Tunable photonic-crystal waveguide Mach–Zehnder interferometer achieved by nematic liquid-crystal phase modulation

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Abstract: Photonic crystals (PCs) have many potential applications because of their ability to control light-wave propagation and because PC-based waveguides may be integrated into optical interferometers. We propose a novel tunable PC waveguide Mach–Zehnder interferometer based on nematic liquid crystals and investigate its interference properties numerically by using the finite-difference time-domain method. We can change the refractive indices of liquid crystals by rotating the directors of the liquid crystals. Then we can control the phase of light propagation in a PC waveguide Mach–Zehnder interferometer. The interference mechanism is a change in the refractive indices of liquid-crystal waveguides. The novel interferometer can be used either as an optically controlled on–off switch or as an amplitude modulator in optical circuits.

OCIS codes: (130.3120) Integrated optics devices; (060.1810) Couplers, switches, multiplexers; (999.9999) Photonic crystal waveguide.

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1. Introduction

Photonic crystals (PCs) are artificial dielectric or metallic structures in which the refractive-index modulation gives rise to stop bands for optical waves within a certain frequency [1,2]. The method used for fabricating PCs consists of suppressing some scatters to create a waveguide inside the PC. This waveguide creates a band of conduction inside the bandgaps. These crystals have many potential applications because of their ability to control light-wave propagation and because PC-based optical waveguides may be integrated into optical circuits. The periodicity is broken by introduction of some defects into the crystals. It has been shown that doped PCs permit the guiding of waves in two different geometric paths for two distinct wavelength ranges [3]. Such structures can be use to design highly efficient new optical devices. Optical waveguides in two-dimensional (2-D) PCs produced by insertion of linear defects into PC structures have been proposed [4] and experimentally proved [5]. Mach–Zehnder interferometers were fabricated from suspended membrane PC waveguides [6]. The path-length difference was fixed after the Mach–Zehnder interferometers were fabricated from PC waveguides. Sugimoto *et al.* recently proposed the idea of a 2D PC-based symmetrical Mach–Zehnder-type ultrasmall and ultrafast optical switching device [7]. An important key issue for the conventional symmetrical Mach–Zehnder device is how to construct an output Y junction that is capable of desirable interference between the two phase-modulated signal pluses. A directional coupler based on a 2-D PC slab waveguide, which however had a defect in its coupling-strength control, was numerically and experimentally proposed [8].

It is important, however, to obtain tunable PC waveguides for applications in optical devices. Tunable PC waveguides that utilize synthetic opals and inverse opals infiltrated with functional materials have been proposed [9,10]. One can control the refractive indices of opals by adjusting various factors and fields. For example, one can change the refractive indices of conducting polymers and liquid crystals (LCs) by changing the temperature and the electric field of the polymer or crystal. Therefore one can change the optical properties of tunable PC waveguides composed of such materials by changing the temperature and the electric field in the same way. Recently the propagation of tunable light in Y-shaped waveguides in 2-D PCs by use of LCs as linear defects was proposed [11,12].

Here we propose a novel tunable PC waveguide Mach–Zehnder interferometer with nematic LCs and investigate its interference properties numerically by using the finite-difference time-domain (FDTD) method. The PC waveguide can be obtained by the

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infiltration of LCs into air regions in a 2-D PC composed of an air channel with triangular lattices. One can change the waveguide modes in PCs based on the orientation of LCs by adjusting the applied field; this makes possible the control of the phase of a light wave with a specific frequency in a PC waveguide.

