Yee algorithm [24]. We first investigate whether an incident light is coupled into the photonic crystal. It is known that an uncoupled mode exists at some high-order photonic bands. Coupling is very important because if the incident light is uncoupled, the light cannot enter the photonic crystal.

Figure 4 shows the structure of the photonic crystal for FDTD simulation in which an incident light enters from the top of the photonic crystal. The transmission spectrum and the photonic band diagram for $n_{\mathrm{lc}} = 1.5$ are shown in Figure 5. To compare with the transmission spectrum, the band diagram in the $\Gamma$-$M$ direction shown in Figure 2 is again plotted. The transmission spectrum and band diagram are calculated by the FDTD method and plane-wave method, respectively. In the FDTD simulation, the transmitted light is detected at the bottom of the photonic crystal. As is evident from Figure 5, the transmittance significantly decreases at some frequencies. The gray color backgrounds indicate strong reflection, and almost all of the reflection frequencies correspond to photonic band gaps in the $\Gamma$-$M$ direction. However, despite the 3rd, 5th, and 6th bands exist, the transmittance is quite low at some frequencies in the bands. This means that the incident light is uncoupled to the photonic crystal at these frequencies.

The uncoupled mode is caused by a field pattern of an electromagnetic wave at a high-order band. Figure 6 shows the field patterns of $E_z$ component at 5th and 6th bands. In the field patterns, the blue and red colors represent negative and positive strengths, respectively. The important thing here is that 2D electric field patterns have electric dipoles along the $x$- and $y$-directions. When an incident light is a plane

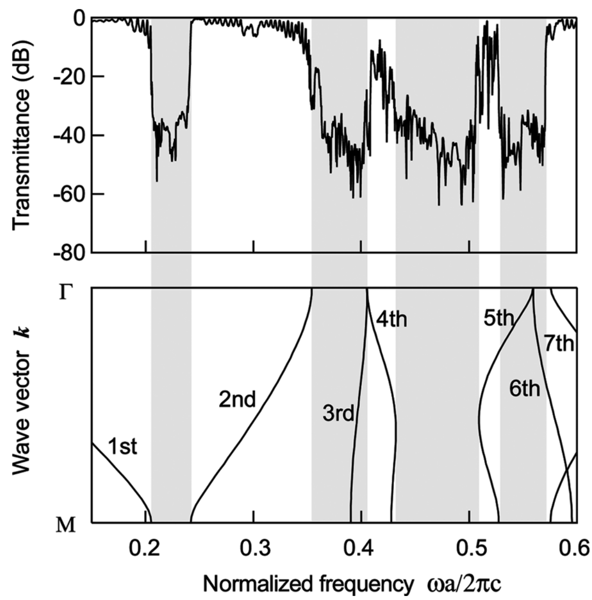


**Figure 5.** Transmission spectrum and the photonic band diagram for $n_{lc} = 1.5$.

wave propagating along the *y*-direction, i.e., the incident light is perpendicular to the *x*-direction, the incident light cannot excite an electric dipole along the *x*-direction because the incident light does not have any *x*-component. In other words, a plane wave which has only the *y*-direction dipole hardly generates a 2D electric field pattern shown in Figure 6. That is the reason that transmittances at 5th and 6th bands are quite low. To resolve such uncoupled mode, an anti-reflection structure has been studied [25]. We here consider that a photonic crystal structure without the top and bottom edges, as shown in Figure 7. The aim of the structure is to disrupt the phase of the incident plane wave at the interface. The phase disruption at the interface gives

