The influence of orienting layers on blue phase liquid crystals in rectangular geometries

M.M. Sala-Tefelska,*[1] K. Orzechowski,[1] F.A. Sala,[1] T.R. Woliński,[1] O. Strzeżysz[2], P. Kula[2]

[1]*Faculty of Physics, Warsaw University of Technology, Koszykowa 75, 00-662, Warsaw, Poland*
[2]*Institute of Chemistry, Military University of Technology, Gen. Witolda Urbanowicza 2, 00-908, Warsaw, Poland*

Received November 30, 2018; accepted December 14, 2018; published December 31, 2018

Abstract—In this paper, the influence of homeotropic and homogeneous orienting layers is presented in a cell filled with chiral nematic liquid crystals stabilized in a blue phase. The change of selective Bragg reflection from red to blue light was observed for homogeneous layers in rectangular geometries. The growth of blue phase crystals domains in a glass cell as well the influence of temperature and electric field on such a structure are also presented.

The discovery of liquid crystals (LC) by Reinitzer [1], an Austrian chemist, in 1888 revolutionized the world almost 100 years later. Technological progress has made it not only possible to study optical properties of liquid crystals, but also to use them in advanced devices.

The Blue Phase (BP) is one of numerous liquid crystal phases, which is very interesting from an optical viewpoint. The Blue Phase is a state between isotropic and chiral phases of liquid crystals. This state appears only for a small helicoidal pitch of chiral nematics, which is related to a high concentration of optical active dopant in an LC mixture. Usually, it also exists in a very narrow temperature range. There are three sub-phases: called BPI, BPII and BPIII (also known as a fog phase). BPI has a body centered cubic structure and BPII has a simple cubic structure (Fig. 1). The BP cubic structure has a lot of ordered rods, where a single rod consists of double twisted cylinders (DTC). In this work, only the BPI and BPII are considered. It should be mentioned that the Blue Phase Liquid Crystal (BPLC) is optically isotropic, and is characterized by selective Bragg reflection. Moreover, its birefringence can be induced by applying an external electric field [2]. The response times of BPLC are relatively short. In recent works [3-4] it has been shown that there is a possibility to switch or control BPLC about 10 times faster (in submilisecond range) than the nematic LC. Furthermore, optical devices based on BPLC do not require any alignment layers, which reduces costs and simplifies the production of such elements. BPLC is a very promising material to use in various optical devices such as tunable color-reflecting mirrors [5], phase modulators [6], phase shifters and wave plates for the THz range [7] and as liquid-crystal lenses with a variable focal length [8]. There are also very promising results for BPLC in cylindrical geometries where the obtained single crystals of BP with different selective Bragg reflection could be used as an equivalent of a Bayer filter in liquid crystal displays. The BPLC domains growth in a capillary has been observed recently [9]. For BPLC applications in optical devices, homogeneity and repeatability of the structure are important. In paper [10] a new method for inducing a monodomain in BPLCs was demonstrated.

The geometry of the system, the alignment layers and also the thermal process where the BP orientation depends on the phase from which it transitions [11], have an impact on the BP orientation.

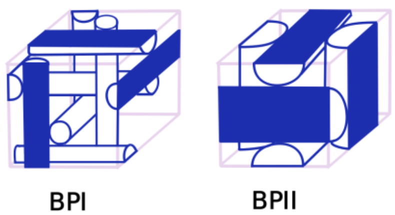

Fig. 1. Cubic structure of Blue Phase I and II.

In this work we present the effects of applying orienting layers in rectangular geometry filled with a liquid crystal material in the BP. For instance, a liquid crystal cell is an example of such rectangular geometry. The obtained results show that the orientation layers have a significant effect on the optical properties of the blue phase. Usually, in BPII, a light reflection appears for lower wavelengths than in BPI [12-14]. In such a case, a green or blue light reflection is observed. In our case it is the opposite as the BPII light reflection appears for higher wavelengths. For BPII in planar orientation, a red light reflection is observed. This phenomenon is caused by the configuration of a liquid crystal material, orienting layers and also by the presence of optical active dopants. In this work we use the 1912 chiral nematic LC mixture which was synthetized in the Institute of Chemistry at the Military University of Technology. This material consists of 11 nematic LC compounds and two optical active dopants with a left-handed configuration. A detailed

