A fast response variable optical attenuator based on blue phase liquid crystal

Ge Zhu,[1] Bing-yan Wei,[1] Liang-yu Shi,[1] Xiao-wen Lin,[1] Wei Hu,[1,2] Zhang-di Huang,[1] and Yan-qing Lu[1,3]

[1] *National Laboratory of Solid State Microstructures and College of Engineering and Applied Sciences, Nanjing University, Nanjing 210093, China*
[2] *huwei@nju.edu.cn*
[3] *yqlu@nju.edu.cn*

Abstract: Blue phase liquid crystals (BPLCs) are promising candidates for next generation display thanks to their fast response and quasi-isotropic optical properties. By taking these advantages, we propose to introduce the material into fiber-optic applications. As an example, a BPLC based variable optical attenuator (VOA) is demonstrated with a polarization independent design. The device shows normally-off feature when no field is applied. Response time down to submillisecond scale is achieved in switching between two arbitrary attenuation states. The attenuation range is also measured from 1480 to 1550 nm, which cover the whole telecomm S-band and part of the C-band. The overall performances reach the requirements for practical use; while still have room for further improvement. Through this example, the applicability of BPLC in fiber-optic devices is presented, which may impel the development of many other photonic applications from infrared to even microwave regions.

OCIS codes: (160.3710) Liquid crystals; (060.2340) Fiber optics components; (060.5060) Phase modulation.

References and links

1. H. Kikuchi, M. Yokota, Y. Hisakado, H. Yang, and T. Kajiyama, "Polymer-stabilized liquid crystal blue phases," Nat. Mater. **1**(1), 64–68 (2002).
2. Z. Ge, S. Gauza, M. Jiao, H. Xianyu, and S. T. Wu, "Electro-optics of polymer-stabilized blue phase liquid crystal displays," Appl. Phys. Lett. **94**(10), 101104 (2009).
3. L. Rao, J. Yan, and S. T. Wu, "Prospects of emerging polymer-stabilized blue-phase liquid crystal displays," J. Soc. Inf. Disp. **18**(11), 954–959 (2010).
4. J. S. Patel and M. W. Maeda, "Tunable polarization diversity liquid-crystal wavelength filter," IEEE Photon. Technol. Lett. **3**(8), 739–740 (1991).
5. Y. H. Fan, H. Ren, and S. T. Wu, "Electrically controlled lens and prism using nanoscale polymer-dispersed and polymer-networked liquid crystals," Proc. SPIE **5289**, 63–73 (2004).
6. J. L. West, G. Q. Zhang, A. Glushchenko, and Y. Reznikov, "Fast birefringent mode stressed liquid crystal," Appl. Phys. Lett. **86**(3), 031111 (2005).
7. S. Jutamulia, G. M. Storti, W. M. Seiderman, J. Lindmayer, and D. A. Gregory, "Infrared signal processing using a liquid crystal television," Opt. Eng. **30**(2), 178–182 (1991).
8. X. J. Wang, Z. D. Huang, J. Feng, X. F. Chen, X. Liang, and Y. Q. Lu, "Liquid crystal modulator with ultra-wide dynamic range and adjustable driving voltage," Opt. Express **16**(17), 13168–13174 (2008).
9. X. W. Lin, W. Hu, X. K. Hu, X. Liang, Y. Chen, H. Q. Cui, G. Zhu, J. N. Li, V. Chigrinov, and Y. Q. Lu, "Fast response dual-frequency liquid crystal switch with photo-patterned alignments," Opt. Lett. **37**(17), 3627–3629 (2012).
10. Y. H. Lin, H. S. Chen, H. C. Lin, Y. S. Tsou, H. K. Hsu, and W. Y. Li, "Polarizer-free and fast response microlens arrays using polymer-stablized blue phase liquid crystals," Appl. Phys. Lett. **96**(11), 113505 (2010).
11. H.-Y. Liu, C.-T. Wang, C.-Y. Hsu, T.-H. Lin, and J.-H. Liu, "Optically tuneable blue phase photonic bandgaps," Appl. Phys. Lett. **96**(12), 121103 (2010).
12. Y. Li and S. T. Wu, "Polarization independent adaptive microlens with a blue-phase liquid crystal," Opt. Express **19**(9), 8045–8050 (2011).
13. C. T. Wang and T. H. Lin, "Bistable reflective polarizer-free optical switch based on dye-doped cholesteric liquid crystal Invited," Opt. Mater. Express **1**(8), 1457–1462 (2011).
14. Y. H. Lin, H. S. Chen, T. H. Chiang, C. H. Wu, and H. K. Hsu, "A reflective polarizer-free electro-optical switch using dye-doped polymer-stabilized blue phase liquid crystals," Opt. Express **19**(3), 2556–2561 (2011).