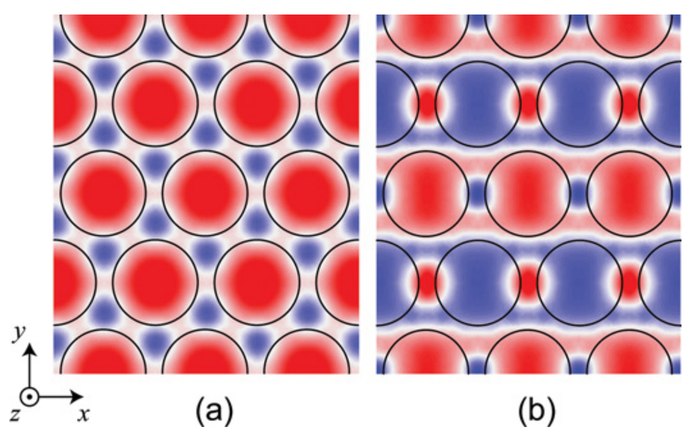


**Figure 6.** Electric field patterns of $E_z$ component at (a) 5th and (b) 6th bands. (Figure appears in color online.)

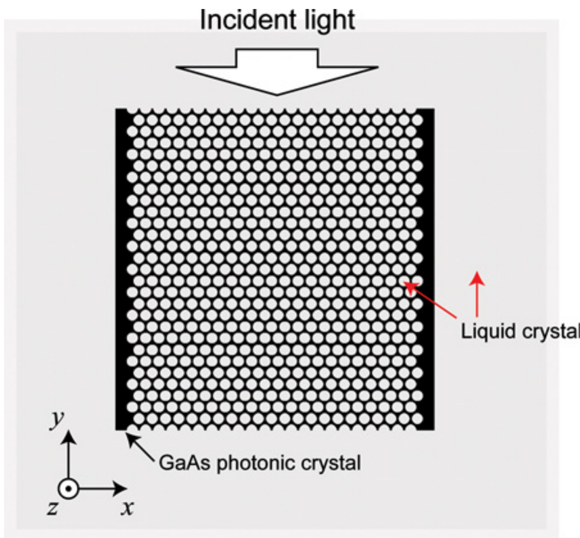


**Figure 7.** Photonic crystal structure without the top and bottom edges for FDTD simulation. (Figure appears in color online.)

rise to the *x*-direction dipole, and that will improve the coupling efficiency. Figure 8 shows the transmission spectrum from the structure. It is clear that the transmittance of the 5th band is dramatically improved. The improvement of coupling efficiency is due to the fact that the incident plane wave is not in-phase at the interface. On the

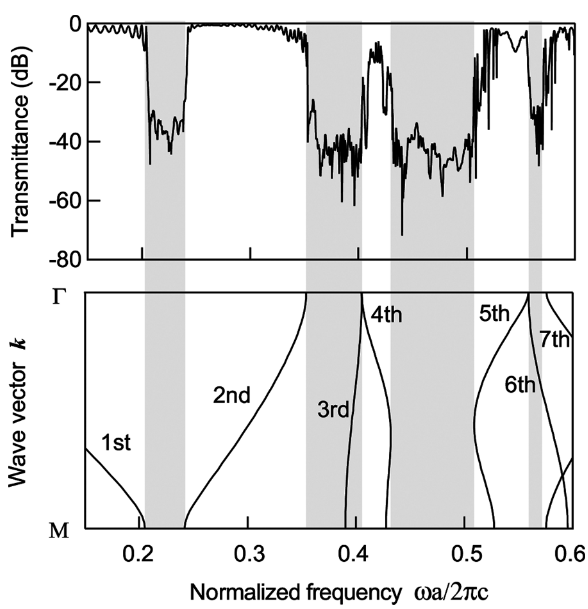


**Figure 8.** Transmission spectrum and the photonic band diagram of the tunable photonic crystal without the top and bottom edges. The refractive index of the liquid crystal is 1.5.

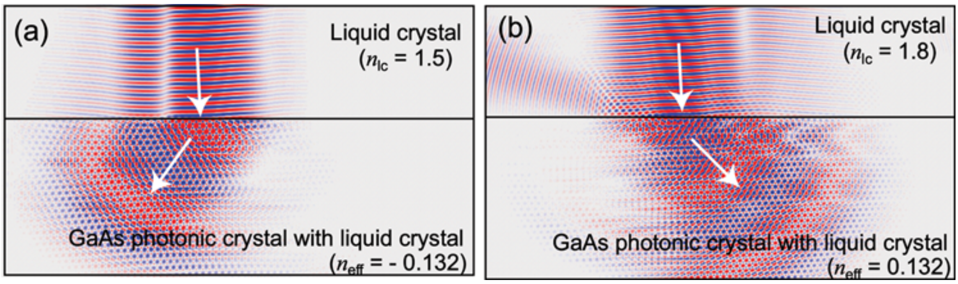


**Figure 9.** FDTD simulated propagation from the liquid crystal into the photonic crystal at $\omega a/2\pi c = 0.545$ with incident angle of 3°: (a) $n_{lc} = 1.5$ and (b) $n_{lc} = 1.8$. The tunable photonic crystal is placed at lower part. (Figure appears in color online.)



other hand, the 6th band is hardly improved and is still uncoupled. Since the 5th and 7th bands are available in the structure, we could use the frequency at the intersection between the 5th and 7th bands in Figure 2(b) in order to control the sign of an effective index.

