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Temperature effect on lasing from Penrose photonic quasicrystal

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Abstract: Temperature effect on lasing from a Penrose photonic quasicrystal made of low index contrast materials holographic polymer dispersed liquid crystals was investigated. A blue-shift of lasing peak was observed with increased temperature in the range of 25 °C~50 °C. The transmission spectra of Penrose photonic quasicrystal was studied through FDTD simulation, which showed a correlation between the lasing peak and the transmission spectrum. The tunable property could be understood by the elliptical shape of liquid crystal droplets formed in the Penrose quasicrystal.

OCIS codes: (140.3600) Lasers, tunable; (160.3710) Liquid crystals.

References and links

1. T. J. Bunning, L. V. Natarajan, V. P. Tondiglia, and R. L. Sutherland, "Holographic polymer-dispersed liquid crystals (H-PDLCs)," Annu. Rev. Mater. Sci. **30**(1), 83–115 (2000).
2. R. L. Sutherland, V. P. Tondiglia, L. V. Natarajan, S. Chandra, D. Tomlin, and T. J. Bunning, "Switchable orthorhombic F photonic crystals formed by holographic polymerization-induced phase separation of liquid crystal," Opt. Express **10**(20), 1074–1082 (2002).
3. S. P. Gorkhali, J. Qi, and G. P. Crawford, "Switchable quasi-crystal structures with five-, seven-, and ninefold symmetries," J. Opt. Soc. Am. B **23**(1), 149–158 (2006).
4. K. Sakoda, "Enhanced light amplification due to group-velocity anomaly peculiar to two- and three-dimensional photonic crystals," Opt. Express **4**(5), 167–176 (1999).
5. R. Jakubiak, V. P. Tondiglia, L. V. Natarajan, R. L. Sutherland, P. Lloyd, T. J. Bunning, and R. A. Vaia, "Dynamic lasing from all-organic two-dimensional photonic crystals," Adv. Mater. **17**(23), 2807–2811 (2005).
6. D. Luo, X. W. Sun, H. T. Dai, H. V. Demir, H. Z. Yang, and W. Ji, "Two-directional lasing from a dye-doped two-dimensional hexagonal photonic crystal made of holographic polymer-dispersed liquid crystals," Appl. Phys. Lett. **95**(15), 151115 (2009).
7. M. S. Li, A. Y. Fuh, and S. T. Wu, "Multimode lasing from the microcavity of an octagonal quasi-crystal based on holographic polymer-dispersed liquid crystals," Opt. Lett. **37**(15), 3249–3251 (2012).
8. H. J. Coles and S. M. Morris, "Liquid-crystal lasers," Nat. Photonics **4**(10), 676–685 (2010).
9. W. Cao, A. Muñoz, P. Palffy-Muhoray, and B. Taheri, "Lasing in a three-dimensional photonic crystal of the liquid crystal blue phase II," Nat. Mater. **1**(2), 111–113 (2002).
10. D. Luo, Q. G. Du, H. T. Dai, H. V. Demir, H. Z. Yang, W. Ji, and X. W. Sun, "Strongly linearly polarized low threshold lasing of all organic photonic quasicrystals," Sci Rep **2**, 627 (2012).
11. D. E. Lucchetta, L. Criante, O. Francescangeli, and F. Simoni, "Wavelength flipping in laser emission driven by a switchable holographic grating," Appl. Phys. Lett. **84**(6), 837–839 (2004).
12. D. E. Lucchetta, L. Criante, O. Francescangeli, and F. Simoni, "Compact lasers based on HPDLC gratings," Mol. Cryst. Liq. Cryst. (Phila. Pa.) **441**(1), 97–109 (2005).
13. R. Jakubiak, L. V. Natarajan, V. Tondiglia, G. S. He, P. N. Prasad, T. J. Bunning, and R. A. Vaia, "Electrically switchable lasing from pyrromethene 597 embedded holographic-polymer dispersed liquid crystals," Appl. Phys. Lett. **85**(25), 6095–6097 (2004).
14. V. K. S. Hsiao, C. Lu, G. S. He, M. Pan, A. N. Cartwright, P. N. Prasad, R. Jakubiak, R. A. Vaia, and T. J. Bunning, "High contrast switching of distributed-feedback lasing in dye-doped H-PDLC transmission grating structures," Opt. Express **13**(10), 3787–3794 (2005).