2. Photonic-crystal waveguide Mach–Zehnder interferometer

The finite-difference time-domain method was introduced by Yee in 1966. The approach is based on a direct numerical solution of the time-dependent Maxwell equations by use of the finite-difference technique [13]. The FDTD method is a powerful, accurate numerical method that permits computer-aided design and simulation of PC devices. The FDTD algorithm must be modified at the boundaries of the computational region where suitable numerical absorbing boundary conditions are applied. The perfectly matched layer [14] boundary condition has been used because it yields high performance. The photonic device is laid out in the *x*–*z* plane. The propagation is along the *z* direction. The space steps in the *x* and *z* directions are Δx and Δz, respectively. Yee's numerical scheme is applied to the 2D TE case. It uses central-difference approximations for the numerical derivatives in space and time, both with second-order accuracy. The sampling in space is on a subwavelength scale. Typically, 10–20 steps per wavelength are needed. We assume that $\Delta x = 0.07$ and $\Delta z = 0.07$. The sampling in time is selected to ensure numerical stability of the algorithm. The time step is determined by the Courant limit [13]. A more-detailed treatment of the FDTD method is given in Ref. 13.

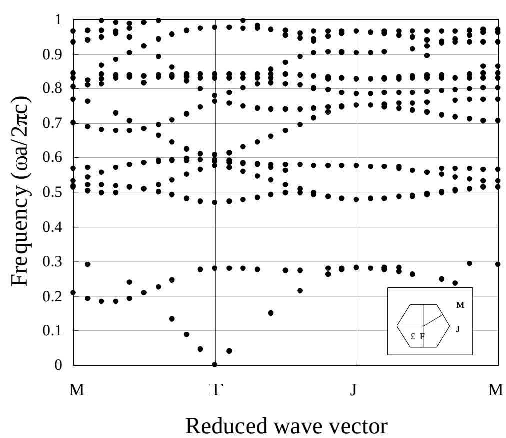

Fig. 1. Photonic band structure for the triangular array of dielectric columns. Inset, the Brillouin zone.

We consider a PC waveguide Mach–Zehnder interferometer composed of dielectric pillars in air in a triangular array with lattice constant $a = 0.54$ μm. The radius and the refractive index of the rods are taken as $r = 0.18a$ and $n = 3.4$ (Si), respectively. A plane-wave expansion calculation [2,15] yields the photonic band structure for the triangular array of dielectric columns shown in Fig. 1; the inset shows the Brillouin zone. Therefore this PC structure has a photonic bandgap for transverse electric modes that extends from $\lambda = 1.2$ to 1.7 μm, where λ is the wavelength in free space. We have designed Mach–Zehnder interferometers in 2-D PCs with a range of path-length differences between the arms of the interferometers. Devices with path-length differences between the two arms of 0 and of 4*a* were designed and are shown in Fig. 2. This amplitude-splitting interferometer uses two Y junctions and two arms. The incident light is divided into two arms. The relative phase of the two arms is determined by the intensity of the light. Figure 3 shows the electric field patterns observed in the frequency domain of the PC waveguide Mach–Zehnder interferometer with path-length differences. Input wavelength $\lambda = 1.42$ μm is the TE-polarized continuous wave

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with Gaussian profile launched into port 1. We can see that the output reaches a maximum, as shown in Fig 3(a), when the recombined light is in phase and that the interferometer output is null, as shown in Fig 3(b), when the recombined light from the two arms is out of phase.

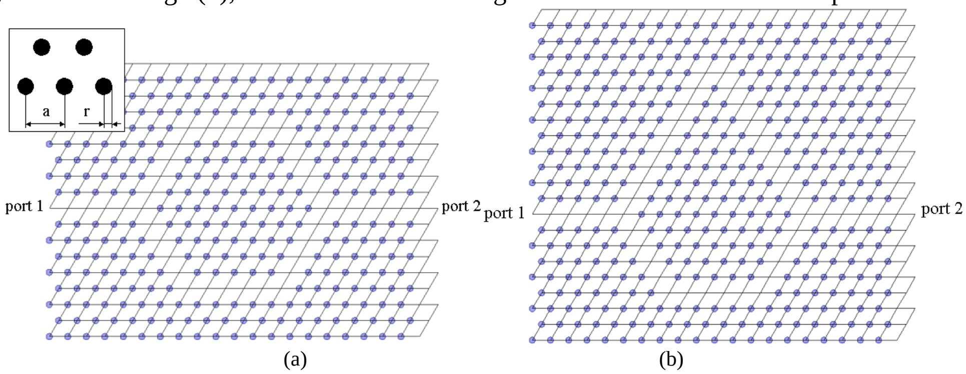

Fig. 2. PC waveguide Mach–Zehnder interferometer with path-length differences of (a) 0 and (b) 4*a*. Inset, lattice constant *a* and radius of rods *r*.

