Journal of Materials Chemistry C

ROYAL SOCIETY OF CHEMISTRY

View Article Online

PAPER



Cite this: J. Mater. Chem. C, 2017, 5, 10828

Received 28th August 2017, Accepted 3rd October 2017

DOI: 10.1039/c7tc03915h

rsc.li/materials-c

Introduction

Cholesteric liquid crystals (CLCs), as one-dimensional (1D) photonic crystals with a self-assembled periodic helical structure, have attracted considerable research interest due to their various applications during the past few decades, such as displays,^{1,2} lasers,^{3,4} smart windows,⁵ mirrors⁶ and biosensors.⁷ The circularly polarized light with the same handedness as the CLC will be reflected, due to the Bragg reflection.^{8–12} Therefore, the reflectance of a single CLC cell is limited to 50% for an unpolarized incident light beam.¹³

Flexible cholesteric films with super-reflectivity and high stability based on a multi-layer helical structure[†]

Y. Li,^a Y. J. Liu, ^(b) ^a H. T. Dai,^b X. H. Zhang,^a D. Luo ^(b) *^a and X. W. Sun^a

The growing demand for flexible low-power reflective photonics and display devices has fueled research into high quality flexible materials with super-reflectivity and high stability to environmental influences including broad working temperature ranges and excellent mechanical stress insensitivity. Although tremendous effort has been dedicated towards developing cholesteric film materials with superreflectivity or high stability, challenges still remain in achieving both due to the existence of liquid crystals that are susceptible and sensitive to external stimuli, such as temperature or mechanical stress. Herein, we fabricate a novel flexible film having super-reflectivity (>80%), a broad working temperature range (-70 °C to 70 °C) and excellent mechanical stress insensitivity (up to 7.88 \times 10⁵ Pa) via a "washout-refill-assemble" approach by refilling a polymer (optical adhesive) into a cholesteric film assembled using two cholesteric templates with opposite handedness based on a liquid crystal/reactive mesogen mixture, where no liquid crystals exist in the final fabricated multi-layer film. The all-polymer structure of the film selectively reflects color due to the helical structure of the cholesteric liquid crystals applied in the fabrication procedure of the cholesteric templates with both super-reflectivity and high stability to temperature and mechanical stress. Flexible displays with vivid colors based on proposed films have been demonstrated using the direct printing method on glass and flexible substrates. These materials show great potential for applications such as low-power flexible reflective displays, and other photonic flexible devices including lasers, smart windows, color pixels in digital photographs, and colored cladding of a variety of objects.

> In many optical and photonic applications, it is highly desirable to have high reflectivity (>50%) to improve device performance. Earlier efforts in achieving super-reflective CLCs include stacking two individual CLC cells with opposite handedness,¹⁴ or inserting a half-wave plate sandwiched between separated CLCs with the same handedness,^{15,16} both of which suffer from disadvantages of increased weight, increased insertion loss due to multiple interfaces, and complicated electrical design. Recently, a single film with the ability to reflect both left- and right-handed (LH and RH) circularly polarized light has been developed for overcoming the aforementioned drawbacks.^{17,18} Mitov proposed CLCs polymerized by a monomer doped with a thermal inverter, where the mixture initially formed a RH helical structure at high temperature (120 °C) and then returned to a LH when cooled down (60 °C).¹⁸ Guo et al. reported a helical polymer structure using a multi-step "wash-out/refill" procedure, which was achieved by refilling a CLC with a RH helical structure into the polymer network with a LH helical structure.¹⁹⁻²² McConney et al. realized photoinduced and thermally super-reflective CLCs with spatially segregated reflection through the thickness of

^a Department of Electrical & Electronic Engineering, Southern University of Science and Technology, Xueyuan Road 1088, Nanshan District, Shenzhen, Guangdong, 518055, China. E-mail: luo.d@sustc.edu.cn

^b Tianjin Key Laboratory of Low Dimensional Materials Physics and Preparing Technology, School of Science, Tianjin University, Weijin Road 92, Nankai, Tianjin, 300072, China

