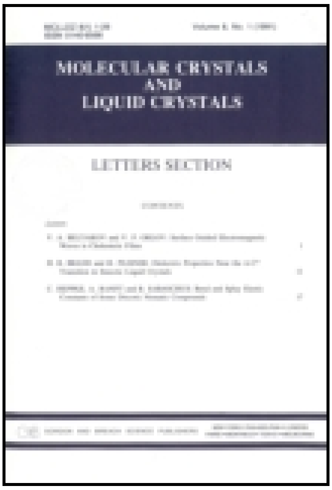


Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl20

# Tri-Stable Polarization Switching of Fluorescent Light Using Photo-Luminescent Cholesteric Liquid Crystals

Suk-Hwan Joo[a], Jang-Kyum Kim[ab], Hoon Kim[b], Ki-Chul Shin[b], Heesub Kim[b] & Jang-Kun Song[a]

[a] School of Electronic & Electrical Engineering, Sungkyunkwan University, Suwon, Republic of Korea

[b] R&D Centre, Samsung Display Co., Ltd, Yongin-City, Gyeonggi-do, Republic of Korea
Published online: 06 Dec 2014.

To cite this article: Suk-Hwan Joo, Jang-Kyum Kim, Hoon Kim, Ki-Chul Shin, Heesub Kim & Jang-Kun Song (2014) Tri-Stable Polarization Switching of Fluorescent Light Using Photo-Luminescent Cholesteric Liquid Crystals, Molecular Crystals and Liquid Crystals, 601:1, 29-35, DOI: 10.1080/15421406.2014.940489

To link to this article: http://dx.doi.org/10.1080/15421406.2014.940489

*Mol. Cryst. Liq. Cryst.*, Vol. 601: pp. 29–35, 2014

ISSN: 1542-1406 print/1563-5287 online
DOI: 10.1080/15421406.2014.940489

Taylor & Francis
Taylor & Francis Group

# Tri-Stable Polarization Switching of Fluorescent Light Using Photo-Luminescent Cholesteric Liquid Crystals

SUK-HWAN JOO,[1] JANG-KYUM KIM,[1,2] HOON KIM,[2] KI-CHUL SHIN,[2] HEESUB KIM,[2] AND JANG-KUN SONG[1,*]

[1]School of Electronic & Electrical Engineering, Sungkyunkwan University, Suwon, Republic of Korea
[2]R&D Centre, Samsung Display Co., Ltd, Yongin-City, Gyeonggi-do, Republic of Korea



*Using a photo-luminescent cholesteric liquid crystal (PL-CLC) cell, tri-stable electro-optic switching behaviour was demonstrated. Stable planar, uniformly lying helix (ULH), and focal conic states were obtained at an electric field of zero after applying proper electric signals corresponding to each state. When a PL-CLC cell was placed on a ultraviolet (UV) back-light, the cell emitted fluorescent light with different types of polarization corresponding to the liquid crystal (LC) state: the planar, ULH, and focal conic states emitted circularly polarized light, linearly polarized light, and un-polarized light, respectively. Hence, the proposed PL-CLC cell worked as a tri-stable polarization-switching light source. We also demonstrated that the PL-CLC cell can be used to fabricate a bistable fluorescent LC device.*

**Keywords** Cholesteric liquid crystals; fluorescence; light polarization; light sources; liquid crystal devices; molecular orientation; optical tuning; photoluminescence

## I. Introduction

Since natural light is un-polarized, polarized light can be obtained only by using a polarization-converter called a ‘polarizer’. A polarizer is an essential component in numerous optical applications including liquid crystal (LC) displays and organic light-emitting diode displays [1]. A polarizer converts the polarization of light once light has been generated from a light source. In particular, a LC layer is a controllable birefringence material, which can actively change the polarization of light that passes through the LC layer [2, 3]. Thus, the polarization conversion of light is an easy way to achieve polarized light and is widely used in various optical applications.