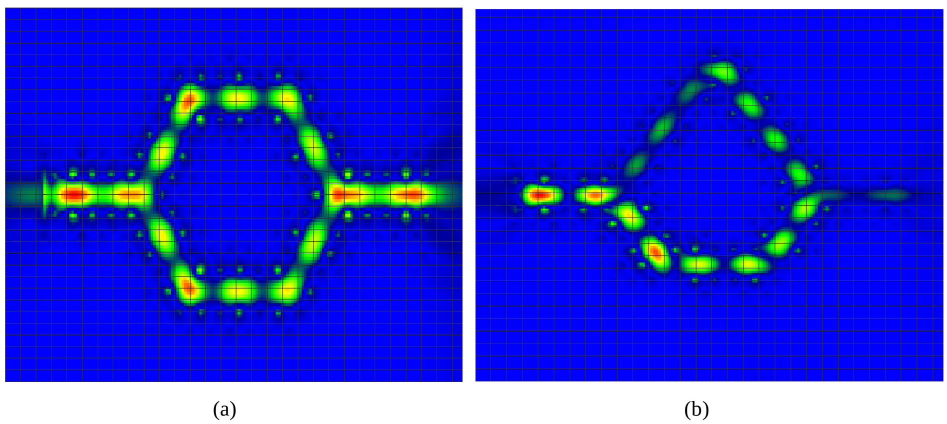

Fig. 3. Electric field patterns observed in the frequency domain of the PC waveguide Mach–Zehnder interferometer with path-length differences of (a) 0 and (b) 4*a*.

3. Liquid-crystal phase modulation

The novel tunable PC waveguide Mach–Zehnder interferometer composed of dielectric pillars in air in a triangular array with lattice constant a = 0.54 μm is shown in Fig. 4. The radius and the refractive index of the rods are taken as r = 0.18a and n = 3.4, respectively. The air channel in the 2-D PC forms the PC waveguide, and the shaded regions are infiltrated with LCs. The ordinary and extraordinary refractive indices of the LCs (5CB type) are $n_{\mathrm{LC}}^{o} = 1.522$ and $n_{\mathrm{LC}}^{e} = 1.706$, respectively. We treat a situation in which the TE mode and the directors of the LCs are parallel to the plane of a 2-D PC because the electric field exists only in the 2-D planes in this mode. The electric field is strongly affected by rotating directors of LCs. To determine the dispersion relations of guided modes in PC waveguides with nematic LCs we can express the light-wave equation that is satisfied by the magnetic field for 2-D planes as

$$\nabla \times [\frac{1}{\varepsilon(\mathrm{r})} \nabla \times \mathrm{H(r)}] = (\frac{\omega}{\mathrm{c}})^2 \mathrm{H(r)}, \tag{1}$$

where dielectric tensor $\varepsilon(r) = \varepsilon(r + R)$ is periodic with respect to lattice vector R generated by primitive translation, and $\nabla \cdot H(r) = 0$.