#210261 - $15.00 USD Received 15 Apr 2014; revised 9 May 2014; accepted 9 May 2014; published 13 May 2014

15. Y. J. Liu, X. W. Sun, H. I. Elim, and W. Ji, "Effect of liquid crystal concentration on the lasing properties of dye-doped holographic polymer-dispersed liquid crystal transmission gratings," Appl. Phys. Lett. **90**(1), 011109 (2007).
16. D. Luo, X. W. Sun, H. T. Dai, H. V. Demir, H. Z. Yang, and W. Ji, "Electrically tunable lasing from a dye-doped two-dimensional hexagonal photonic crystal made of holographic polymer-dispersed liquid crystals," Appl. Phys. Lett. **97**(8), 081101 (2010).
17. D. Luo, X. W. Sun, H. T. Dai, H. V. Demir, H. Z. Yang, and W. Ji, "Temperature effect on the lasing from a dye-doped two-dimensional hexagonal photonic crystal made of holographic polymer-dispersed liquid crystals," J. Appl. Phys. **108**(1), 013106 (2010).
18. T. T. Alkeskjold, J. Lægsgaard, A. Bjarklev, D. S. Hermann, A. Anawati, J. Broeng, J. Li, and S. T. Wu, "All-optical modulation in dye-doped nematic liquid crystal photonic bandgap fibers," Opt. Express **12**(24), 5857–5871 (2004).

1. Introduction

Holographic polymer dispersed liquid crystals (H-PDLCs) are polymer/liquid crystal composites, which have been used to fabricate various types of photonic crystals (PCs) [1, 2] and quasicrystals [3]. Lasing [4–7] from PCs/quasicrystal made by H-PDLCs can be generated due to the local field enhancement from periodic/quasi-periodic structure acting as an optical cavity, despite of low index contrast. As an all organic materials, H-PDLCs based tunable lasers are attractive due to its small size and tunability in a broad wavelength range, which enable them to find applications in many fields including microlaser source in all-optical integrated circuits, medical diagnostics, and holography. Comparing to the pure liquid crystal laser, e.g. chiral liquid crystal laser [8] and blue phase liquid crystal laser [9], high pumping threshold in H-PDLCs photonic crystal laser prevents it from real application. However, this problem could be partially solved by applying quasicrystal structure because of the optical oscillation enhancement. In our previous studies, we have demonstrated a lasing from H-PDLCs Penrose quasicrystal with lower threshold than that from photonic crystals [10].

Lasing from H-PDLC devices is controllable due to the fact that the optical property of liquid crystal is tunable by external stimuli such as temperature, electrical field, and light intensity. The effects of temperature and electrical field have been reported in H-PDLCs based grating [11–15] and two-dimensional (2D) PCs [5, 16, 17]. However, the study on the effects of external stimuli on H-PDLCs Penrose quasicrystal has never been reported. In this paper, we firstly demonstrated the temperature tuning effect on lasing from Penrose quasicrystal made of H-PDLCs. A blue-shift of lasing wavelength was observed with increased temperatures in the range from 25 °C to 50 °C. Both experimental studies on liquid crystal droplets shape and finite difference time domain (FDTD) simulation were carried out to investigate the underlying mechanism. We found that the shift of lasing peak wavelength was consistent with the movement of transmission spectrum as we changed environmental temperatures, and the lasing was insensitive to external electric field.

2. Experiments

The liquid crystal (LC)/prepolymer in this study is a mixture comprising of trimethylolpropane triacrylate (TMPTA, 63.76 wt%), N-vinylpyrrollidone (NVP, 7.05 wt%), Rose Bengal (RB, 0.49 wt%), N-phenylglycine (NP, 0.98 wt%), octanoic acid (OA, 9.30 wt%), 4-dicyanomethylene-2-methyl-6-p-dimethylaminostyryl-4H-pyran (DCM, 1.18 wt%), all from Sigma-Aldrich, and liquid crystal E7 (17.24 wt%, where n_o = 1.5216 and n_e = 1.7462), from Merck. The mixture was firstly filled in a cell with gap of 4 μm, which was formed by two pieces of indium tin oxide (ITO) coated glasses, and then exposed under laser beam passed through a specially designed prism, where a five-beam interference pattern was produced to form the 2D Penrose photonic quasicrystal. The prism and generated five wave vectors are shown in Fig. 1(a). The process can be found in elsewhere [10].

