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Flexible blue phase liquid crystal film with high stability based on polymerized liquid crystals

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ABSTRACT

Flexible low-power reflective photonics and display devices with high stability to environmental stimuli such as temperature and mechanical stress have attracted significant attention. Although a lot of efforts have been dedicated in developing blue phase liquid crystals films with high stability and low sensitivity to circumstance, challenges still remain due to the existence of liquid crystals that are sensitive to temperature or mechanical stress. Herein, we demonstrate a flexible blue phase liquid crystal film with high stability through one-step fabrication based on polymerisable liquid crystal. Broad temperature range from −50°C~260°C has been achieved, and the mechanical stress effect has been investigated. The fabricated film is solid without liquid crystal material. This flexible blue phase liquid crystal film with a broad working temperature range, good mechanical stress insensitivity, easy and simple fabrication procedure shows application potential in flexible reflective display, lasers and sensors, where the premier requirement is stability instead of tenability.

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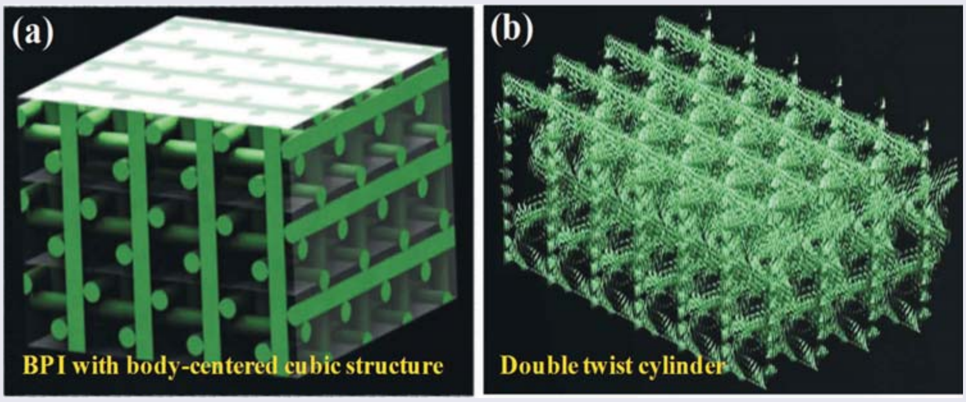

(a) Schematic of blue phase liquid crystal film in BPI with body-centred cubic structure; (b) Double twist cylinder consisted by liquid crystal molecular in BPI.

Introduction

The concept behind photonic crystals (PCs) is to design materials to affect the properties of photons, structures with periodic variations in dielectric constant or random refractive index variation was suggested from early years [1]. Well-organised periodic structure, such as multi-colours of the wings of butterflies and double helix of DNA of lives, with natural periodic structures, contributes to the miraculous and colourful nature. Based on these ideas, PCs structures are widely investigated and designed to enable manipulation of the light or photons [2–10]. Liquid crystals (LCs) are representative soft matter with excellent self-organised behaviour, which are generally used for micromirrors [11,12], smart windows [13–15], liquid crystal microfluidics [16–18], liquid crystal sensors [19–21], blue phase liquid crystal displays [22–24] and so on. Moreover, modulation of the lattice constant is more favourable for liquid crystals to adjust photonic periodicity.

Blue phases (BPs) appear as highly twisted chiral nematic liquid crystals (LCs) between isotropic phase and cholesteric phase, display self-assembly three-dimensional (3D) cubic architectures with lattice dimension of hundreds of nanometres [25–28]. The presented light within visible range is determined by lattice dimension

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and orientation. Such a delicate, 3D, cubic nanostructure endows BPs significant selective photonic reflection, with wavelength determined by the equation, $\lambda = 2na/\sqrt{h^2 + k^2 + l^2}$, where a is lattice constant (h, k, l) is crystallographic direction, h, k, l are Miller indices, and n is the average refractive index of BPs [29].

Blue phase liquid crystal can be fabricated to film through adding high percentage of reactive mesogen into chiral dopant doped liquid crystals, bringing the advantages of better flexibility and broadened stable temperature range for wearable photonic device and sensor applications, where a complicated multi-step method called 'wash-out'and 'refill' process is usually applied [30–37]. In addition, the existence of liquid crystal in blue phase liquid crystal films (BPLCF) is vulnerable to the external circumstance such as temperature and mechanical stress. It is a drawback in applications such as static colourful display, and laser safety filter, where the premier requirement is stability instead of tenability.

In this paper, we demonstrate a flexible blue phase liquid crystal film with high stability through one-step fabrication based on polymerisable liquid crystal. Broad temperature range from −50°C~260°C has been achieved, and the mechanical stress effect has been investigated. The fabricated film is solid without liquid crystal material. This flexible blue phase liquid crystal film with a broad working temperature range, good mechanical stress insensitivity, easy and simple fabrication procedure shows application potential in a flexible reflective display, lasers and sensors, where the premier requirement is stability instead of tenability.