## 4. Control of Light Propagation

We here mainly examine light propagation into the tunable photonic crystal having a positive or negative refractive index. Figure 9 shows the FDTD simulated propagation from the liquid crystal into the tunable photonic crystal at $\omega a/2\pi c = 0.545$ with incident angle of 3°. In Figure 9, the photonic crystal is placed at lower part. That is, the upper medium is liquid crystal, and the lower medium is the tunable photonic crystal. Figure 9(a) and (b) are for $n_{lc} = 1.5$ and $n_{lc} = 1.8$, respectively. As is evident in the figures, the refraction direction in the photonic crystal depends on the refractive index of the liquid crystal. This indicates that we could control refraction direction between positive and negative by using reorientation of liquid crystal. The effective refractive indices of the photonic crystal with $n_{lc} = 1.5$ and $n_{lc} = 1.8$ are $-0.132$ and 0.132, respectively, which are determined by $|n_{eff}| = ck/\omega$. Although the value of the effective refractive index is less than the index of air $n_{air} = 1$, it is not wrong. This is because that the effective refractive index is for phase

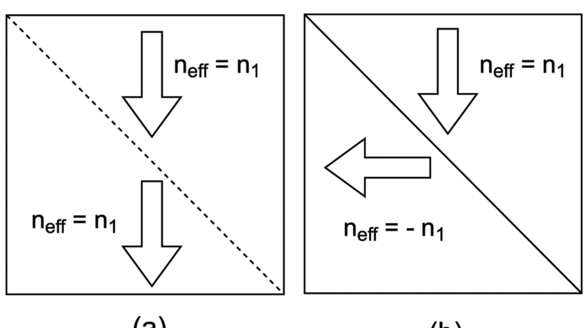


**Figure 10.** Optical switch using two triangular shaped photonic crystals having positive or negative refractive index: (a) positive and positive and (b) positive and negative.

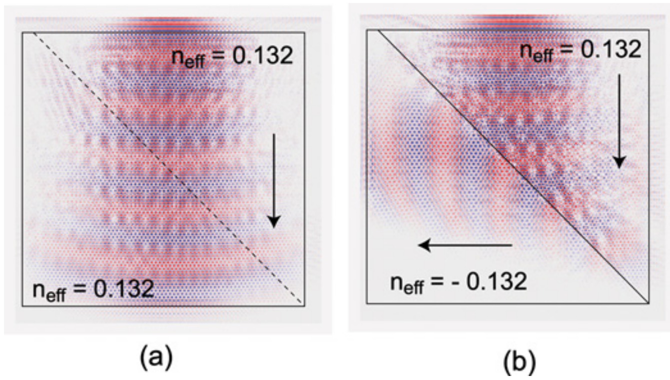


**Figure 11.** FDTD simulated propagation in the combination of two triangular shaped photonic crystals: (a) Photonic crystals have the same effective index. (b) Photonic crystals have opposite index signs each other. (Figure appears in color online.)



velocity, not for group velocity. According to Snell's law, the refractive angles are $-36.5°$ and $45.5°$ for $n_{lc}/n_{eff} = -1.5/0.132$ and $n_{lc}/n_{eff} = 1.8/0.132$, respectively. The arrows in Figure 9 are written using the angles determined by Snell's law. It is clear that the arrow directions well agree with FDTD simulated propagation.

Light propagation through a combination of positive and negative index media is also examined. Several groups have studied the optical splitter using a combination of triangular shaped photonic crystals [26,27]. We here consider an optical switch using two triangular shaped photonic crystals shown in Figure 10. The greatest advantage in our photonic crystal system is the controllable index sign. When the two triangular shaped photonic crystals have the same effective index, an incident light propagates straight. However, if we use two triangular shaped photonic crystals having the same absolute value of effective index but opposite signs, an incident light could turn 90° at the interface due to negative refraction. Figure 11 shows the propagating electric field simulated the system. In Figure 11(a), the light propagates straight because they have the same effective index. In contrast, when the two triangular shaped photonic crystals have positive and negative indices, the light turns 90° to the left. Note that the light is deflected at right angle without a waveguide structure. However, in this calculation, the reflection at the interface between two triangular photonic crystals is not zero. The interface should be optimized to reduce the reflection. We now are working to resolve the problem. Aside from internal reflection problem, the FDTD simulation suggests that light propagation can be controlled with the tunable effective refractive index of photonic crystal.

## 5. Conclusion

We numerically examined light propagation into the photonic crystal infiltrated with a nematic liquid crystal at a high-order photonic band. The photonic band calculation indicated that the photonic crystal could have a positive or negative effective refractive index depending on liquid crystal refractive index. The coupling efficiency at a high-order photonic band was improved by changing the interface of the photonic crystal. The FDTD simulation showed that positive or negative refraction could be controlled by reorientation of the liquid crystal. Further, in the combination of two triangular shaped photonic crystals having opposite index signs each other, an incident light could be turned 90° without a waveguide structure.

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