In general, during the photopolymerization process, LCs and polymer are redistributed according to light interference intensity pattern, where high intensity regions mainly consist of polymer matrix and low intensity regions mainly consist of LC droplets. The light inference pattern is generated according to:

$$I(\boldsymbol{r}) = \Re\left(\sum_{i,j=1}^{5} E_i \cdot E_j \exp[i(\boldsymbol{k}_i - \boldsymbol{k}_j)\cdot \boldsymbol{r}]\right), \tag{1}$$

where E is the amplitude of the electric field, $\boldsymbol{r} = (x, y, z)$ is the position vector, and $\Re[\ldots]$ denotes the real part of the argument.

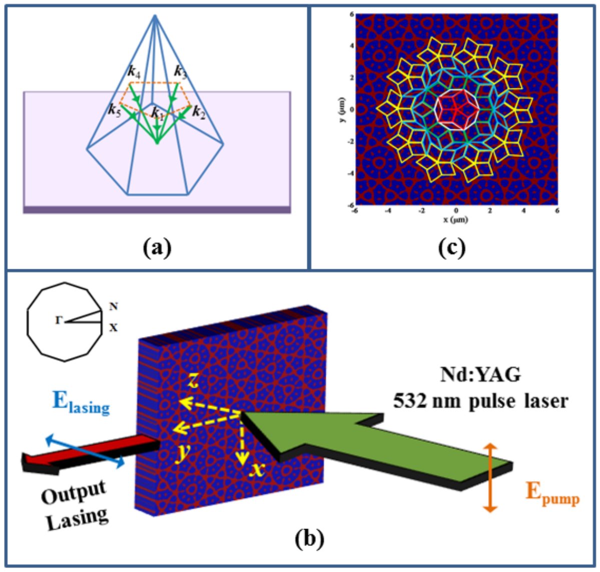

Fig. 1. (a) Prism and wave vectors of five beams. (b) Schematic optical setup of the lasing experiment. Lasing is generated along y direction (ΓX). Inset figure, Pseudo-Jones zone in reciprocal space with symmetry point. (c) Quasicrystal is consisted of two tiles, which are 36° and 72° rhombus tiles.

To generate the laser, a Q-switched frequency-doubled Nd:yttrium-aluminum-garnet (Nd:YAG) pulsed laser, operating at 532 nm with a pulse duration of 7 ns and a repetition rate of 10 Hz, was used to pump the dye-doped 2D H-PDLC quasicrystal sample, where a cylinder lens was used to focus the laser beam in a shape of narrow line along y direction (ΓX direction, Fig. 1(b)). Inset figure is Pseudo-Jones zone in reciprocal space with symmetry point. The output lasing spectrum was captured by a fiber coupled spectrometer with a resolution of 0.6 nm. The optical setup is shown in Fig. 1(b), which shows a surface image of Penrose quasicrystal obtained by field emission scanning electron microscope (FESEM), where the LC droplets had been removed before the sample was checked under the FESEM. Generally, the intensity distribution calculated from Eq. (1) is continuous. However, because of phase separation, LC droplets and polymer will primarily reside in low and high intensity region respectively, i.e. we can use a binary refractive index approximation. Therefore, we properly select a threshold value to generate a binary intensity pattern, by comparing the actual image (not shown here) and simulation. The binary intensity distribution of Penrose quasicrystal is shown in Fig. 1(c), where the blue color represents the polymer region and the red color represents the LC region, respectively. The generated quasicrystal can be considered to be consisted by tiling model (Fig. 1(c)), where two types of tiles with equal edge lengths, 36° and 72° rhombus tiles, could fully fill the whole present Penrose quasicrystal.

