Photonic crystals (PCs) that have periodic dielectric structures with a periodicity that is in the range of optical wavelengths, exhibit photonic band gaps (PBGs) that are analogous to the electronic band gaps in semiconductors. Earlier investigations of PCs have focused on full PBGs and the propagation of light at the photonic band gap edges. Hence, such investigations calculate the band structures, the band gap sizes and the resonant modes of PCs. PCs, depending on their band gap structures, resemble photonic insulators, semiconductors and conductors. The interesting dispersive properties of PCs near the gap edges have already led to their being applied in superprisms, supercollimators, spot-size converters and other devices that exploit their birefringent properties. 

The superprism effect, the so-called band-edge mode of PCs, depends strongly on frequency and is strongly enhanced near PBG edges. These strong dispersive effects were first investigated by Lin et al. They fabricated two-dimensional PCs with alumina-ceramic rods and explained the nonlinear frequency dependence of the phase velocity. Notably, the superprism effect is caused by the strong anisotropy and nonlinear frequency dispersion, so a full band gap is not required. Kosaka et al. later demonstrated that this angular dispersion is particularly strong if a beam is incident onto the interface such that the change in the incidence angle or wavelength of the incident beam can cause strong variations in the group velocity of the refracted beam. Recently, Oya et al. observed strong angular dispersion in silica-based one-dimensional PCs. The output beam deviates 5° with a wavelength change of ~1%. 

In this investigation, the superprism effect is demonstrated using a holographic polymer-dispersed liquid crystal (HPDLC) film. The film is fabricated by exposure to three coplanar laser beams. The photoinduced polymerization-induced phase separation makes liquid crystal molecules gather into nano-sized domains with solid polymer boundaries. Also, the photonic band structure and the anisotropic equi-frequency dispersion surface (EDS) are simulated to analyze the superprism effect. To the authors’ knowledge, this is the first investigation to demonstrate the superprism effect based on a HPDLC film.

In fabrication, the technique relies on the anisotropic diffusion and phase separation of liquid crystal in a photopolymerizable monomer when the solution is subjected to an inhomogeneous light pattern. Films made of a homogeneous mixture of monomer, liquid crystal and photoinitiator dye are exposed to the light interference pattern caused by multiple laser beams to produce hexagonal HPDLC PCs. The homogeneous mixture is composed of a photopolymerizable monomer (NOA81, Norland; n=1.56) and a nematic LC (E7, Merck; n∞=1.5216, n∞=1.7462 at 589 nm, 20°C). Also, a little photoinitiator dye, rose bengal, was added to generate free radicals during curing. The weight ratio of the monomer, LC and the photoinitiator is 27:73:0.1. The mixture is sandwiched between two glass substrates coated with transparent indium tin oxide electrodes. The thickness of the cell is 25 μm. The sample was exposed using a holographic setup shown in Fig. 1. Briefly, a TE-polarized diode pumped solid-state laser beam (λ=532 nm) was split into three coplanar beams (using 50/50 quartz beam splitters and a series of mirrors). The three beams had approximately equal power (~800 mW/cm²). The incident angles θ1, θ2 and θ3 were 60°, 60° and 0°, respectively, as shown in Fig. 1(b). The exposure time was 30 s.

FIG. 1. Experimental setup for causing interference among three coplanar beams. Two beam splitters (BS; 50/50) and three mirrors split the laser beam into three beams. The angles θ1, θ2 and θ3 are 60°, 60° and 0°, respectively.
The interference intensity of three coplanar coherent TE-polarized beams is

\[
I(\mathbf{r}) = \sum_i E_{0i}^2 + 2 \sum_{i < j} E_{0i} E_{0j} \cos \theta_{ij} \times \cos[(\mathbf{k}_i - \mathbf{k}_j) \cdot \mathbf{r}] + (\varphi_{0i} - \varphi_{0j}), \quad i, j = 1, 2, 3, \tag{1}
\]

where the spatial position is defined as \( \mathbf{r} = (x, y, z) \), where \( E_{0i} \), \( \mathbf{k}_i \), and \( \varphi_{0i} \) are the amplitude, the wave vector and the initial phase of the \( i \)th beam, respectively. \( \theta_{ij} \) is the angle between the directions of polarization of the \( i \)th and the \( j \)th beams. In the simulation process, the initial phases of the three beams are set to zero. Figure 2(a) shows the intensity distribution in the \( x-z \) cross section. The pre-polymer and LC diffuse anisotropically, so the LCs gather in the low-intensity regions while the high-intensity regions become polymer rich. Therefore, the resolved black points in Fig. 2(a) (low-intensity regions) are expected to be where the LC domains are formed. Figure 2(b) shows a unit cell. The formed HPDLC films have hexagonal lattices in the \( x-z \) plane and narrow cylinders (with LCs inside) in the \( y-z \) plane. The long narrow morphology of the LC domain aligns the liquid crystals parallel to the \( y \) direction. Figures 2(c) and 2(d) show scanning electron microscopic (SEM) images of the formed HPDLC films, viewed as an \( x-z \) plane cross section (top view) and a \( y-z \) plane cross section (side view), respectively. The lattice constant estimated from the SEM image is \( \sim 350 \) nm and the diameter of the dark voids is \( \sim 150 \) nm, so the structural parameters of the PCs are related by \( 2r/a = 0.43 \), where \( r \) and \( a \) are the radii of dark voids and lattice periods, respectively.