On the other hand, a light source that emits intrinsic polarized light is rare, and only a few light sources that emit polarized light have been reported [4–14]. Unlike the polarization converter, a polarized light source provides polarized light without the aid of

*Address correspondence to Prof. Jang-Kun Song, School of Electronic & Electrical Engineering, Sungkyunkwan University, Suwon, Republic of Korea. Tel.: (+82)31-299-4599. Fax: (+82)50-302-0912; E-mail: jk.song@skku.edu

Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/gmcl.

any other optical component. Sariciftci *et al.* and Chen *et al.* reported that linearly polarized light and circularly polarized light are emitted from planar nematic LCs and cholesteric LCs doped by photoluminescence (PL) molecules, respectively [4, 6, 10]. They showed that the polarization of fluorescent light emitted from the PL-doped LC medium is sensitively influenced by the PL molecular orientation and the photonic bandgap of the medium. However, the PL-doped LC mediums that they used emitted only one type of polarized light [5, 15].

Recently, we demonstrated a method to control the polarization of light emitted from a fluorescent layer by controlling the molecular orientation and the photonic bandgap of the medium [16]. By electrically controlling the molecular orientation, we were able to selectively produce linearly polarized light, circularly polarized light, un-polarized light, and partially polarized light from a single photo-luminescent cholesteric liquid crystal (PL-CLC) cell having interdigitated electrodes. We showed that not only the type of polarization but also the degree of polarization can be readily controlled in the cell, where the tunable polarization of fluorescent light was achieved by applying particular corresponding electric fields in a cell containing interdigitated electrodes. However, the obtained polarization of light in the cell was not sustained when the applied electric field was removed.

In this paper, we demonstrate an alternative way to control the polarization of fluorescent light by switching among a planar alignment, a uniformly lying helix (ULH) alignment [17], and a focal conic alignment in a PL-CLC cell. Unlike our previous work, the alternative method we used in the study provides three stable polarizations that are sustained even after the electric fields are removed. Therefore, it is possible to achieve three stable fluorescent light sources with different polarizations. The light source with tunable polarization may be used in various optical applications such as displays, optical devices, and light sources for optical instruments.



## II. Experimental

A PL-CLC mixture consists of a host nematic LC (ZSM0000, Merck Company, Germany) with positive dielectric anisotropy and 30 wt% of chiral dopant (R-811, Merck Company, Germany), and 0.5 wt% of PL dopant (coumarin6 (C6), Sigma-Aldrich Corporation, USA) [18]. The optical pitch of the helix of the PL-CLC sample was about 515 nm, giving rise to spectral reflectance within the corresponding photonic band-gap, which roughly coincides with the peak wavelength of the fluorescent light of C6, as shown in Fig. 1. Here, the optical pitch is defined as pitch ($p$) $\times$ average refractive index ($(n_e + n_o)/2$), where $n_e$ and $n_o$ are the refractive indices of extraordinary and ordinary axes, respectively. The molecular shape of C6 is similar to calamitic LCs; we confirmed that the molecular long axis of C6 molecules aligns well along the director of the host LCs by measuring the order parameter of the molecular transition dipole moment of C6 for a planar cell in our previous work [16]. A pair of substrates that have a square indium tin oxide (ITO) electrode and a planar alignment layer were prepared. The substrates were rubbed and assembled to be antiparallel to each other. A PL-CLC cell with a thickness of 4 um was fabricated and the PL-CLC mixture was injected into the cell.