[†] Electronic supplementary information (ESI) available: Effect of external disturbance on film properties and the chemical structures of reactive mesogen monomers. See DOI: 10.1039/c7tc03915h

Paper

the cell by constructing two separated homogeneous regions (polymer and CLC) with different handedness.^{23,24} One advantage of super-reflective films, which are usually fabricated based on a polymer network and CLCs, is their tunability to external stimuli such as temperature, mechanical stress, optical radiation, electric fields, or magnetic fields.^{25–28} However, the susceptibility of super-reflective films composed of CLCs to stimuli such as temperature or mechanical stress turns out to be a drawback in applications including static colorful advertisements and laser safety glass, where the premier requirement is stability instead of tunability.

In this paper, we demonstrate flexible cholesteric films with super-reflectivity and high stability based on a multi-laver helical structure. The films are formed via a "wash-out" and "refill" process to refill the optical adhesive NOA81 into two cholesteric films with opposite handedness. Super-reflectivities over 80% for all red, green, and blue colors have been achieved. In addition, the effects of temperature and mechanical stress on the films have been investigated. Compared with non-solid films that are refilled with nematic liquid crystals, the fabricated films can maintain their super-reflectivity over a broad temperature range from -70 °C to 70 °C, and under a high stress up to 7.88 \times 10⁵ Pa, showing excellent stability. Based on the proposed films, static flexible displays with vivid colors are demonstrated by directly printing liquid crystal/monomer mixtures as "inks" on glass/flexible substrates. These flexible films with super-reflectivity and high stability over a broad working temperature range and excellent mechanical stress insensitivity show great potential for applications such as reflective displays, lasers, smart windows, color pixels in digital photographs, and colored cladding of a variety of objects where the premier requirement is stability instead of tunability.

Results and discussion

Fig. 1 depicts the fabrication process of the proposed superreflectivity film based on templated cholesteric liquid crystals. (i) Firstly, LH and RH chiral templates were formed by doping LH and RH chiral dopants into a LC/RM mixture, respectively. (ii) Then, the films were exposed to UV light at an intensity of 15 mW cm⁻² for 15 min. (iii) After that, the films were separated from the LC cell, immersed in toluene for 2 minutes to soak out CLCs/unpolymerized monomers, and refilled with adhesive NOA 81. (iv) Finally, a roll-to-roll laminating process was used to assemble the two films with opposite handedness together to achieve a super-reflectivity flexible film by (v) UV exposure. Fig. 2 show scanning electron microscopy (SEM) images of the composite multi-layer cholesteric films. Fig. 2(a) shows the cross-sectional image of the multi-layer film (layers 1 to 3, with thicknesses of 25 µm, 30 µm, and 25 µm, respectively) that consists of two stacked individual films with opposite handedness of the cholesteric film and a lamination layer of isotropic material NOA 81. It can be seen that, through polymerization of NOA 81, the LH and RH cholesteric films were firmly combined together and became a super-reflectivity film.



Fig. 1 Fabrication process of a cholesteric liquid crystal film. (i) LC/RM mixture was doped with a LH and RH chiral dopant, respectively; (ii) the mixture was photo-polymerized under UV exposure; (iii) the sample was immersed in toluene to soak out CLCs and unpolymerized monomers, and then refilled with NOA81; (iv) a roll-to-roll laminating process was used to assemble films with opposite handedness; and (v) UV exposure for NOA81 polymerization.

The thicknesses of layers 1 and 3 are both fixed at 25 μ m which consist of more than 50 periods for each color and provide enough reflection. The thickness of layer 2 is not optimized here. And a reduction of scattering and increase of reflection are expected if the thickness of layer 2 can be reduced. Fig. 2(b–d) show the SEM images of multi-layer cholesteric films designed for red, green, and blue, respectively.

