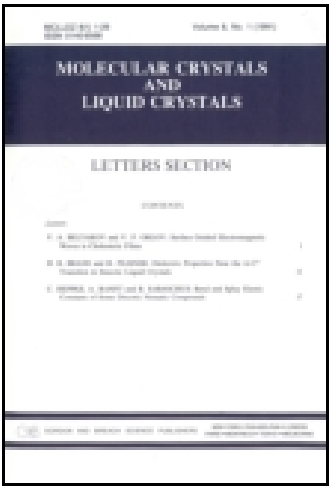

Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl20

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Published online: 30 Sep 2014.

Mol. Cryst. Liq. Cryst., Vol. 595: pp. 63–69, 2014

ISSN: 1542-1406 print/1563-5287 online
DOI: 10.1080/15421406.2014.917788

Do the Reflection Colors of BPI Depend Linearly on Chiral Concentration?

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In this study, we explore a relation between reflection colors and a chiral concentration. Basing on our observation, the reflection colors in BPI are dominated by lattice surface of the platelets and the lattice constant of a unit cell, but they do not depend linearly on the chiral concentration. The reflection peak moves to a short wavelength as increasing the chiral concentration because of contracting the lattice constant. However, when the lattice plane is changed, the reflection is dominated by the lattice plane, and it may move to a longer wavelength.

Keyword Blue phase; Bragg reflection; lattice plane; reflection

1. Introduction

Among the liquid-crystal (LC) science, blue phases (BPs) are such one of the interesting phases, because they are soft solids spontaneously constructed through a network of disclination lines in three-dimensional space [1]. Usually, when the chirality of the chiral nematic LC (N*) is strong enough, three thermotropic BPs may display between the isotropic phase and N* [1, 2]. Upon cooling process from the isotropic liquid phase, one can observes BP III, BP II and BP I to appear in a row. In BP I and II, because the disclination networks and the double-twisting cylinders form cubic lattices, they can reflect bright and colorful light as the Bragg condition is satisfied. For cubic crystals with lattice constant a, the spacing $d_{h,k,l}$ between adjacent lattice planes (denoted by Miller indices, h, k and l) is:

$$d_{h,k,l} = \frac{a}{\sqrt{h^2 + k^2 + l^2}} \tag{1}$$

Combing the relation with Bragg's law, the reflection wavelength of BP with cubic structures can be expresses as [3]

$$\lambda = \frac{2na\cos\theta}{\left(h^2 + k^2 + l^2\right)^{(1/2)}} \tag{2}$$

where θ is the Bragg's angle.

In Eq. (2), the lattice constant, referring to a constant distance between unit cells in a crystal lattice, is determined by the diameter of the double-twisting cylinder (i.e. a quart of the pitch) in blue phases [4]. It means that the reflection color of the BPs is dominated by two

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Table 1. Samples consist of nematic LC and chiral dopant NL

	Nematic LC	Chiral dopant NL (HTP = 16.7 μm^{-1})	Cell gap
Sample N-1	85.83 wt.%	14.17 wt.%	51.47μm
Sample N-2	85.22 wt.%	14.76 wt.%	47.41 μm
Sample N-3	84.72 wt.%	15.28 wt.%	53.72 μm

issues: lattice surface of the platelets and the lattice constant of a unit cell. Referring other previous studies [4–6], the reflection colors of the cubic BPs may be different in the heating and cooling processes. When the LC was heated from cholestric phase to BPI, the lattice plane of BPI does not change, but the lattice constant does [4]. Thus, the uniform reflection color is usually seen in the heating process. Because the lattice constant changes with the temperature, the reflection wavelength shifts to longer or shorter wavelength slightly. The wavelength-shifting direction in BPI relates to the temperature-dependent pitch length in cholestric phase [5, 6]. However, when the LC cools from the isotropic phase, in BPI or BPII, the lattice plane and lattice constants are random, and the BPs reflect different colors at the same time. A uniform lattice plane in cooling process can be obtained by using a cell with alignment layers [7] or by thermal recycle [8].