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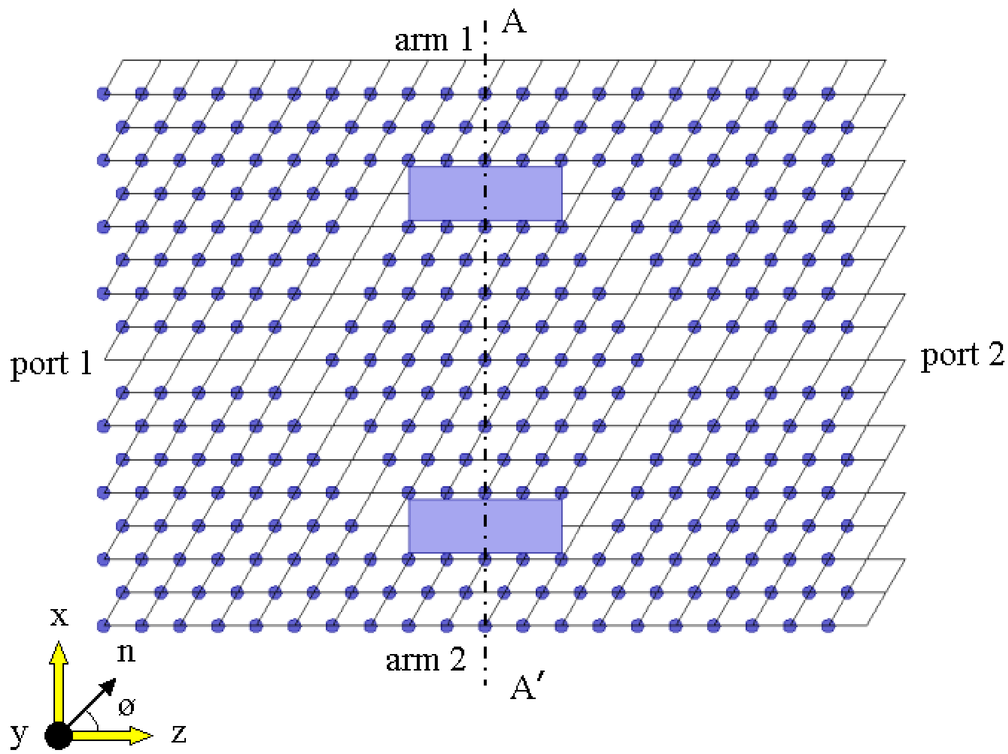

Fig. 4. PC waveguide Mach–Zehnder interferometer with LCs. Shaded regions, parts infiltrated with LC waveguides. Diagram at lower left, director of a LC.

Generally LCs possess two kinds of dielectric index. One is ordinary dielectric index ε^{o}, and the other is extraordinary dielectric index ε^{e}. Light waves with electric fields perpendicular and parallel to the director of the LC have ordinary and extraordinary refractive indices, respectively. In the 2-D planes, the components of the dielectric tensor of the nematic LC are represented as [16]

$$\varepsilon_{xx}(\mathrm{r}) = \varepsilon^{o}(\mathrm{r})\sin^2\phi + \varepsilon^{e}(\mathrm{r})\cos^2\phi\,, \tag{2}$$

$$\varepsilon_{zz}(\mathrm{r}) = \varepsilon^{o}(\mathrm{r})\cos^2\phi + \varepsilon^{e}(\mathrm{r})\sin^2\phi\,, \tag{3}$$

$$\varepsilon_{xz}(\mathrm{r}) = \varepsilon_{zx}(\mathrm{r}) = [\varepsilon^{e}(\mathrm{r}) - \varepsilon^{o}(\mathrm{r})]\cos\phi\sin\phi\,, \tag{4}$$

where ϕ is the rotation angle of the director of the LCs and $n = (\cos\phi, \sin\phi)$ is the director of the LC, as shown in Fig. 4.

The mesogenic temperature range of a single LC substance is usually quite limited [16]. For example, 5CB melts at 24 °C and clears at 35.3 °C. 5CB crystal is a nice material to work with because it exhibits a nematic phase at room temperature and its nematic rage is more than 10˚. We assume that the operating temperature is constant room temperature and that the absorption loss is negligible.