For samples C1, C2 and C3 (representing composite samples of R1 & L1, R2 & L2 and R3 & L3, respectively), the measured pitches (p) are 412 nm (p/2 = 206 nm), 354 nm (p/2 = 177 nm), and 290 nm (p/2 = 145 nm), respectively, corresponding to the reflected red, green, and blue colors. For the fabricated cholesteric films, the central wavelength of the reflection band can be calculated according to $\overline{\lambda} = n \times p$, where *n* is the average refractive index, and *p* is the pitch length. Herein, the average refractive index of the film is estimated to be around 1.56. The theoretically predicted central wavelengths are located at 643 nm, 552 nm, and 452 nm, which are highly consistent with the measured results of 645 nm, 554 nm and 453 nm. The insets of Fig. 2(b-d) show optical images of the multi-layer cholesteric films observed under a polarizing optical microscope (POM, Nikon Ti) with the reflective mode for red, green, and blue colors. It can be seen that the planar state textures



Fig. 2 SEM images of the composite multi-layer cholesteric films. (a) Cross sectional SEM image of a multi-layer film (layers 1 to 3). SEM image of multi-layer cholesteric films designed for (b) red, (c) green, and (d) blue colors, respectively. The insets show the corresponding optical images of the films observed under a polarizing optical microscope.

that are typical of CLCs still exist in the all-solid-state film, indicating a helical structure of the cholesteric film observed.

Fig. 3 shows the optical setup (Fig. 3(a)) and reflectance spectra of multi-layer cholesteric films that were refilled with the adhesive NOA 81 for reflective red, green and blue colors (Fig. 3(b-d)), respectively. All reflectance spectra were measured using unpolarized light. In order to obtain multi-layer films with super-reflectivity for different colors, the concentrations of the chiral dopants in cholesteric films with LH and RH were



Fig. 3 Reflectance measurement system and measured spectra of films. (a) Optical setup for the reflectance measurement that consists of a white-light source, a type Y fiber, an optical spectrometer and a sample stage. Reflectance spectra of the multi-layer cholesteric films refilled with adhesive NOA 81 corresponding to reflective (b) red, (c) green and (d) blue colors, respectively. The insets show photos of the cholesteric films taken under a fluorescent lamp, corresponding to the red, green and blue colors, respectively.

carefully adjusted to ensure that the central wavelengths of the reflectance spectra of the two films with opposite handedness were completely superposed. The blue and red curves represent the reflectance spectra of the LH and RH single cholesteric films, respectively. At the central wavelength, the maximal reflectances of R1-R3 (L1-L3) were 37% (38%), 42% (44%) and 34% (43%), respectively. After laminating the two films with the adhesive, the reflectance spectra of the multi-laver cholesteric films were obtained, which are indicated by the black curves. It can be seen that the reflectance spectra of the multi-layer cholesteric films refilled with NOA 81 (C1, C2 and C3) were centered at 645 nm, 554 nm and 453 nm, with maximal reflectances of 81%, 82% and 83%, respectively. Therefore, the fabricated multi-layer cholesteric films (C1, C2 and C3) have super-reflectivities that are greater than 80% for all red, green, and blue colors. The insets of Fig. 3(b-d) show photos of the cholesteric films taken under a fluorescent lamp, indicating full-color, super-reflectivity, and flexible films fabricated using our method. Compared with previously reported super-reflectivity films composed of at least one layer of CLCs,^{14,19–22} the proposed all-solid-state multi-layer cholesteric film with super-reflectivity possesses intrinsic advantageous features such as being free of substrates, compact, and flexible.