It has been well known that the reflectance of the BPI can be tuned by an electric field due to the lattice distortion and director reorientation [7]. Basing on the electro-optical properties of the BPs, a concept of a full-color-reflective BP display is proposed and demonstrated in recent paper [9]. In that paper, they made red, green and blue sub-pixels of the polymer-stabilized BP (PSBP) with different pitch lengths [9]. However, they did not mention the relation between the pitch lengths and the reflection colors. To reproduce their idea, one should know the relation between the reflection color and the chiral dopant concentration (or pitch lengths). It will be a key point for manufacturing reflective PSBP displays.

From these previous studies [4–6] we mention above, one is not hard to find that there are many parameters will affect the reflection colors of the BPs. In this study, we try to focus on discussing the relation between the reflection colors of BPI and the chiral concentration. We summarize the conclusions from our experimental results and observations. (1) The order of the lattice plane in BPI and the temperature range of BPs relates to the variation in the pitch length with temperature in the cholesteric phase. When the pitch length in the cholesteric phase changes rapidly with the temperature, the lattice plane of BPI in the

Table 2. Samples consist of nematic LC and chiral dopant S811

	Nematic LC	Chiral dopant S811(HTP = 10 μm^{-1})	Cell gap
Sample S-1	75.4 wt.%	24.6 wt.%	50.32 μm
Sample S-2	73.4 wt.%	26.6 wt.%	49.74 μm
Sample S-3	71.4 wt.%	28.6 wt.%	56.01 μm

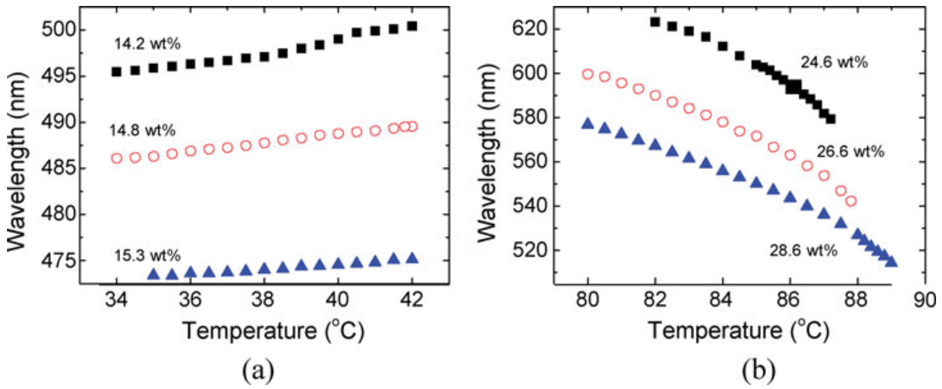

Figure 1. Temperature-dependence wavelengths of the reflection peak in chiral nematic phase when the chiral dopant is (a) NL or (b) S811.

cooling process is not unifrom and the temperature range is narrow. (2) In the cooling process, the reflection color in BPI does not depend linearly on the concentration of the chiral dopant. It is determined by the lattice constant and the lattice plane. When the lattice plane does not change, the reflection peak moves to a short wavelength as increasing the chiral concentration because of contracting the lattice constant. However, when the lattice plane changes, the reflection wavelength is dominated by the lattice plane, and it may move to a longer wavelength. These results will be helpful for developing the display application.

2. Experimental

To study effects of chiral dopants, there are two left-handenss chiral dopants, NL and S811, mixed with a positive-dielectric-anisotropy nematic liquid crystal ($\Delta\varepsilon = 5.24$). Their helical twisting powers (HTP) are 16.7 μm^{-1} and 10 μm^{-1} with respect to NL and S811. We added these chiral dopants into the nematic liquid crystal with different concentrations, as listing in Tabs. 1 and 2. In order to have blue phases in our samples, the concentrations of these chiral dopants were limited in a specific region.

These samples were filled into empty cells with anti-parallel alignment layers in the isotropic phase. The lattice planes of the blue phases can be more order due to the alignment layers on the glass substrates. In ordet to enhance the reflection intensity, a cell thinkess is about 50 μm. To keep these samples in blue phases, they are put into a precision hot stage (an accuracy of 0.1K), and the cooling and heating rates were 0.2 K/min. All the observations in this study were done by a crossed polarizing optical microscope and an optical spectrometer.