#182862 - $15.00 USD Received 4 Jan 2013; revised 5 Feb 2013; accepted 18 Feb 2013; published 25 Feb 2013

15. Y. H. Chen, C. T. Wang, C. P. Yu, and T. H. Lin, "Polarization independent Fabry-Perot filter based on polymer-stabilized blue phase liquid crystals with fast response time," Opt. Express **19**(25), 25441–25446 (2011).
16. J. Yan, Y. Li, and S. T. Wu, "High-efficiency and fast-response tunable phase grating using a blue phase liquid crystal," Opt. Lett. **36**(8), 1404–1406 (2011).
17. G. Zhu, J. N. Li, X. W. Lin, H. F. Wang, W. Hu, Z. G. Zheng, H. Q. Cui, D. Shen, and Y. Q. Lu, "Polarization-independent blue-phase liquid-crystal gratings driven by vertical electric field," J. Soc. Inf. Disp. **20**(6), 341–346 (2012).
18. C. W. Chen, H. C. Jau, C. T. Wang, C. H. Lee, I. C. Khoo, and T. H. Lin, "Random lasing in blue phase liquid crystals," Opt. Express **20**(21), 23978–23984 (2012).
19. Y. H. Wu, Y. H. Lin, Y. Q. Lu, H. W. Ren, Y. H. Fan, J. R. Wu, and S. T. Wu, "Submillisecond response variable optical attenuator based on sheared polymer network liquid crystal," Opt. Express **12**(25), 6382–6389 (2004).
20. Y. Q. Lu, F. Du, Y. H. Lin, and S. T. Wu, "Variable optical attenuator based on polymer stabilized twisted nematic liquid crystal," Opt. Express **12**(7), 1221–1227 (2004).
21. F. Du, Y. Q. Lu, H. W. Ren, S. Gauza, and S. T. Wu, "Polymer-stabilized cholesteric liquid crystal for polarization-independent variable optical attenuator," Jpn. J. Appl. Phys. **43**(10), 7083–7086 (2004).
22. K. Y. Wu, J. Y. Liu, and Y. C. Chen, "Optical attenuator using polarization modulation and a feedback controller," U.S. patent 5,963,291 (October 5, 1999).
23. E. E. Bergmann, "Optical attenuator with combined polarization functions," U.S. patent 5,771,120 (June 23, 1998)
24. J. Yan and S. T. Wu, "Polymer-stabilized blue phase liquid crystals: a tutorial," Opt. Mater. Express **1**(8), 1527–1535 (2011).
25. J. Yan, M. Jiao, L. Rao, and S. T. Wu, "Direct measurement of electric-field-induced birefringence in a polymer-stabilized blue-phase liquid crystal composite," Opt. Express **18**(11), 11450–11455 (2010).
26. P. R. Gerber, "Electro-optical effects of a small-pitch blue-phase system," Mol. Cryst. Liq. Cryst. **116**(3-4), 197–206 (1985).
27. L. H. Rao, Z. B. Ge, S. Gauza, K. M. Chen, and S. T. Wu, "Emerging Liquid Crystal Displays Based on the Kerr Effect," Mol. Cryst. Liq. Cryst. **527**(1), 30–42 (2010).
28. Y. Chen, J. Yan, J. Sun, S. T. Wu, X. Liang, S. H. Liu, P. J. Hsieh, K. L. Cheng, and J. W. Shiu, "A microsecond-response polymer-stabilized blue phase liquid crystal," Appl. Phys. Lett. **99**(20), 201105 (2011).

1. Introduction

Recent years have witnessed the tremendous development of blue phase liquid crystals (BPLCs), a kind of special double-twisted chiral nematic LCs. The unique molecular structure endows BPLC with characteristics of quasi-optical isotropy, fast response and so on. Thanks to these properties, BPLCs are considered as promising candidates for next generation display and much effort has been devoted to optimize their performances [1–3].

The applications of BPLC are definitely not limited in display field. Conventional nematic LCs have already been widely used in photonic applications [4–9] for their advantages of low power consumption, compact size, simple fabrication, no moving parts and reliable performance. However, a major drawback is their relatively slow response. The employment of BPLC would be a great approach to overcome this problem. Moreover, other advantages such as good dark state and no need for phase compensation could also be expected. Most recently, several BPLC-based non-display applications have been demonstrated [10–18]. For instance, Lin *et al.* presented BPLC lens in 2010 [10] and tunable gratings based on BPLC were first proposed by Yan *et al.* [16]. Among all the photonic applications, Lin *et al.* demonstrated a BPLC FP filter which was first applicable in infrared range [15].