The super-high reflectivity makes our cholesteric films promising for many potential applications. However, many applications require the films to be stable or insensitive to the external environment. We therefore further investigate the influence of temperature and stress on the stability of the fabricated super-reflective films. The temperature effect on the films was studied using a hot stage (INSTEC, MK2000). Fig. 4(a) shows the reflectance spectra of the sample (C2) versus temperature of the designed multi-layer film (NOA 81 refilled). The central wavelength of reflectance spectra remained almost unchanged with a negligible red-shift of 5 nm (from 551 nm to 556 nm) within the -70 °C to 70 °C temperature range. This negligible red-shift could be attributed to the slight pitch increase induced by thermal expansion.²⁶ The temperature effect on the central wavelength of reflectance spectra for the green color is also summarized in Fig. 4(b). It can be seen that only a very tiny red-shift is observed and no color-change and reflectivity reduction, indicating a very weak influence of temperature on the multi-layer super-reflective films refilled with NOA 81. The reflectance spectra of the samples (C1 and C3) with temperature changes are also shown in Fig. S1(a-c) (see the ESI[†]). In contrast, the reflectance curves of the films refilled with E7 nematic liquid crystals (sample C4 represents a composite sample of R4 & L4) at different temperatures are plotted in Fig. 4(c and d). The reflectance, central wavelength, and bandgap width of the reflectance spectrum vary significantly with the change in temperature. It can be explained by combination effects including thermally induced expansion of the polymer network (red-shift) and reduction in the average refractive index (blue-shift).29

It is worth noting that when the temperature reaches 70 $^{\circ}$ C, the liquid crystal is in the isotropic phase, with a reflectivity of 80%, and the narrowest band gap width of 49 nm. According to



Fig. 4 Temperature and stress effects on films. (a) Reflectance spectrum and (b) central wavelength *versus* temperature of a green multi-layer film refilled with NOA 81 (C2). (c) Reflectance spectra of the green film refilled with E7 nematic liquid crystals (C4) at different temperatures. (d) Temperature effect on the central wavelength and bandgap width of the film refilled with E7 (C4). The inset figures of (a) and (c) show photographs of samples C1 and C4 observed under the POM at 70 °C (top) and -70 °C (bottom), respectively. (e) Reflectance spectrum and (f) central wavelength *versus* stress of the film refilled with E7 (C4) at different stresses. (h) Stress effect on the central wavelength and bandgap width of the film refilled with E7 (C4) at different stresses. (h) Stress effect on the central wavelength and bandgap width of the film refilled with E7 (C4). The inset figures of (e) and (g) show photographs of samples C1 and C4 observed under the POM at 0 Pa (top) and 7.84 × 105 Pa (bottom), respectively.

the scattering formula: $I = I_0 \times e^{-SL}$, where *I* and I_0 are the output and input light intensity, respectively, *S* is the scattering coefficient and *L* is the thickness of medium. Therefore, refilling with isotropic materials instead of LCs can effectively enhance the reflectivity of the film, as for isotropic materials, S = 0, and for anisotropic materials such as LCs, S > 0. In our experiment, the scattering (reflectivity) of the film refilled with isotropic materials (NOA81, reflectivity of 82%) is smaller (larger) than that of the film refilled with LC (E7, reflectivity of 69%) at room temperature. As the temperature continues to decrease, the reflectivity of the device decreases. When the temperature reaches the glass transition temperature ($-40 \ ^{\circ}C$) of the liquid crystal, the reflectivity of the device is basically

stable at the lowest point of ~44%. In addition, with the increase in temperature (from -70 °C to 70 °C), the central wavelength of the sample first exhibits a red shift of 11 nm and then a blue shift of 25 nm, while the bandgap width becomes narrow (from 109 nm to 49 nm). The insets of Fig. 4(a and c) show photographs of samples C1 and C4 observed under the POM at 70 °C (top) and -70 °C (bottom), respectively, where the color of sample C1 is essentially stable and the central wavelength of sample C4 changes from 512 nm to 559 nm.