* E-mail: marzena.sala-tefelska@pw.edu.pl

 © 2018 Photonics Society of Poland

description of its chemical formulas and weight concentrations can be found in [8]. The 1912 LC mixture has medium birefringence Δn=0.178 at 589nm and relatively low electric anisotropy $\Delta\varepsilon$=12.6 at 1kHz (the given parameters were measured at 20°C). The helical pitch of the 1912 chiral nematic LC mixture (with estimated measurement uncertainties) is 435(9)nm and was measured by the Grandjean-Cano wedge method. The refractive indices of light for BPLC were measured by the wedge-cell technique. The results and the method are described elsewhere [15]. In the LC cell, BP II appears in a range of temperatures from about 58.4°C up to 56.6°C and BPI from 56.5°C to 53.0°C, in a cooling process.

In this experiment the LC cell was prepared with two glass plates separated from each other by a spacer of 20 µm thickness. On the glass plates an Indium Tin Oxide (ITO) conductive layer was deposited. Both plates had also the alignment layers: homogeneous – horizontal anchoring (HA) and homeotropic – vertical anchoring (VA) (Fig. 2).

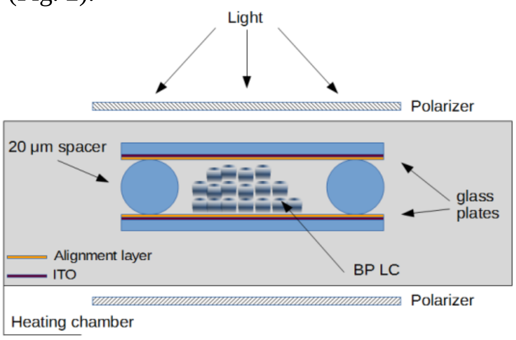

Fig. 2. Experimental setup with LC cell.

The LC cell was placed in a heating chamber and transmitted light was observed through crossed polarizers under Nikon Eclipse Ts2R microscope. BPLC textures were obtained in a slow cooling process from the isotropic phase, with a speed of 0.1°C/min. The temperature was controlled and stabilized by THMS600 Linkam microscope stage.

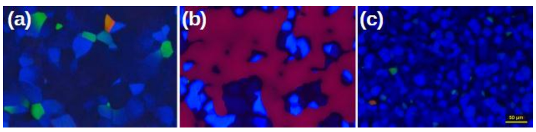

Fig. 3. BPII texture observed in an LC cell with (a) no alignment layer (NAL), (b) horizontal anchoring (HA) and (c) vertical anchoring (VA) at temperature 58°C (scale is 50µm).

In Fig. 3 it can be seen that the orienting layers significantly influence the texture of BPII and the selective Bragg reflection. For HA, the BPII domains reflect the red light (Fig. 3b) whereas for NAL and VA layers the reflection is almost the same in a blue light range (Fig. 3a, c). Some green and orange domains can be also noticed. Various clusters of BP cubic structures, called domains, with identical orientation and the same selective Bragg reflection were observed. These domains' orientation depends on the anchoring conditions on the walls of the LC cell. They are positioned at appropriate angles in relation to the incident light, hence various selective light reflections and many colorful areas appear. Here we can only speculate what happened in such a structure. It should be mentioned that the most valuable method to determine the orientation of BP is to measure the Kossel patterns. It will be covered in the future works. The number of BPII domains appearing in the VA layer (Fig. 3 c) is much larger than for the NAL and HA layers (observed at the same temperature). Besides, for NAL the BP domains are larger than for VA. The growth of BP II domains in rectangular geometries at a constant temperature of 58.4°C is presented in Fig. 4. Obtaining a fully uniform domain is not easy and requires multiple heating and cooling processes with a slow temperature rate of change.

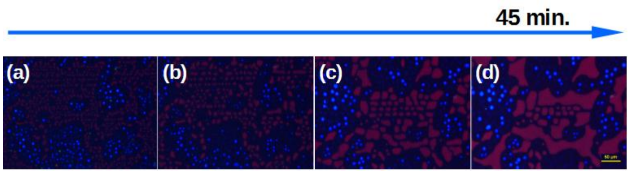

Fig. 4. Growth of BP II domains in a glass cell with HA, left for: (a) 5, (b) 10, (c) 20, (d) 45 min. at a constant temperature of 58.4°C. Observation was made under a polarizer microscope (scale is 50µm).