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3. Results and discussion

Lasing generation could be generated even in low index contrast materials H-PDLCs Penrose quasicrystal because of the enhanced localized field [10]. Due to the response of liquid crystals to external stimuli such as temperature and electric field, liquid crystals based photonic and optics devices exhibit excellent tunable properties. Here, we have examined the temperature effect on lasing from H-PDLCs Penrose quasicrystal along specific direction ΓX, and only lasing with TM polarization (electric field perpendicular to the *x-y* plane) was observed. A hot stage (HCS402, Instec) was used for environment temperature control of the 2D H-PDLCs Penrose quasicrystal sample. Spectra of lasing with TM polarization were shown in Fig. 2, which were measured at different temperatures in the range from 25 °C to 50 °C. The pumping direction was set to along the ΓX direction and pumping energy level was fixed at 180 µJ/pulse, where the threshold is 14 µJ/pulse [10]. A blue-shift of lasing peak wavelength was clearly observed when temperature increased from 25 °C to 50 °C. The lasing peak was 636.7 nm at 25 °C and gradually shifted to 630.9 nm when the temperature was increased to 50 °C. The procedure was reversible and a red-shift could be achieved if decreasing the temperature from 50 °C to 25 °C. Generally, the varying temperatures lead to a change of LC refractive index. When temperature increases (less than the clearing temperature), the extraordinary index (n_e) and ordinary index (n_o) of nematic LC will decrease and increase, respectively.

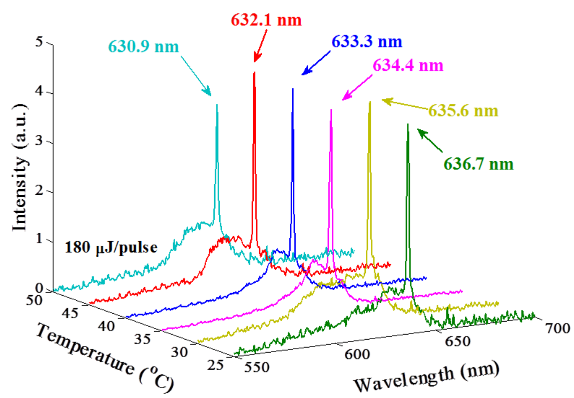

Fig. 2. Lasing spectrum measured with different temperature from 25 °C to 50 °C along ΓX direction, at pump energy of 180 µJ/pulse.

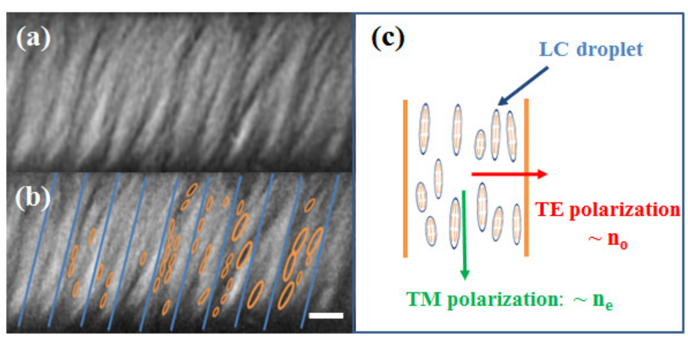

Fig. 3. (a) (b) Cross section of our sample checked under field emission scanning electron microscopy (FESEM). The holes left by LC droplets are marked by ellipses, while quasi-period structures formed by polymer are marked by solid lines (Scalar bar: 1 µm). (c) Schematic of the LC droplets shape and refractive indices experienced by TE and TM polarizations.

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To understand the underlying mechanism of temperature dependent property of lasing, we studied the LC droplets shape formed in H-PDLCs Penrose quasicrystal. The cross section of our sample was investigated under the FESEM, shown in Figs. 3(a) and 3(b). The holes represent the place occupied by LC droplets, marked by circles, and the quasi-period structure was formed by polymer matrix, marked by solid lines. The morphology of examined cross section indicated that the LC droplets formed the elliptical shape within the H-PDLC Penrose quasicrystal, which determined the polarization property of generated lasing. Due to the orientation of LC droplets (shown in Fig. 3(c)), the TE (electric field parallel to the *x-y* plane) and TM polarizations will experience different index contrast. For TE polarization, it will experience a small index contrast of n_p(1.5220)/n_o(1.5216), and the index contrast is too small to provide enough oscillation feedback to generate a laser. For TM polarization, it will experience a large index contrast of n_e (1.7462)/n_p (1.5220), and the index contrast is big enough to provide sufficient feedback to support a laser. As a result, lasing from our H-PDLC Penrose quasicrystal sample became linearly polarized (TM polarization). While the temperature increases, the TM polarization will experience a reduced index contrast, leading to a different quasicrystal structure with different transmittance spectra, and finally resulting in a shift of lasing spectrum.