The FDTD method is used to solve the light propagation in the 2-D PC waveguide Mach–Zehnder interferometer with a LC in the air channel of the waveguide. The dispersion relations of guided modes in PC waveguide with nematic LC at ϕ = 0 °, 45 °, 90 ° are shown in Fig. 5. The shaded regions correspond to the projected band structures of the perfect

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crystals. The guided modes can travel freely within the narrow waveguide channel. Inasmuch as the frequency of the guided mode lies within the photonic bandgap, the mode is forbidden to escape into the crystal. Rotation angle ϕ_1 of the LC of arm 1 is fixed at $\phi_1 = 0°$, and rotation angle ϕ_2 of the LC of arm 2 is variable. The refractive-index profile at cross section AA' of Fig. 4 is shown in Fig. 6. The transmission spectrum for the structure in Fig. 4 with variable rotation angle ϕ_2 is shown in Fig. 7. The input wave is the TE-polarized continuous wave with Gaussian profile and wavelength λ = 1.42 μm launched into port 1. Such a light beam launched into the device with TE polarization is divided into two equal parts in the input Y junction. Both of these beams propagate in one of the two arms of the Mach–Zehnder interferometer, and thus they experience different optical paths. This results in the introduction of a phase difference:

$$\phi_d = \frac{2\pi}{\lambda}\left[n_e(\phi_2) - n_e(\phi_1)\right]L_{\mathrm{LC}}, \tag{5}$$

where n_e is the effective refractive index that depends on rotation angle ϕ and L_{LC} is the length of the LC waveguide.

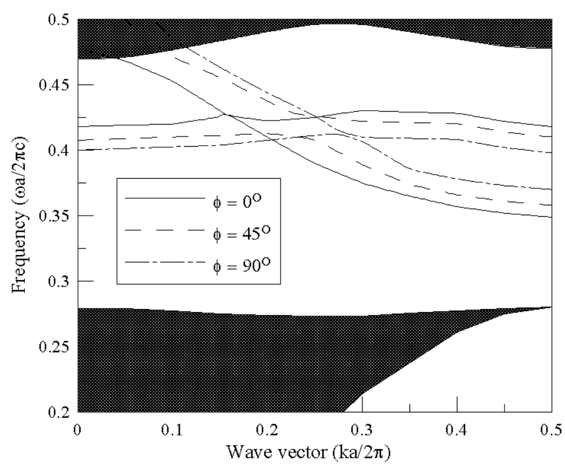

Fig. 5. Dispersion relations of guided modes in the PC waveguide with a nematic LC at ϕ = 0°, 45°, 90°. Shaded regions, projected band structures of the perfect crystals.

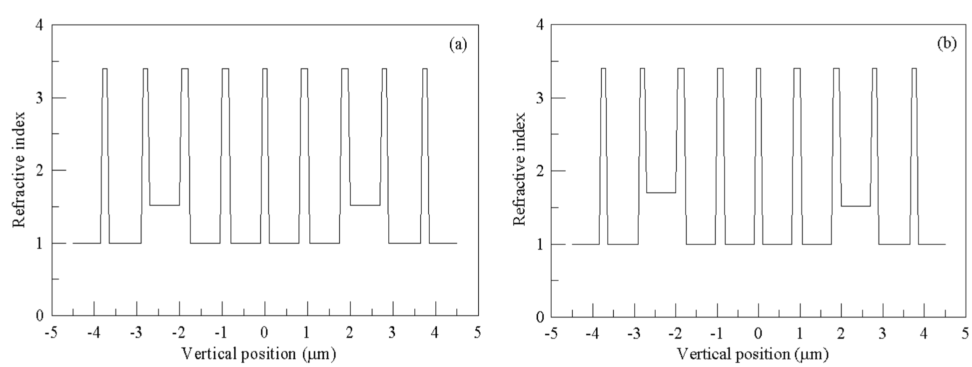

Fig. 6. The refractive index profile of cross-section *AA*' of Fig. 4 with phases (a) $\phi_1 = 0°$, $\phi_2 = 0°$ and (b) $\phi_1 = 0°$, $\phi_2 = 90°$.