3. Results and Discussion

Before studying optical properties of BPI, we explored the reflection spectra of these samples listed in Tabs. 1 and 2 when they are in the chiral nematic phase. Figure 1 displays that the reflection peaks may shift to a longer or a shorter wavelength as decreasing the temperature. When the chiral doping is S811, the red shift in the reflection peaks is seen

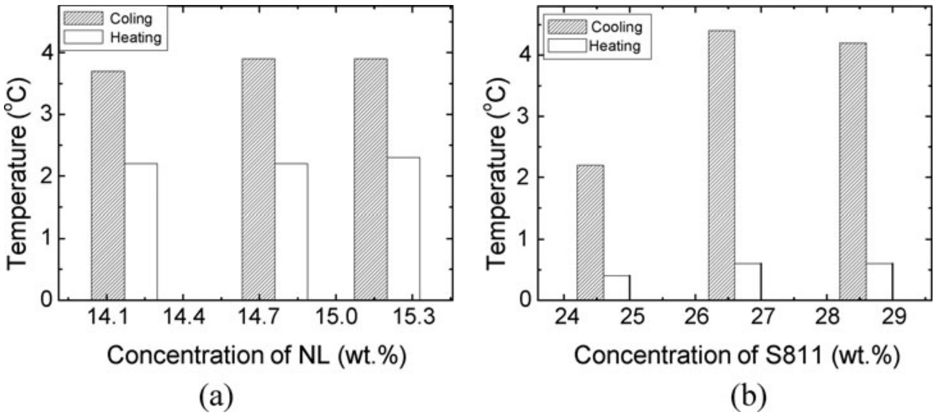

Figure 2. Temperature ranges of blue phases under heating or cooling process when the chiral dopant is (a) NL or (b) S811.

in the lower temperature. However, replacing the chiral dopant by NL, the reflection peaks move to the short wavelength.

Comparing the variations in the reflection wavelength with temperature in both two chiral-dopant systems, one may find that in S811 system the variation is huge. Moreover, when the chiral concentration is increased in the nematic LC, as we expect, the reflection peal moves to a shorter wavelength.

The temperature ranges of BPs in these samples were also recorded and summarized in Fig. 2. According to the results in Figs. 1 and 2, one can see that the variation in the reflection wavelength with temperature affects the temperature range and the thermal stability of BPs. When we filled these samples into cells without alignment layers and compared the order of the lattice plane in the samples with NL to those with S811, we observe that the samples with NL shows more uniform color than the samples with S811. It can be understood through studying the variation of the pitch length with the temperature in the cholesteric phase.

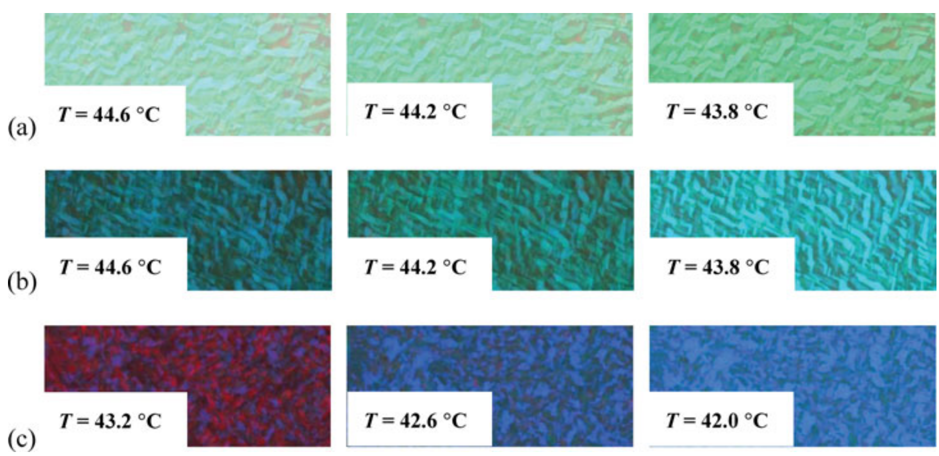

Figure 3. Reflection colors of BPI in the samples doping with chiral dopant NL.