The spectral measurement of the fluorescent light from the cell was performed by using a spectrometer (SV-2100, K-Mac Company, Korea) after placing the cell on top of a UV lamp (0.1 mW/cm$^2$) with a peak wavelength of 365 nm (Fig. 2). In order to measure the degree of linear or circular polarization of the fluorescent light from the sample, a rotating linear polarizer or a rotating circular polarizer was placed between the cell and the detector, respectively, as shown in Fig. 2. The circular polarizer consisted of a linear polarizer and a

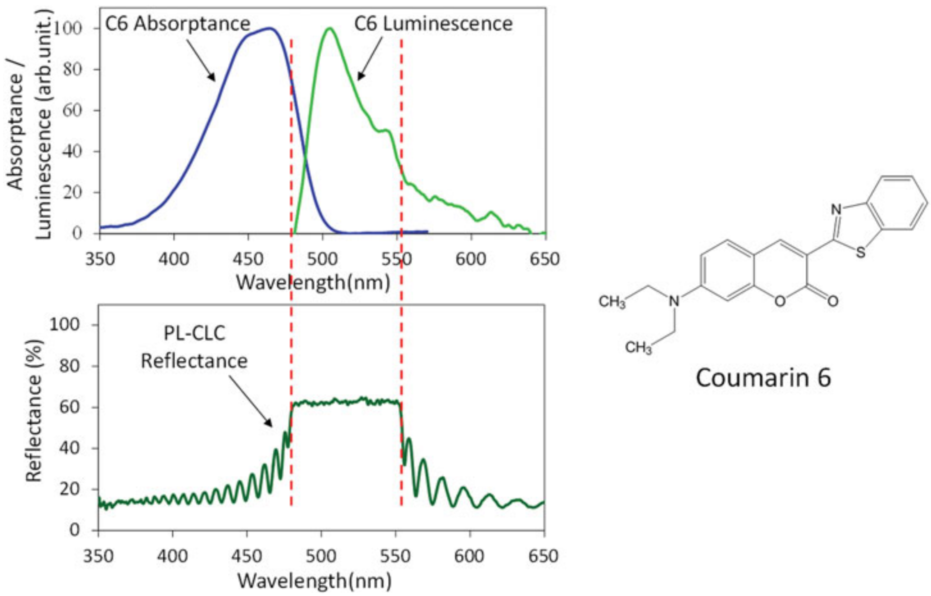


**Figure 1.** The molecular structure of C6 (right) and its absorptance and luminescent spectra (top left). The Bragg reflection spectrum of the PL-CLC cell used in this study (bottom left).

quarter wave plate; by rotating the linear polarizer, one can measure the degree of circular polarization.

## III. Tri-Stable Switching of PL-CLC Cell

The fabricated PL-CLC cell initially exhibited a quality planar helicoidal alignment. The planar alignment was well observed under polarized optical microscopic (POM) observation, as shown in Fig. 2(a).

Recently, Wang *et al.* reported that a stable ULH structure could be obtained by applying a low frequency electric field in a cell containing CLC with a positive dielectric anisotropy, and that the field-induced ULH was stably sustained even after removing the electric fields [17]. We followed a similar procedure to obtain a quality ULH state. We applied 30 Hz with 20 V in the cell, which caused electro-hydrodynamic flow in the cell [19]. The electro-hydrodynamic circulation was well indicated in the POM observation. When we slowly reduced the amplitude of the voltage down to zero, the electro-hydrodynamic flow stopped and the uniform ULH state stably settled down. The ULH alignment was confirmed by observing the cell under crossed polarizers. When the rubbing direction is parallel to the polarizer axis, the cell appears dark, and when cell is rotated 45 degrees, the cell becomes bright. This was observed in both microscopically and macroscopically, as shown in Fig. 2(b). The uniform ULH state was sustained as long as there were no imposing external stimuli such as finger pressure or electric fields, which easily broke the ULH alignment.

Uniform planar alignment was readily regained by applying a high voltage (30 V) for inducing a homeotropic state, and then promptly removing the voltage. An alternative way to obtain a planar state was with finger pressure, that is, by pressing a cell with a finger, any state became a planar state.