Experiments

In our experiment, the BPLCF was fabricated from polymerisable liquid crystal HRM1001-002 (95.2 wt.%, Δn= 0.1386, n_e= 1.6529, n_o= 1.5143 at λ= 589 nm), chiral dopant R5011 (3.8 wt.%, HTP≈126/μm) and photoinitiator 1173 (1 wt.%), all from Hecheng Display. The cell was assembled by two polyimides (PI) coated glass substrates with anti-parallel rubbing. The thickness of the cell was 10 μm.

Figure 1 depicts the fabrication process of the BPLCF. The mixed material was stirred at 350 K for 30 min for sufficient mixing, and then was injected in the cell. The sample was firstly heated above the clearing point to 345 K, then cooled down slowly by 0.1 K/min to 340.2 K in BP I. During the cooling process, the monomer of BPLC was firstly self-assembled to three-dimensional super-molecular periodic structure consisted of double twist cylinder, leading to BP I with body-centred cubic structure. The self-assembly BPLC was then completely solidified after polymerisation. An ultraviolet (UV) light (365 nm, 5 mW) was exposed on the sample for 30 min. Here, the weak and uniform UV light was used for exposure to reduce defects within BPLCF caused by polymerisation. Comparison to traditional BPLCF, the BPLCF in our experiment was fabricated by a quite simple one-step procedure of polymerisation instead of 'wash-out' and 'refill' process.

Figure 2(a) shows the reflectance spectrum of fabricated BPLCF from 400 nm to 700 nm. The reflection centre wavelength is 460 nm with reflectance of 23%. The low reflectance is majorly due to the strong absorption of film and light scattering in the two interfaces of glass substrates and BPLCF. The polarised opticalmicroscope (POM) image of the BPLCF after polymerisation is demonstrated in Figure 2(b), the scale bar is 500 μm. It can be seen that the BPLCF in BPI shows a quite uniform blue colour. The corresponding Kossel diagram of the BPLCF is presented in Figure 2(c), which shows the crystallographic orientation of [110]. The dashed white lines of the right side depict the corresponding planes of BP I, which is

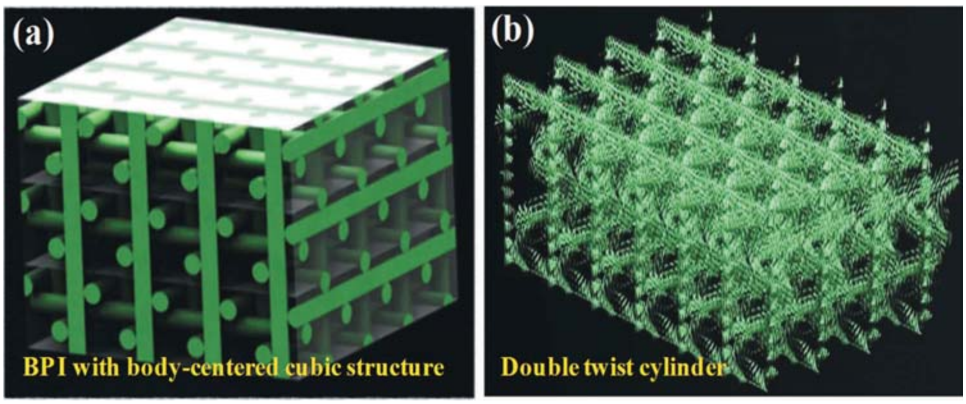

Figure 1. (Colour online) (a) Schematic of blue phase liquid crystal film in BPI with body-centred cubic structure; (b) Double twist cylinder consisted of liquid crystal molecular in BPI.

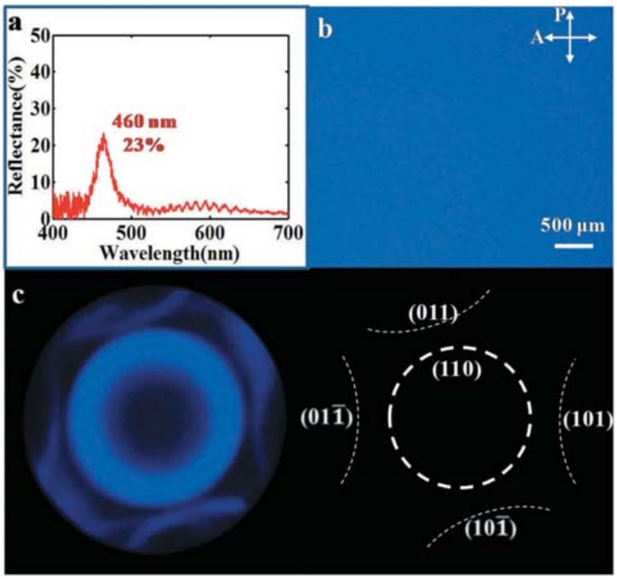

Figure 2. (Colour online) (a) Reflective spectrum of the BPLCF; (b) Polarised optical microscope image of the BPLCF; (c) Kossel diagram of the BPLCF, where the dashed white lines represent the crystallographic planes. Scale bar: 500 μm.

consisted with the diffracted laws of blue phase liquid crystal lattice published by Hauser A et al. [38,39] shows a quite good alignment.