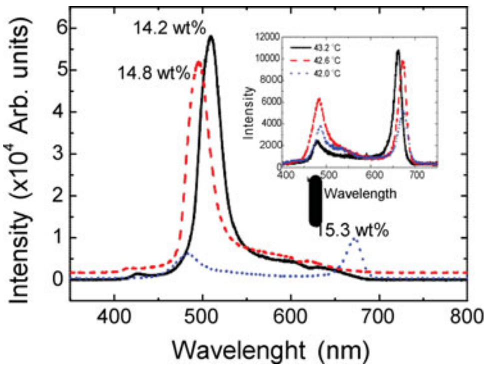

Figure 4. Reflection spectra of BPI in sample NL-1 ($T = 44.2$ °C), NL-2 ($T = 44.2$ °C), and NL-3 ($T = 42.6$ °C). The insert is the reflection spectra in sample NL-3 by decreasing the temperature.

We focus on observing the optical properties in BPI for each NL sample in Fig. 3 and record the reflection spectra at various temperatures in the cooling process, as shown in Fig. 4. From Fig. 3, one may see that, when the concentration of NL (14.2 wt%) is lower, the reflection color does not change obviously with decreasing the temperature. It agrees with the behavior of the reflection peak in Fig. 1(a). Moreover, as increasing the concentration of NL to 14.8 wt%, the reflection color changes from cyan to the light sea green (i.e. shift to shorter wavelength), such as the tendency we saw in chiral nematic phase in Fig. 1(a). Continuously increasing the concentration of NL to 15.3 wt%, the reflection color does not keep changing to violet, but shows dark red and blue in the high temperature and shows dark blue in the low temperature.

The reflection spectra of BPI in Fig. 4 show that, in the low NL concentrations, only one reflection peak is seen. The shorter reflection wavelength is detected in 14.8-wt% NL sample.

Because the pitch length does not change rapidly with the temperature, the lattice constants in the sample NL-1 and sample NL-2 changes slightly at various temperatures in NL samples when the lattice plane is the same. While the NL concentration is increased to 15.3 wt%, two reflection peaks shows up at 660 nm and 480 nm, as shown in Fig. 4.

As decreasing the temperature, the intensity of the 660-nm reflection peak becomes weaker, accompanying with red shift in wavelength. At the same time, the 480-nm reflection peak grows and shifts to a longer wavelength. Before the sample transfers to the chiral nematic phase, the intensities of these two reflection peaks are almost equal. Because the BPI is bcc structure, the first two possible lattice planes are (1, 1, 0) and (2, 0, 0). By calculating the ratio of these two reflection peaks in the insert of Fig. 4 and referring Eq. (2), the 660-nm reflection peak comes from (1, 1, 0) and the 480-nm reflection peak comes from (2, 0, 0), when the lattice constant is about 298 nm. According to Eq. (2), the reflection wavelength is inversely proportional with the lattice plane and is proportional with lattice constant, which depends on the pitch length (i.e. chiral concentration). When the chiral concentration is increased, the lattice constant of BPI should contract. It means that the lattice constants in the Sample NL-1 and the Sample NL-2 should be larger than it in the sample NL-3. Assuming that the lattice plane is (2, 0, 0), one can obtain the lattice constants are 318 nm and 312 nm with respect to the Sample NL-1 and the Sample NL-2. From the experimental results in Figs. 3 and 4, it implies that when the chiral concentration is too

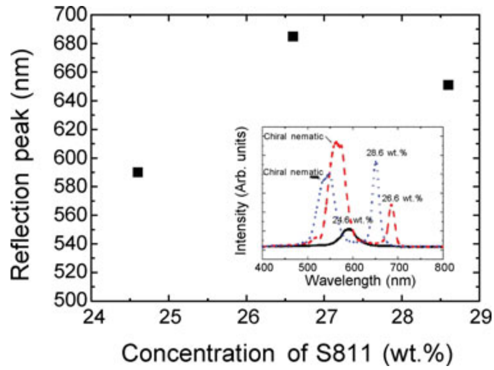

Figure 5. Reflection peaks of BPI in sample S-1 ($T = 86.4°C$), S-2 ($T = 85.6\ °C$), and S-3 ($T = 86.2°C$). The insert is the reflection spectra in these samples.

high, a linear relation between the reflection color of BPI and the chiral concentration is broken due to the different lattice plane.