In Fig. 5, the phase transition from BPII (Fig. 5a÷d) through BPI (Fig. 5e÷h) to chiral phase (Fig. 5i) in BPLC cell with HA layers is presented. By a slow cooling process from 58.4°C to 57°C a quasi-uniform BPII structure with a brightly red light reflection was obtained (Fig. 5c÷d). For BPI, for the same process, the quasi-uniform structure with a blue light reflection was observed (Fig. 5g÷h). This effect was repeatable. The transition between BPI and chiral phase is presented in Fig. 5i.

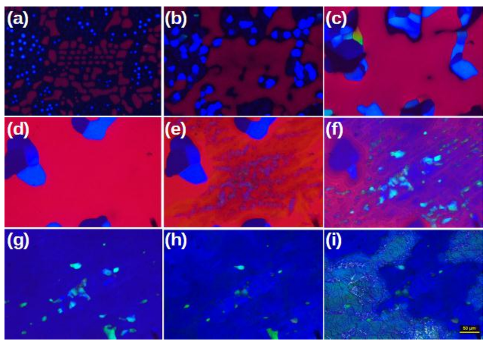

Fig. 5. Slow cooling process, of a LC cell with HA filled with BPLC, BPII at temperature: (a) 58.4°C, (b) 58.0°C (c) 57.8°C (d) 57°C, BPI at: (e) 56.5°C, (f) 56.4°C, (g) 56.3°C, (h) 54°C and transition to chiral phase (i) at 51.3°C (scale is 50µm).

 © 2018 Photonics Society of Poland

The same procedure was carried out for BPLC with a VA layer. The use of another anchoring of BP domains resulted in the reflection of blue light (Fig. 6). During the process of BP domains growth, many small BP crystals appear (Fig. 6a). Phase transitions for a VA layer are no longer as spectacular as for HA. The BPI can be observed when a violet light reflection appears (Fig. 6e÷g). By using a slow cooling process the texture of BP is quasi uniform. The phase transition from BPI at 54°C to a chiral phase at a temperature of 51.5°C is presented in Fig. 6h÷i.

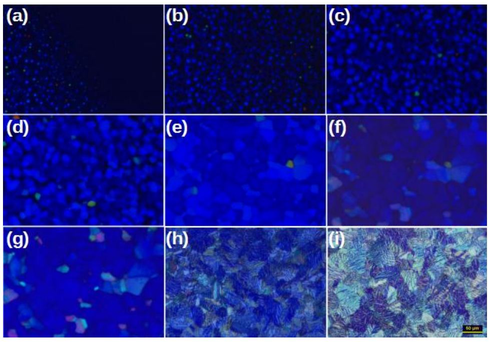

Fig. 6. Slow cooling process, of a LC cell with VA filled with BPLC, BPII: (a) 58.6°C, (b) 58.5°C, (c) 58.3°C, (d) 58.0°C, (e) 57.0°C BP I: (f) 56.5°C , (g) 56.0°C and transition from BP I to the chiral phase (h) 54°C, (i) 51.5°C (scale is 50µm).

To obtain a monodomain texture of BP, we applied the external electric field E=0.53V/µm of 1kHz frequency to the LC cell. Then, the electric field was switched off and a uniform BPII structure strongly reflecting the red light was observed (Fig. 7b). The response time was below 1ms. We observed the electro-optical Kerr effect, which induced the optical birefringence. The monodomain texture was stable in a wide range of temperatures.

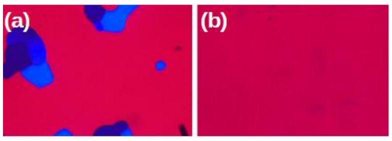

Fig. 7. BPLC cell with BP II at 57°C under the influence of the electric field: (a) 0V, (b) $10.6V_{RMS}$.

Next, the cell with BPLC was put into an experimental set-up consisting of a halogen lamp, heating chamber and HR4000 Ocean Optics spectrometer as a detector.