However, BPLC has not been employed in fiber-optic devices, which play an important role in the areas of telecommunication, sensing, integrated optics, etc. By taking the above advantages of BPLC, it is significant to introduce the material into fiber-optic applications. To present the applicability, herein we propose as an example a reflective type BPLC-based variable optical attenuator (VOA), one kind of useful device which has already been demonstrated through other LC modes, such as sheared polymer network LC [19], polymer-stabilized nematic [20] and cholesteric LC [21]. The BPLC VOA demonstrated here possesses the characteristics of fast response, no residual phase, high dynamic range and wide band application.

#182862 - $15.00 USD Received 4 Jan 2013; revised 5 Feb 2013; accepted 18 Feb 2013; published 25 Feb 2013

2. Principles and experiments

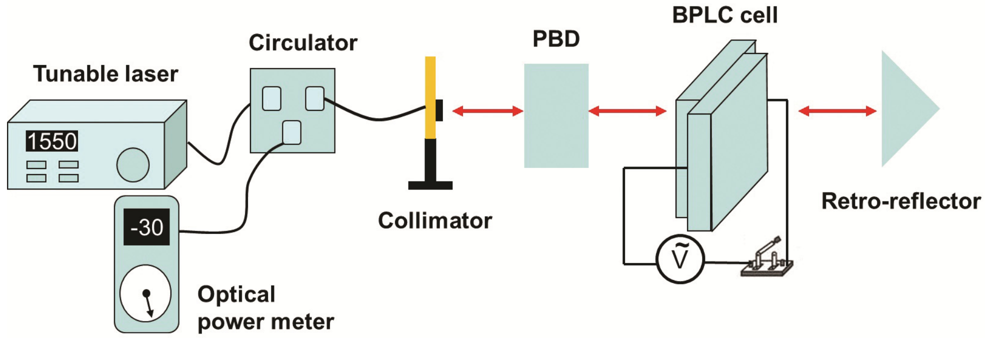

Fig. 1. The schematic setup of a BPLC-based VOA.

Figure 1 depicts the schematic setup of our BPLC-based VOA. Light beam from a tunable laser (λ = 1480-1550 nm) illuminates into a fiber-optical circulator then through a collimator, followed by a polarization beam displacer (PBD) and our BPLC cell. The system is a reflective type and the output light is collected by an optical power meter. Our design could be viewed as a folded version of typical LC VOAs [22, 23], making the device more compact with only half of the required phase retardation range. The cell operates at IPS mode with electrodes of 10 μm width separated by 10-μm gaps on one side. No alignment layers are settled and the cell gap is 9.5 μm. The cell is infiltrated with a mixture of 99.5 wt.% BPLC precursor (HCM-057, HCCH) and 0.5 wt.% photoinitiator (IRG-184). Then the precursor is UV-cured at an intensity of 5 mW/cm^2 for 6 minutes at 68 °C. After polymer stabilization, the BP range reaches over 70 degrees in the cooling (from 73.1 °C to below 0 °C). The cell was driven by 1 kHz square waves.

The principle of BPLC-based VOA is illustrated in Fig. 2. Being different from a sheet polarizer, the PBD just splits light into o-beam and e-beam rather than absorbs or drops any portion of the light. We set the direction of electrode stripes to be 45° to the polarizations of either o-rays or e-rays. Thus the BPLC cell acts as a tunable waveplate with its fast axis kept 45° to both o-beam and e-beam. At voltage-off state, BPLC shows quasi optical isotropy. Therefore no phase retardation occurs and the incident polarization direction would not be changed. As a result, the reflected light beam could not be coupled into the collimator, as shown in Fig. 2(a). This is the dark state of the VOA. When voltage is applied onto the cell, o-rays and e-rays face the same phase retardation within the cell after a roundtrip and position swap. Both beams experience the same attenuation rate depending on the phase retardation in BPLC. Thus the final light intensity collected back into the fiber is only controlled by the incident intensity and the applied voltage, while independent of the intensities of o-ray and e-ray respectively. As a result, our device shows polarization independency although a polarization selective beam splitter is used. When the cell is applied with a suitable voltage, the BPLC cell plays as a quarter-wave plate ($\delta = \pi/2$) to both o-rays and e-rays. Upon reflection from the retro-reflector, the total phase difference of the outgoing beams passing through the cell twice is π, therefore the polarization direction of the light beam rotated by 90°. Two retro-beams will go back to the collimator, as shown in Fig. 2(b). This is the bright state of the VOA. Between the bright and dark states, the output intensity could be continuously attenuated by applying different voltages.