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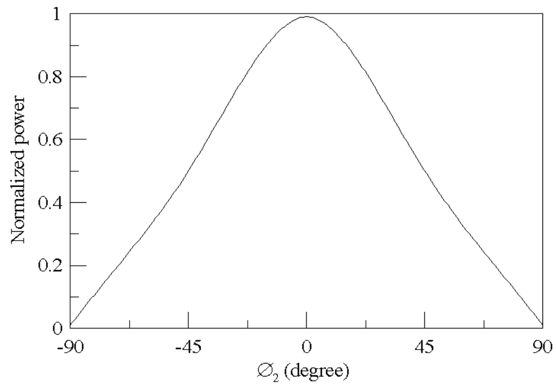


Fig. 7. Transmission spectrum for the structure in Fig. 4 with input wavelength λ = 1.42 μm and variable rotation angle ϕ_2.

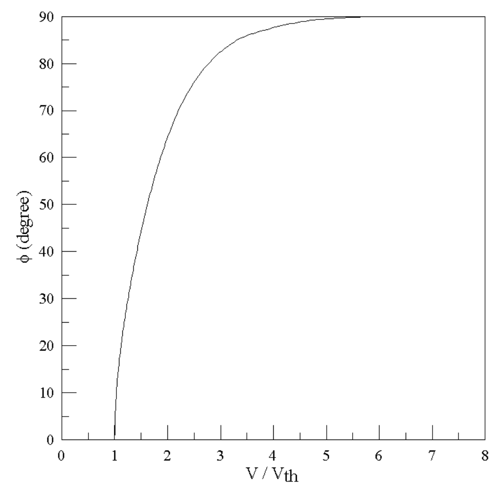
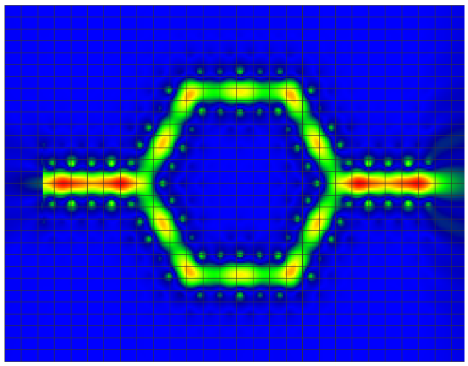
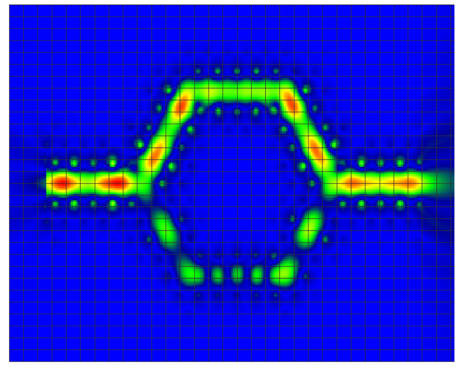


Fig. 8. Calculated rotation angle ϕ as a function of normalized voltage. V_{th} is the threshold voltage.