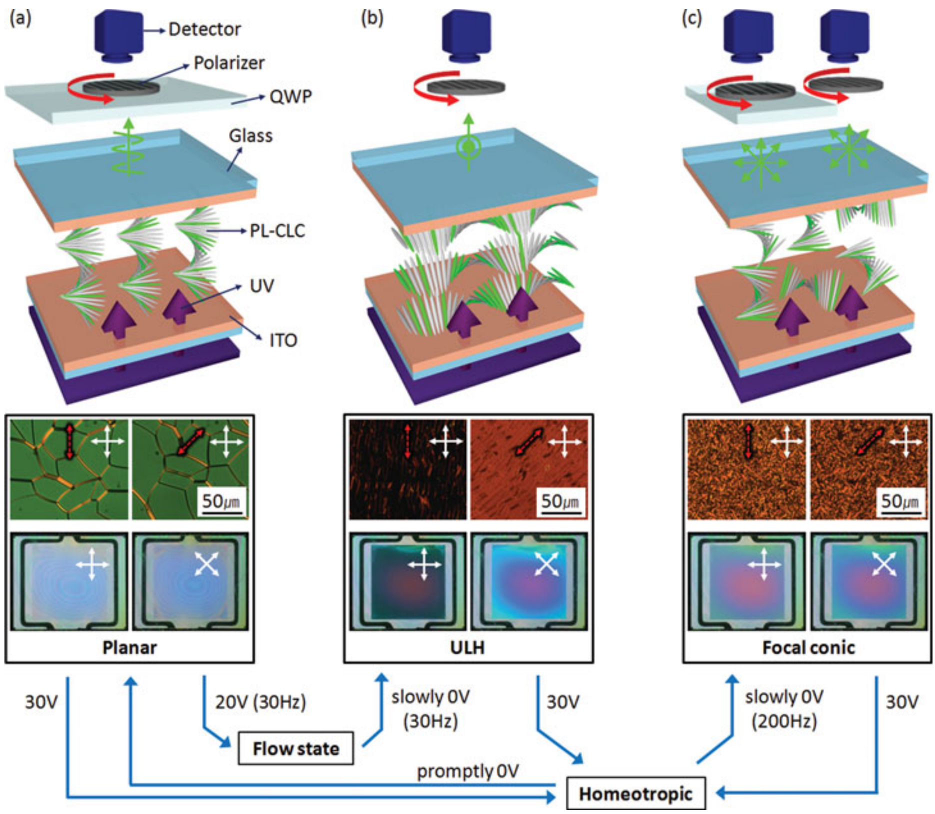


**Figure 2.** (a) A planar state of a PL-CLC cell and its polarized optical microscopic (POM) image and macroscopic images with rotating polarizers (the solid arrows indicate the axes of the polarizers and the dotted arrow indicates the rubbing direction.) (b) A ULH state and its POM and macroscopic images, (c) a focal conic state and its POM and macroscopic images.

When the applied voltage had a high frequency (200 Hz) and middle voltage (20 V), a focal conic state with random orientation was obtained; the focal conic state was sustained when the field was promptly removed (Fig. 2(c)). In this way, we could obtain three stable states: a planar helicoidal state, a ULH state, and a focal conic state, all of which were stable at an electric field equal to zero.

## IV. Tri-Stable Switching of Polarization of Fluorescence

The fluorescent spectra for each state of the cell were measured under rotating crossed polarizers; the results are shown in Fig. 3. In the planar state, a circular polarizer that consists of a linear polarizer and a quarter wave plate was inserted between the cell and the detector, as shown in Fig. 2(a). The spectral peak changes with the rotation of the linear polarizer of the circular polarizer, and the maximum and minimum peaks appear when the angle between the polarizer and the quarter wave plate is – 45 and + 45 degrees, respectively. This implies that the fluorescent light from the planar helicoidal state is left-circularly polarized. Meanwhile, the fluorescent spectra from the ULH state vary when a linear polarizer is rotated as shown in Fig. 3, which confirms that the fluorescent light