#182862 - $15.00 USD Received 4 Jan 2013; revised 5 Feb 2013; accepted 18 Feb 2013; published 25 Feb 2013

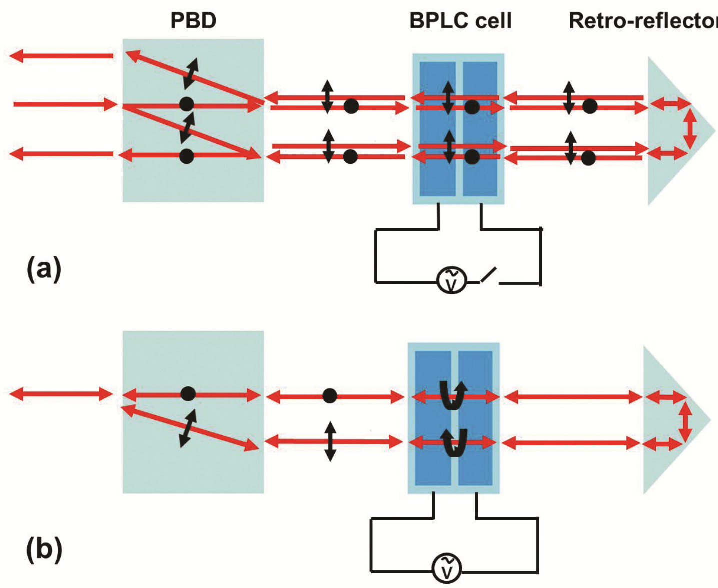

Fig. 2. The working principle of the BPLC-based VOA: (a) dark state (voltage-off) and (b) bright state (at saturation voltage).

3. Results and discussions

Figure 3 presents the voltage dependent attenuation recorded at $\lambda = 1550$ nm. The attenuation reduces as the voltage increases, resulting from the phase retardation caused by field-induced Kerr effect of BPLC. All the voltages given in this work are root-mean-square values. The attenuation changes continuously with applied voltages due to no threshold voltage existing in BPLC devices. We measured both rise and decay curves which match well with each other. The low hysteresis is mainly attributed to the weak field intensity applied [24]. The result suggests the component could be applied in traversable processes. At V = 37.5 V, the measured intensity reaches a maximum, which we set as 0 dB. From the above results, the Kerr constant of our BPLC is 1.87 nm/V^2 at 1550 nm and the attenuation range of the VOA is –29.2 dB. The quasi optical isotropy of BPLC results in no residual phase, permitting a good dark state and a wide attenuation range. However, the improvement on attenuation range is not satisfying compared with that of VOAs employing common nematic materials [8]. The limited improvement may be attributed to three aspects. First, the whole setup contains many interfaces with no coating, causing certain reflection; second, scattering of BPLC still exists, though less severe than that in visible range; third, dead zones induced by the IPS mode decrease the optical efficiency. To address the above issues, several approaches are applicable, including antireflection treatment on interfaces, well-packaging, material optimization and employing uniform applied field [25].

#182862 - $15.00 USD Received 4 Jan 2013; revised 5 Feb 2013; accepted 18 Feb 2013; published 25 Feb 2013

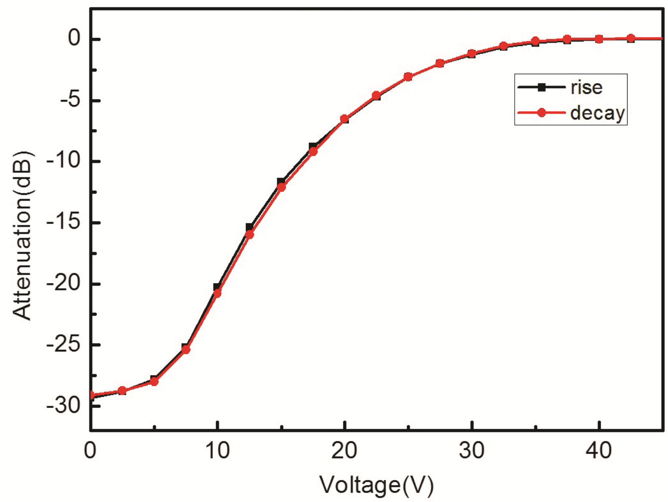

Fig. 3. The voltage dependent attenuation at λ = 1550 nm of both rise and decay processes.