In Fig. 8 the light transmission spectrum is presented for the BPLC cell with HA under the crossed polarizers. The dots correspond to the selective Bragg reflection spectrum of BPII, which is around 630nm. By increasing the externally applied voltage, the selective Bragg reflection changes. We observed two flattened maxima (the blue line in Fig. 8) for 448nm and 557nm related to the electrostriction effect. For relatively large voltages, the reflection of light disappears.

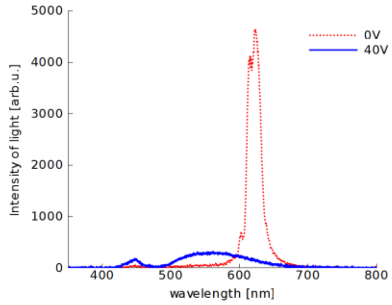

Fig. 8. The influence of the electric field on the light transmission under the crossed polarizers in the HA cell with BPLC.

Summarizing, it should be noticed that both the orienting layers and the geometry of the system influence the optical properties of the blue phase. The change of a selective Bragg reflection from the red to the blue light was observed for a homogeneous anchoring layer. Moreover, by applying an external electric field it was also possible to achieve a monodomain structure. The change of a selective Bragg reflection was also observed under the influence of an electric field.

This work has been supported by the National Science Centre, Poland under the grant number 2015/19/D/ ST3/02432. KO is supported by the grant of the Faculty of Physics, Warsaw University of Technology. We would like to thank Mr Wojciech Staniszewski from PRECOPTIC Co. for his technical support.

References

[1] F. Reinitzer, Monatsh Chem. **9**, 421 (1888).
[2] J. Yan, M. Jiao, L. Rao, S.-T. Wu, Opt. Expr. **18**, 11450 (2010).
[3] Y. Chen, D. Xu, S.-T. Wu, S.-i. Yamamoto, Y. Haseba, Appl. Phys. Lett. **102**, 141116 (2013).
[4] Y. Huang, H. Chen, G. Tan, H. Tobata, S. Yamamoto, E. Okabe, Y.-F. Lan, C.-Y. Tsai, S.-T. Wu, Opt. Mater. Expr. **7**, 641 (2017).
[5] V. Sridurai, M. Mathews, C.V. Yelamaggad, G.G. Nair, ACS Appl. Mater. Interf. **9**(45), 39569 (2017).
[6] E. Oton, E. Netter, T. Nakano, Y. D.-Katayama, F. Inoue, Sci. Rep. **7**, 44575 (2017).
[7] Q. Liu, D. Luo, X. Zhang, S. Li, Z. Tian, Liq. Cryst. **44**(2), 348 (2017).
[8] Y. Li, Y. Liu, Q. Li, S.-T. Wu, Appl. Opt. **51**(14), 2568 (2012).
[9] M.M. Sala-Tefelska, K. Orzechowski M. Sierakowski, A. Siarkowska, T.R. Woliński, O. Strzeżysz, P. Kula, Opt. Mater. **75**, 211 (2018).
[10] H. Claus, O. Willekens, O. Chojnowska, R. Dąbrowski, J. Beeckman, K. Neyts, Liq. Cryst. **43**(5), 688 (2016).
[11] M. Takahashi, T. Ohkawa, H. Yoshida, J. Fukuda, H. Kikuchi, M. Ozaki, J. Phys. D: Appl. Phys. **51**(10), 104003 (2018).
[12] P. Joshi, X. Shang, J. De Smet, E. Islamai, D. Cuypers, G. Van Steenberge, S. Van Vlierberghe, P. Dubruel, H. De Smet, Appl. Phys. Lett. **106**, 101105 (2015).
[13] K. Orzechowski, M.W. Sierakowski, M. Sala-Tefelska, P. Joshi, T.R. Woliński, H.D. Smet, Opt. Mater. **69**, 259 (2017).
[14] P.-J. Chen, M. Chen, S.-Y. Ni, H.-S. Chen, Y.-H. Lin, Opt. Mater. Expr. **6**, 1003 (2016).
[15] K. Orzechowski, M.W. Sierakowski, M. Sala-Tefelska, T.R. Woliński, O. Strzeżysz, P. Kula, Phot. Lett. Poland **9**(2) 54 (2017).

 © 2018 Photonics Society of Poland