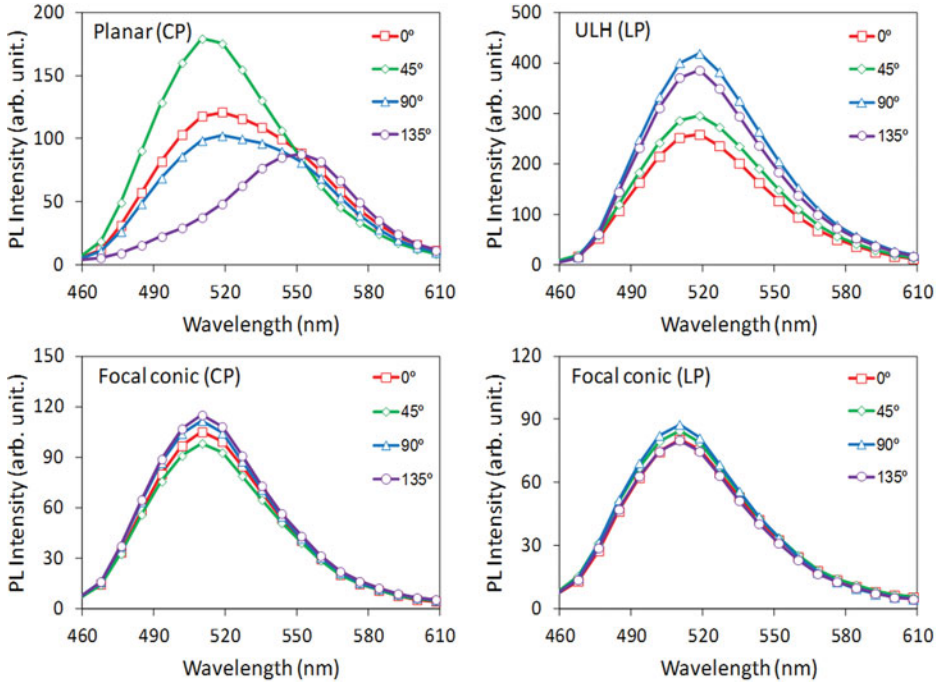


**Figure 3.** The spectra of a PL-CLC cell with rotating polarizers in a planar state (a), in a ULH state (b), and in a focal conic state (c) and (d). The abbreviations CP and LP represent the circular polarizer and linear polarizer, respectively (see the illustration of Fig. 2(a) and (b)).

from the ULH state is linearly polarized. For the focal conic state, the fluorescent spectrum did not change when a circular polarizer or a linear polarizer rotated, indicating that the fluorescent light from the focal conic state is unpolarized.

The degree of polarization for each state of the cell was measured. The degree of linear polarization ($P_{LP}$) was calculated using the light intensities of horizontal-linear polarization ($I_{HLP}$) and of vertical-linear polarization ($I_{VLP}$), as shown in Eq. (1). Similarly, the degree of circular polarization ($P_{CP}$) was calculated using the light intensities of left-circular polarization ($I_{LCP}$) and of right-circular polarization ($I_{RCP}$).

$$P_{LP} = \frac{I_{HLP} - I_{VLP}}{I_{HLP} + I_{VLP}}, \text{ and } P_{CP} = \frac{I_{LCP} - I_{RCP}}{I_{LCP} + I_{RCP}} \tag{1}$$

The results are shown in Fig. 4. In the planar alignment, the cell emitted a strong circularly polarized light, as expected. The degree of circular polarization was about 0.7. In the ULH state, the cell emitted a linearly polarized light. The degree of linear polarization was about 0.25. In our previous work, we obtained a linearly polarized light with a degree of polarization of 0.45 in the field induced unwound state [16]. Compared to the results, the degree of polarization of the ULH state was about 55%. This is because the molecules in the ULH state distribute helicoidally with the helical axis parallel to the rubbing direction, which means that roughly half of the molecules align vertically rather than planarly, whereas most of the molecules align homogeneously along the electric field direction in the cell with the interdigitated electrodes used in our previous work. In the focal conic state, the degree of polarization was almost zero.