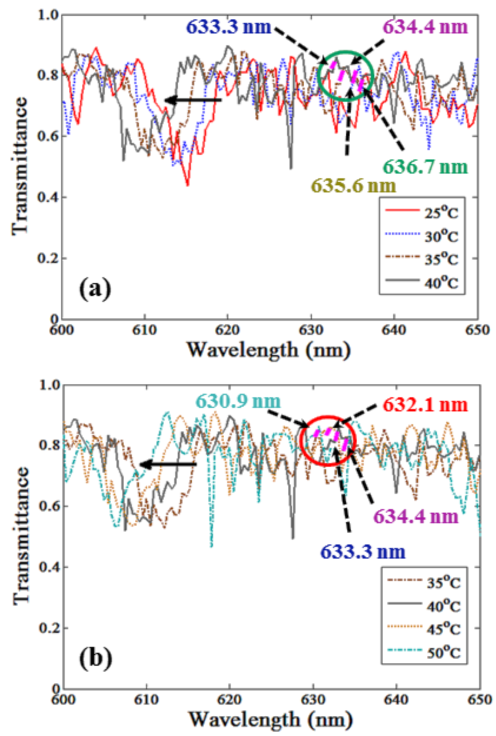

Fig. 4. Transmittance spectrum calculated along ΓX direction by FDTD method. (a) 25 °C~40 °C and (b) 35 °C~50 °C. Curves corresponding to 35 °C and 40 °C were repeated shown here for clearer comparison purpose.

For future investigation, we calculated the relationship of n_e with different temperatures in the range of 25 °C~50 °C, at wavelength of 633 nm. The result is shown in Table 1, based on the data reported in the literature [18]. The values of n_e under different temperatures were used as the input parameters of a simulated binary quasicrystal intensity distribution (Fig. 1(c)) for transmittance spectra calculation.

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Table 1. The calculated relationship of ne (E7) with temperature at 633 nm

	25 °C	30 °C	35 °C	40 °C	45 °C	50 °C
n_e	1.7352	1.7278	1.7160	1.7030	1.6909	1.6773

The calculated transmittance spectra for TM polarization in the temperature ranges of 25 °C to 40 °C and 35 °C to 50 °C are shown in Figs. 4(a) and 4(b), respectively. The calculation was carried out by a commercial finite-difference time-domain (FDTD) software package, Lumerical. The transmittance spectra at temperature of 35 °C and 40 °C are shown both in Figs. 4(a) and 4(b), for a better and clearer comparison purpose. An apparently blue-shift of transmittance spectrum was achieved when the temperature increased. The lasing generation position also experienced a blue-shift accordingly and adhered to a relatively "fixed position" on the transmittance spectra. It means that the lasing peak shifted according to the transmittance spectrum under changed temperatures. From the Fig. 4, we can see that the experimental results are well fitted to the simulated results. The blue-shift of lasing wavelength with increased temperature can be fully understood by the shift of transmittance spectrum of quasicrystal, and the movement of spectrum is due to the refractive index change of liquid crystal under changed temperatures.

Besides the temperature, the effect of external voltage on the Penrose quasicrystal was also investigated. However, because of the elliptical shape of LC droplet aligned to *z* axis, we expected no significant tuning effect of electric field on our sample. The experimental results confirmed our expectation. Both the lasing wavelength and intensity didn't move at all with increased electric field up to 30 V/μm, beyond which the sample cell was broken down. Here, all measurements were carried at room temperature of 25 °C.

4. Conclusion

In summary, we reported the temperature effect on lasing from a 2D H-PDLC Penrose quasicrystal. Laser peak showed a blue-shift with increased temperatures. The shift of lasing wavelength followed the shift of the transmittance spectrum, which was due to the changed refractive index of nematic liquid crystal under changed temperatures. Electric field showed no significant effect on the laser peak because of the elliptical shape of LC droplets. The sensitivity to temperature promises the 2D H-PDLC Penrose quasicrystal laser many potential applications in photonic devices .

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