Fig. 4(e) shows the reflectance spectrum versus external stress for the film refilled with NOA81. In contrast to temperature, the observed slight blue-shift of the reflectance curve is due to the reduction of the chiral pitch, which is further caused by the shrinkage of the polymer network induced by the external stress. We can see that the 4 nm blue-shift was achieved for the green color, when the applied stress was increased from 0 to 7.84 \times 10⁵ Pa, as shown in Fig. 4(f). However, the color change and polymer structure deformation under the stress for the solid multi-layer film was guite small compared to that of the film refilled with E7, as shown in Fig. 4(g). It can be seen that a significant 47 nm blue-shift (from 559 nm to 512 nm) of the central wavelength was observed with the same external stress applied, indicating a stress sensor based on the reflective color (the changes in the reflectance spectra of samples C1 and C3 with temperature are shown in Fig. S1(a-c) (see the ESI[†])). In Fig. 4(h), there was a significant increase in reflectance of the sample (11%, from 69% to 80%) with the increase of stress (from 0 to 7.84 \times 10⁵ Pa). The insets of Fig. 4(e and g) show photographs of samples C1 and C4 observed under the POM at 0 Pa (top) and 7.84 \times 10⁵ Pa (bottom), respectively, where the color of sample C1 remains constant, and the color of sample C4 changes from green to blue. According to the scattering formula: $I = I_0 \times e^{-SL}$, the thickness (L) of the NLC (E7) layer between the RH and LH films decreases with increasing stress, leading to reduced scattering within the sample and hence increase of the reflectivity (the fabrication process of the superfilm with refilled E7 is the same as that of sample C2). NOA 81 can withstand temperature change from -150 °C to 125 °C. The tensile limit, elastic modulus, tensile strength, and cured Shore hardness of NOA 81 are 25%, 200 000 psi, 4000 psi, and 90, respectively. We can see that the proposed multi-layer films refilled with the isotropic material, *i.e.*, the adhesive NOA81, demonstrate excellent super-reflectivity and super-resistance to external stimuli such as temperature and mechanical stress, making them promising for static colored advertisements.

Here, an application of the proposed super-reflective color films, static displays with vivid colors on glass/flexible substrates, is proposed and demonstrated. In Fig. 5(a and b), it can be seen that the films patterned with our university logo reflect vivid colors under the illumination of white light on non-bendable glass and flexible polyethylene terephthalate (PET) substrates, respectively, indicating their high potential for applications including advertisements, displays, and wearable devices with low energy consumption. Fig. 5(c) depicts the fabrication process of the colorful logo of our university using screen printing



Fig. 5 Schematic representation of a colorful logo fabricated with superreflective films. The university logo was printed on (a) glass and (b) flexible PET substrates, respectively. (c) Schematic representation of colorful logo fabrication based on super-reflective films. The screen printing technology and polymerization were combined in the procedure. (i) A film with RH was formed using silk screen printing technology, where different colors were printed sequentially. (ii) The sample was exposed to UV light. (iii) The sample was then flushed with ethanol and dried to form a polymer scaffold. (iv) The film with LH can be fabricated *via* a similar procedure to steps i–iii. (v) The sample was exposed to UV light. (vii) The sample was refilled with ethanol and dried to form a polymer scaffold. (vii) The sample was refilled with adhesive NOA 81 and cured by UV light.

technology. The CLC/RM mixtures, corresponding to red, green, and blue colors (R1–R3, L1–L3), were printed on glass or flexible substrates as "inks" and polymerized under UV light, separately. The colorful logo with super-reflectivity was produced by combining two films with opposite handedness. Firstly, a film with RH was formed using silk screen printing technology, where different colors were printed sequentially (step i). Then, the sample was exposed to UV light at an intensity of 2 W cm⁻² for 15 min (step ii). The sample was then flushed with ethanol for 10 seconds to soak out CLCs/unpolymerized monomers and dried to form a polymer scaffold (step iii). The film with LH can be fabricated *via* a similar procedure to steps i–iii, as shown in steps iv, v and vi. Finally, the sample was refilled with adhesive NOA 81 and cured by UV light (step vii).