Figure 3(a) depicts the absorption of the BPLCF in range from 350 nm to 700 nm, where the absorptance becomes significant when the wavelength is shorter than 470 nm. The significant absorption in UV and blue light range result in the low reflectance at 460 nm as depicted in Figure 2(a). Figure 3(b) shows the stability of fabricated BPLCF. It can be seen that before polymerisation, the reflection central wavelength of BPLC is highly sensitive due to limited existing temperature range around 3 K (343 K~346 K, or 70°C~73°C). In contrast, after polymerisation, the BPLC turns to BPLCF and the temperature stability increases significantly. We can see that, the temperature range is broadened to at least of 310 K (223 K~533 K, or −50°C~260°C). It is noticed that due to limited testing condition the stability of the film below 223 K and over 533 K is not measured in our experiment, and the range of 223 K~533 K should not be the real limitations. Therefore, an extremely broad stable temperature range more than 310 K has been achieved here, which is much broader than previously reported range of 250 K (148 K~398 K, or −125°C~125°C) [34]. In addition, there is no much change of central wavelength of reflection when the environment temperature changes, providing a quite good property for its practical application in hard circumstance. Figure 3(c) shows the stretching effect of the film with thickness of 100μm and the width of 2 mm. The deformation (Δl) should be corresponding to the length (represented as l), the thickness (fixed) and the width (fixed). We used a machine to pull the film and measured the force it used. The BPLCF can persist 0.4 N of tension without significant deformation (<0.5%), indicating that the BPLCF can persist about 2 Mpa without lattice deformation, which is strong enough as a thin film. When the applied tension is larger than 0.4 N, the film is fractured and the deformation is dramatically increased. The factors that affect the mechanical properties are the fabrication technology of the film. If the film is fabricated uniform and pure, it will possess good mechanical properties.

Figure 4 depicts the BPLCF fabricated on a flexible substrate of polyethylene terephthalate (PET) with a thickness of 200 μm. The BPLCF on flexible substrate demonstrated an excellent bending property, which shows good stability and is not vulnerable to external environments, such as high temperature, touching and bending. The self-assembled BPLCF can be regarded as a fantastic intelligent material for versatile applications in next-generation nanophotonic technology because of the functionalised flexibility, as well as easy-fabrication for large-scale production.

Conclusion

In summary, a flexible blue phase liquid crystal film with high stability has been demonstrated through one-step fabrication based on polymerisable liquid crystal. Broad temperature range from −50°C~260°C has been achieved

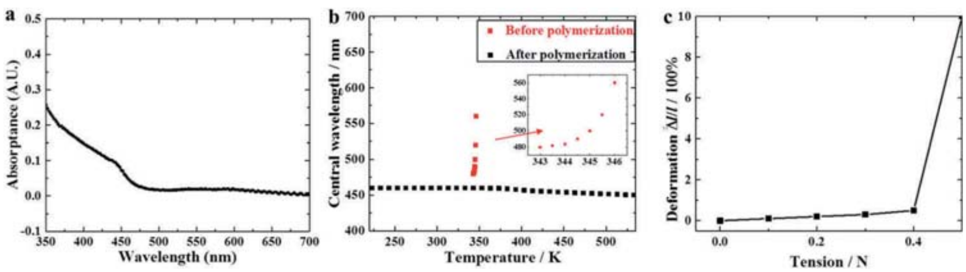

Figure 3. (Colour online) (a) Absorption spectrum of the BPLCF; (b) Temperature effect of the BPLCF before and after polymerisation; (c) Stretching deformation of BPLCF as the tension applied.

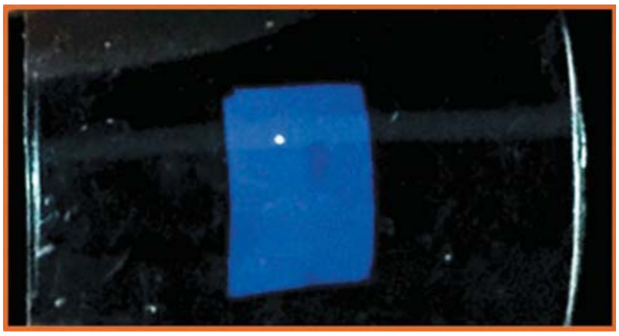

Figure 4. (Colour online) Photograph of the flexible BPLCFs.

for this BPLCF. The BPLCF can persist beyond 2 Mpa, indicating a good stability under mechanical stress. The fabricated film is solid without liquid crystal material. This flexible blue phase liquid crystal film with a broad working temperature range, good mechanical stress insensitivity, easy and simple fabrication procedure shows application potential in flexible reflective display, lasers and sensors, where the premier requirement is stability instead of tenability.

Disclosure statement

No potential conflict of interest was reported by the authors.

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