We measured the response (both rise and decay) time at different applied voltages at λ = 1550 nm. The results are given in Table 1. T_{rise} and T_{decay} are defined as 10% to 90% of optical intensity and the reverse. All data are in the unit of submillisecond. The rise time decreases as the voltage increase due to the larger force generated under stronger electric field. However, the decay time almost has no changes, for it is only determined by the intrinsic properties of material [26, 27]. Through further optimization of BPLC materials, response time down to 10 μs is achievable [28]. The fast response permits the proposed component being widely applied in telecommunication.

Table 1. Rise and Decay Time at Different Applied Voltages at λ = 1550 nm

Voltage/V_{rms}	14	20	25	30	35	40	45
T_{rise} /ms	0.50	0.40	0.35	0.30	0.30	0.30	0.25
T_{decay} /ms	0.65	0.70	0.65	0.65	0.70	0.70	0.70

For fiber-optic applications, it is highly desirable if the VOA has a broad bandwidth over the whole spectral range. To study the wavelength-dependent attenuation performance of our VOA, we chose 5 specific attenuation values: −5 dB, −10 dB, −15 dB, −20 dB and −25 dB and figured out the corresponding voltages to these values at 1550 nm. Then we set the voltages unchanged and measured the attenuation variation at the wavelengths from 1480 nm to 1550 nm. Figure 4 shows the wavelength-dependent attenuation of the proposed VOA. The attenuation flatness is 0.11 dB, 0.17 dB, 0.26 dB, 0.32 dB and 0.38 dB, respectively. We attribute the reason for a little discrepancy of each curve to two aspects: one is output voltage fluctuation especially at low voltages and the other is noise, such as background light and the circulator's crosstalk between the input and returning output port. All above issues could be properly addressed in industrial fabrication processes, which are much more accurate than laboratory techniques.

#182862 - $15.00 USD Received 4 Jan 2013; revised 5 Feb 2013; accepted 18 Feb 2013; published 25 Feb 2013

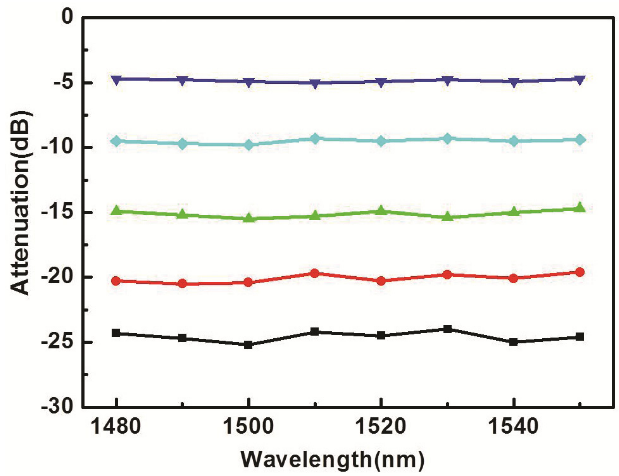

Fig. 4. Spectral response from 1480 nm to 1550 nm of a BPLC based intensity modulator. Different curves correspond to different attenuations states.

By taking the proposed VOA as an example, the applicability of BPLC based fiber-optic devices is presented. The introduction of BPLC may impel the development of many photonic applications, from telecommunication to sensing, covering infrared to THz and even microwave regions.

4. Conclusion

In summary, we introduced BPLC into fiber-optics and a fast response VOA is demonstrated as an example. A large dynamic range over −29 dB is achieved at a comparatively low operation voltage of 37.5 V_{rms}. All data of rise and decay time at different attenuation values are in submilisecond range. The proposed VOA has a broad bandwidth over 1480 to 1550 nm with attenuation flatness less than 0.4 dB. This may open the door to wide applications in fiber-optics with fast response.

Acknowledgments

The authors thank the constructive discussions from Dr. Zhi-gang Zheng and Dr. Hong-qing Cui. This work is sponsored by 973 programs with contract No. 2011CBA00200 and 2012CB921803, National Science Fund for Distinguished Young Scholars with contract No. 61225026, Research Fund for the Doctoral Program of Higher Education of China with contract No. 20120091120020. The authors also thank the supports from PAPD and Fundamental Research Funds for the Central Universities. Correspondences about this paper should be addressed to Dr. Wei Hu or Prof. Yan-qing Lu.