Table 1 The sample composition

Sample	NLC (E7) (wt%)	R5011	S5011	RM (wt%)	Darocur 1173 (wt%)	Refill material
R1	72.2	1.7	_	25	1.1	NOA 81
R2	71.7	2.2	_	25	1.1	NOA 81
R3	71.3	2.6	_	25	1.1	NOA 81
R4	70.9	3	—	25	1.1	E7
L1	72.3	_	1.6	25	1.1	NOA 81
L2	71.73	_	2.17	25	1.1	NOA 81
L3	71.55	_	2.35	25	1.1	NOA 81
L4	71.05	_	2.85	25	1.1	E7

Conclusions

In summary, super-reflectivity and high stability flexible films by refilling the optical adhesive NOA81 into two cholesteric films with opposite handedness have been fabricated through a "wash-out" and "refill" process. Super-reflectivities over 80% for all red, green, and blue colors have been successfully achieved. Compared to non-solid films that are refilled with nematic liquid crystals, the fabricated films can maintain their super-reflectivity over broad temperature (-70 to 70 °C) and stress (up to 7.88×10^5 Pa) ranges, indicating excellent stability. One application of the proposed films, colorful flexible static displays with vivid colors on glass/flexible substrates, has also been demonstrated. These flexible films are characterized by super-reflectivity and high stability with a broad working temperature range and excellent mechanical stress insensitivity and show great potential for applications such as flexible reflective displays, lasers, smart windows, and colored cladding of a variety of objects.

Experimental

Materials

In our experiment, the liquid crystal (LC)/prepolymer mixture consisted of nematic liquid crystals (NLCs, E7, $n_e = 1.74$, and $n_{\rm o}$ = 15.2, from HCCH), a chiral dopant (R5011, from HCCH), reactive mesogens (RMs), and a photo-initiator (Darocur 1173, Sigma-Aldrich). The RM material was obtained by mixing RM257, RM82, RM006, RM021, and RM010 at a weight ratio of 30:15:20:20:15 (all from Shijiazhuang Sdyano Fine Chemical Co., Ltd, $n_{ave} = 1.58$).²⁹ The chemical structures of reactive mesogen monomers are shown in Fig. S2 (see the ESI[†]). Table 1 lists the different compositions of the samples refilled with NOA 81 (from Norland, n = 1.56) and E7, where R1-R4 and L1-L4 represent samples with LH and RH, respectively. The mixture was sandwiched in a cell, which was assembled with two pieces of indium tin oxide (ITO) coated glass by antiparallel rubbing using polyimide (PI). The thickness of the LC cells was 30 µm.

Reflectance measurements

A reflectance measurement optical setup consisting of a whitelight source (Ocean Optics, HL-2000, non-polarized light), a type-Y fiber, and a fiber optic spectrometer (all from Ocean Optics) was used to collect the reflectance spectra of the cholesteric film, as shown in Fig. 3(a). The broadband white light from the light source was guided by the type-Y fiber to the surface of the sample (yellow arrow), and the reflected light was collected by the fiber and measured using the spectrometer (red arrow).

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

This work was supported by the Natural National Science Foundation of China (NSFC) (61405088), the Shenzhen Science and Technology Innovation Council (JCYJ20160226192528793 and KQTD2015071710313656), the National Key Research and Development Program of China administrated by the Ministry of Science and Technology of China (2016YFB0401702), and the Foshan Innovation Project (2014IT100072).

References

- 1 Y. C. Hsiao, E. R. Yeh and W. Lee, *Mol. Cryst. Liq. Cryst.*, 2017, 644, 12.
- 2 W. Hu, H. Zhao, L. Song, Z. Yang, H. Cao, Z. Cheng, Q. Liu and H. Yang, *Adv. Mater.*, 2010, **22**, 468.
- 3 Z. V. Wardosanidze, A. Chanishvili, G. Petriashvili and G. Chilaya, *Opt. Lett.*, 2014, **39**, 1008.
- 4 M. Uchimura, Y. Watanabe, F. Araoka, J. Watanabe, H. Takezoe and G. Konishi, *Adv. Mater.*, 2010, **22**, 4473.
- 5 H. Lu, W. Xu, Z. Song, S. Zhang, L. Qiu, X. Wang, G. Zhang,
 J. Hu and G. Lv, *Opt. Lett.*, 2014, 39, 6795.
- 6 G. Petriashvili, K. Japaridze, L. Devadze, C. Zurabishvili, N. Sepashvili, N. Ponjavidze, M. P. De Santo, M. A. Matranga, R. Hamdi, F. Ciuchi and R. Barberi, *Opt. Express*, 2013, **21**, 20821.
- 7 H. G. Lee, S. Munir and S. Y. Park, ACS Appl. Mater. Interfaces, 2016, 8, 26407.
- 8 V. G. Arkhipkin, V. A. Gunyakov, S. A. Myslivets, V. P. Gerasimov, V. Y. Zyryanov, S. Y. Vetrov and V. F. Shabanov, *J. Exp. Theor. Phys.*, 2008, **106**, 388.