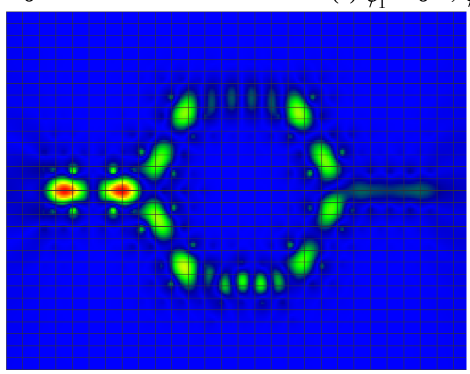
In nematic LCs the directors of the LCs depend on the direction of the electric field in 2-D planes. Indium tin oxide layers can be attached to the top and the bottom of the PC waveguide interferometer. The electric fields can be applied in the *x* and the *z* directions separately. Then we can apply the electric field that sums up the electric fields in the *x* and the *z* directions in arbitrary directions in 2-D planes by adjusting the magnitudes of the electric field in the *x* and *z* directions, respectively, making it possible to rotate the directors of the LCs. Figure 8 shows computer simulations of rotation angle ϕ as a function of normalized voltage. V_{th} is the threshold voltage that is found to be 0.699 V_{rms} at 1-kHz sinusoidal frequency. At $V < V_{th}$, the LC directors remain undisturbed, and no phase change occurs. At $V > V_{\mathrm{th}}$ and the small-voltage region, the phase difference is linear to *V* and the slope is determined by the ratio of refractive indices, elastic constants, dielectric constants, LC thicknesses, and wavelengths. Figure 9 shows the electric field patterns observed in the frequency domain of the tunable PC waveguide Mach–Zehnder interferometer at input wavelength λ = 1.42 μm and at rotation angles $\phi_2 = 0°, \pm 45°, \pm 90°$, respectively. Figure 9(a) shows that the input wave is recombined from both arms into the output guide (switch on). Figure 9(c) shows that the interferometer output is null (switch off). In general, the response time of a LC is of the order of a millisecond. However, it has been reported that the response time of LCs in nanoscale voids becomes of the order of 100 μs [17]. The orientational relaxation times calculated by the molecular dynamics formalism and the experimental data determined by nuclear magnetic resonance spectroscopy for the nematic phase of 5CB crystal at 300 K were presented in Ref. 18. Therefore our novel PC waveguide interferometer achieved by nematic LC phase modulation can be used as either an optically controlled fast switching device or an amplitude modulator in photonic integrated circuits.



(a) $\phi_1 = 0\,°$, $\phi_2 = 0\,°$



(b) $\phi_1 = 0\,°$, $\phi_2 = \pm 45\,°$



(c) $\phi_1 = 0\,°$, $\phi_2 = \pm 90\,°$

Fig. 9. Electric field patterns observed in the frequency domain of the tunable PC waveguide Mach–Zehnder interferometer with LCs at $\phi_2 = 0\,°, \pm 45\,°, \pm 90\,°$.

An integrated III–V semiconductor waveguide modulator designed to generate an optical delay of 100 μm was described in Ref. 19. It was achieved by simultaneous propagation of the TE fundamental mode in both of the arms of a highly unbalanced Mach–Zehnder interferometer with a 29-μm difference in length between the two arms. The total length of that Mach–Zehnder interferometer is 18,000 μm [19]. The total length of our PC Mach–Zehnder interferometer is 10.26 μm. The total length of our PC waveguide interferometer is less than that of a conventional ridge waveguide interferometer. The transition loss of a conventional ridge waveguide interferometer is 10–20% [19]. The transition loss of our PC waveguide interferometer is close to 1%. The transmission of our PC waveguide interferometer is better than that of a conventional ridge waveguide interferometer.

4. Conclusions

In this paper we have demonstrated numerically a versatile device based on photonic-crystal and liquid-crystal technology. The general Mach–Zehnder interferometers were fabricated from suspended membrane PC waveguides [6]. The path-length difference was fixed after

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Mach–Zehnder interferometers were fabricated from PC waveguides. A tunable PC waveguide Mach–Zehnder interferometer based on nematic LCs was proposed, and its interference properties were theoretically investigated by use of the finite-difference time-domain method. We changed the refractive indices of LCs by rotating the directors of the LCs. Thus we could control the phase of light propagation in PC waveguide interferometers. The interference mechanism is a change in the refractive indices of LC waveguides. Therefore our novel tunable 2-D PC waveguide interferometer achieved by nematic LC phase modulation can be used as an optically controlled on–off switch or as an amplitude modulator. These results may facilitate novel applications of switching devices in photonic integrated circuits.