Numerical software BandSOLVE 2.0, which is based on the plane wave expansion method, is then applied. It describes the electromagnetic field by Bloch wave decomposition, and so is operated in \( (k, \omega) \) space to calculate the photonic band structure within the first Brillouin zone. LCs in the long narrow cylinders are assumed to align in the \( y \)-axis direction [Fig. 2(b)]; the TE-polarized beam that is incident on the HPDLC films sees the extraordinary index \( n_e \). Therefore, the difference between the refraction index of long narrow cylinders and that of the background polymer \( \Delta n \) is

\[
\sim 0.2, \text{ causing an anisotropic equi-frequency dispersion surface (EDS) to exhibit the superprism effect.}
\]

Figures 3(a) and 3(b) show the calculated 2D photonic band structure and the EDS, respectively, for the propagation of TE polarization in 2D HPDLC hexagonal lattices with the structural parameters stated above. The EDS can be obtained by selecting \( k \) points that correspond to the selected frequency in the irreducible Brillouin zone. The hexagons marked \( M, K \) and \( \Gamma \) in Fig. 3(a) are the reciprocal lattices, \( (0,0) \), \( (0,10) \) and \( (5,5\sqrt{3}) \), in the \( (k_x, k_y) \) space.

The actual EDS may deviate slightly from the simulated value. Furthermore, the probe beam is not a plane wave. Rather, it diverges slightly. When a probe beam is normally incident onto the HPDLC film, the angle of incidence is small, with respect to the \( z \) axis. Hence, the \( z \) component of the incidence wave vector is zero. Figure 3(b) graphically shows the process for determining the direction of propagation from EDS in this case. With reference to this figure, the propagation wave vector is first determined by applying the momentum conservation rule, which is the continuity condition between the incident wave vector \( k_i \) and the propagation wavevector \( k_p \) for the tangential components that are parallel to the edge of the crystal onto which the wave is incident. Then, the propagation directions (\( \mathbf{v}_g \)) are determined to be normal to the dispersion surface at the end point of the propagation wavevector \( k_p \). This process is used because the group velocity \( \mathbf{v}_g \) determines the direction of propagation

\[
\mathbf{v}_g = \nabla_\kappa \omega(\kappa), \tag{2}
\]

Equation (2) means that the group velocity determines the direction of the gradient of the dispersion surfaces at a wave vector \( \kappa \).
For the experimental setup used to obtain the dispersion spectrum, an Hg Arc lamp (300–750 nm) is used as the probe light source. The angle of incidence $\theta$ is defined as the angle between the incident light and the normal to the HPDLC films. Figure 4 shows the color dispersion of the light output from the HPDLC films when an unpolarized white light is almost normally incident onto the sample ($\theta \sim 1^\circ$). Notably, when the light is normally incident onto the sample ($\theta \sim 1^\circ$, along the $\Gamma$-$M$ direction of sample), a continuously dispersed visible light spectra is observed with deflection angles from $\sim 53^\circ$ ($\lambda \sim 450$ nm) to $\sim 90^\circ$ ($\lambda \sim 680$ nm). The deflection angle $\theta_p$ is defined as the angle between the deflected light and the direction of incidence. Notably, Fig. 4 shows that the reflected dispersion spectrum is much less intense than that of the transmitted spectrum one. This result is understandable since the HPDLC is also a reflection grating.

Further, the dispersion spectrum with a beam being incident onto the sample at an angle $\theta \sim 1^\circ$ is measured. Figure 5(a) illustrates the experimental setup. The deflection angles of the light at wavelengths ($\lambda \sim 400, 450, 500, 550, 600$ nm) from the sample are measured. The results together with the simulated one obtained using the finite difference time domain method (FDTD) with $\Delta n$ of 0.1, 0.2 are shown in Fig. 5(b), where $\Delta n$ is the difference between the refraction index of long narrow cylinders and that of the background polymer. The output beam is estimated to deviate by $1^\circ$ as the wavelength is changed by $\sim 2\%$ in the visible range. It is seen from Fig. 5(b) that the simulated result ($\Delta n=0.2$) agrees well with the experimental one. The result also indicates that the dispersion between blue and red light does not appear if $\Delta n < 0.1$. In addition, the relationship between the deflection of the light at $\lambda \sim 400$ nm from the sample and the refraction index contrast $\Delta n$ ranging from 0.1 to 1.0 of the sample is simulated. The result shows that the dispersion is proportional to the refraction index contrast $\Delta n$ as expected.

In conclusion, HPDLC based PCs are highly promising for optoelectronics, integrated optics and optical communications. Two-dimensional PCs are fabricated using multibeam interference in PDLC films. The formed HPDLC is sensitive to light in the visible range. Accordingly, the angle of deflection of the light out of the 2D HPDLC PCs depends strongly on the light frequency, the incident angle and the polarization. When a TE-polarized white light is incident onto a HPDLC film, it is dispersed to yield a continuous spectrum distributed from red to blue, with an angle $\sim 50^\circ$.

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