- 9 V. G. Arkhipkin, V. A. Gunyakov, S. A. Myslivets, V. Y. Zyryanov and V. F. Shabanov, *Eur. Phys. J. E: Soft Matter Biol. Phys.*, 2007, 24, 297.
- 10 X. Wu, H. Cao, R. Guo, K. Li, F. Wang, Y. Gao, W. Yao, L. Zhang, X. Chen and H. Yang, *Macromolecules*, 2012, 45, 5556.
- 11 X. Wu, L. Yu, H. Cao, R. Guo, K. Li, Z. Cheng, F. Wang, Z. Yang and H. Yang, *Polymer*, 2011, **52**, 5836.
- 12 H. Kitzerow, Liq. Cryst. Today, 2002, 11, 3.
- 13 M. Mitov, Adv. Mater., 2012, 24, 6260.
- 14 D. M. Makow, Appl. Opt., 1980, 19, 1274.
- 15 S. Caveney, Proc. R. Soc. London, Ser. B, 1971, 178, 205.
- 16 J. H. Wang, M. H. Song, B. Park, S. Nishimura, T. Toyooka, J. W. Wu, Y. Takanishi, K. Ishikawa and H. Takezoe, *Nat. Mater.*, 2005, 4, 383.
- 17 M. Mitov and N. Dessaud, Nat. Mater., 2006, 5, 361.
- 18 M. Mitov and N. Dessaud, Liq. Cryst., 2007, 34, 183.
- 19 J. Guo, H. Yang, R. Li, N. Ji, X. Dong, H. Wu and J. Wei, J. Phys. Chem. C, 2009, 113, 16538.
- 20 J. Guo, F. Chen, Z. Qu, H. Yang and J. Wei, *J. Phys. Chem. B*, 2011, **115**, 861.
- 21 J. Guo, H. Wu, F. Chen, L. Zhang, W. He, H. Yang and J. Wei, *J. Mater. Chem.*, 2010, **20**, 4094.
- 22 J. B. Guo, H. Cao, J. Wei, D. Zhang, F. Liu, G. H. Pan, D. Y. Zhao, W. L. He and H. Yang, *Appl. Phys. Lett.*, 2008, 93, 201901.
- 23 M. E. McConney, V. P. Tondiglia, J. M. Hurtubise, T. J. White and T. J. Bunning, *Chem. Commun.*, 2011, **47**, 505.
- 24 M. E. McConney, V. P. Tondiglia, J. M. Hurtubise,
 L. V. Natarajan, T. J. White and T. J. Bunning, *Adv. Mater.*,
 2011, 23, 1453.
- 25 D. Görl, B. Soberats, S. Herbst, V. Stepanenko and F. Würthner, *Chem. Sci.*, 2016, 7, 6786.
- 26 S. M. Wood, F. Castles, S. J. Elstona and S. M. Morris, *RSC Adv.*, 2016, 6, 31919.
- 27 Z. G. Zheng, Y. Li, H. K. Bisoyi, L. Wang, T. J. Bunning and Q. Li, *Nature*, 2016, **531**, 352.
- 28 M. Mur, J. A. Sofi, I. Kvasić, A. Mertelj, D. Lisjak, V. Niranjan, I. Muševič and S. Dhara, *Opt. Express*, 2017, 25, 1073.
- 29 Y. Li and D. Luo, Opt. Mater. Express, 2016, 6, 691.