Figure 5 shows that the concentration-dependent reflection wavelength of BPI when we replaces the chiral dopant NL by the chiral dopant S811. In these S811 samples, only one reflection peak was detected in BPI at various concentrations. When the concentration of S811 was increased from 24.6 wt%, 26.6 wt% to 28.6 wt%, the reflection wavelength of BPI shifts to the longer wavelength at 685 nm, and then shifts to the shorter wavelength at 650 nm. The red shift is due to the change in the lattice planes from (2, 2, 0) to (2, 1, 1) and the blue shift is because of contracting the lattice constant in the high chiral concentration. We repeat the experiment on another nematic LC, and we can find the similar behavior of the reflection wavelength, as shown in Fig. 6.

From these experimental results, one may conclude that, in a particular chiral concentration region, the wavelength peak seems to change linearly and continuously with the chiral concentration because the lattice plane does not change and the lattice constant contracts. However, when the concentration of the chiral dopant is over a value, a discontinuous shift in reflection peak occurs due to the production of the different lattice plane.

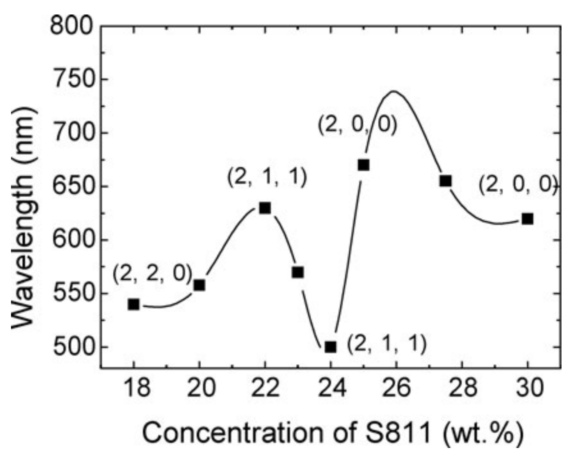

Figure 6. Reflection peaks of BPI in LC05/S811 samples with different chiral concentration.

These results show that the wavelength peak of the reflection does not depend on the concentration of the chiral dopant linearly. The relation between the chiral concentration and the reflection peak in BPI is more complicate than that in the cholestric phase.

4. Conclusion

We demonstrate the reflection behavior of BPI in various concentrations of chiral dopant. From these experimental results, in BPI, the reflected colors are dominated by lattice surface of the platelets and the lattice constant of a unit cell, which relate to the chiral concentration. However, the reflection color in BPI does not depend linearly on the concentration of the chiral dopant. Because of contracting the lattice constant, the reflection peak moves to a short wavelength as increasing the chiral concentration. However, when the change in the lattice plane is induced, the reflection is dominated by the lattice plane, and it may move to a longer wavelength. These results will be helpful for developing the display application.

Acknowledgments

The authors would like to thank the National Science Council of the Republic of China for financially supporting this research under Grant Nos. NSC 101-2112-M-005-006-MY3 and NSC 102-2922-I-035-013

References

[1] de Gennes, P. G., & Prost, J. (1993). *The physics of liquid crystals,* 2nd edition*, Ch. 6*, Oxford University Press: England.
[2] Bowing, M. B., Collings, P. J., Booth, C. J., & Goodby, J. W. (1993). *Phys. Rev. E*, *48*, 4113.
[3] Flack, J. H., & Crooker, P. P. (1981). *Mol. Cryst. Liq. Cryst.*, *69*, 281.
[4] Johnson, D. L., Flack, J. H., & Crooker, P. P. (1980). *Phys. Rev. Lett.*, *45*, 641.
[5] Her, J., Rao, B. B., & Ho, J. T. (1981). *Phys. Rev. A*, *24*, 3272.
[6] Heppke, G., Kitzerow, H.-S., Lötzsch, D., & Papenfuß, Ch. (1990). *Liq. Cryst.*, *8*, 407.
[7] Chen, H.-Y., Chiou, J.-Y., & Yang, K.-X. (2011). *Applied Physics Lett.*, *99*, 181119.
[8] Chen, H.-Y., Liu, H.-H., Lai, J.-L., Chiu, C.-H., & Chou, J. Y. (2010). *Appl. Phys. Lett.*, *97*, 181919.
[9] Yan, J., Wu, S.-T., Cheng, K.-L., & Shiu, J.-W. (2013). *Appl. Phys. Lett.*, *102*, 081102.