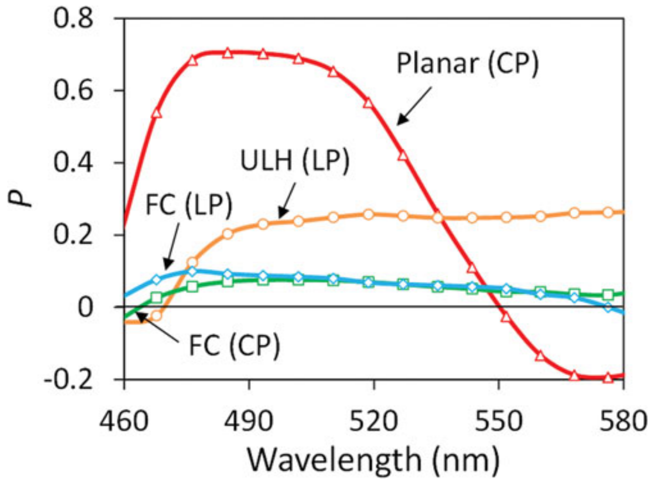


**Figure 4.** The calculated degrees of polarization with respect to the wavelength in the planar, ULH, and focal conic states. FC indicates focal conic state.



By using the polarization switching behaviour of the PL-CLC cell, a bistable fluorescence cell was fabricated. A right-handed circular polarizer, which consists for a linear polarizer and a quarter-wave plate, was attached to a PL-CLC cell. The cell was placed on a UV light. Initially, the cell was in a planar state and emitted a left-handed circularly polarized fluorescence. The fluorescent light was absorbed by the circular polarizer, and the cell appeared dark as shown in Fig. 5. By applying 20 V of electric voltage with 30 Hz frequency temporally, the cell transits into a ULH state, which emits a linearly polarized light. The linearly polarized fluorescent light can pass through the circular polarizer, and the ULH state appeared bright as shown in Fig. 5. The two states were stable at a zero field state. Thus, the bistable fluorescent LC device was successfully fabricated.

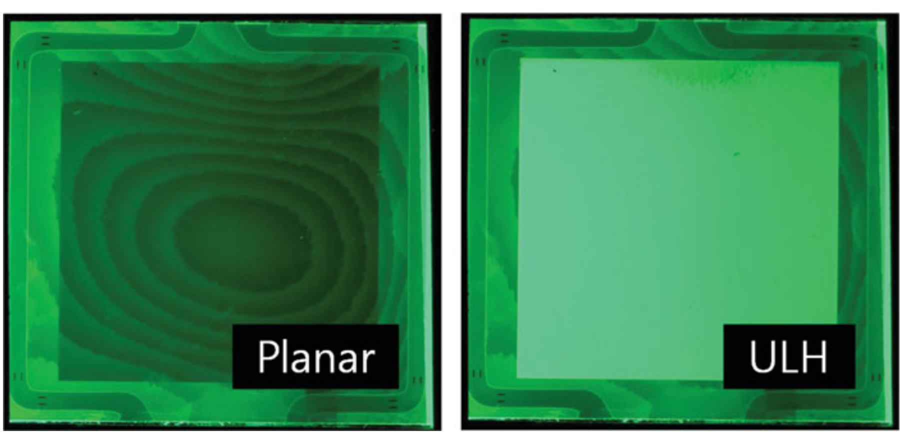


**Figure 5.** Bistable fluorescent electro-optic device. A left-handed circular polarizer was attached to a PL-CLC cell, and the cell was placed on a UV back-light unit. The cell appeared dark in a planar state (left), and it appeared bright in a ULH state (right).

## V. Conclusion

We demonstrated that three stable fluorescent switches were achieved in a PL-CLC cell, where a stable planar state, ULH state and focal conic state were obtained by applying proper electric fields. The three states were stably obtained when the electric field was removed. Each state emits a different state of polarization: the planar state emits a circularly polarized light, the ULH state emits a linearly polarized light, and the focal conic state emits an un-polarized light. Thus, the proposed PL-CLC cell worked as a tri-stable polarization-switching light source. We also demonstrated that the PL-CLC cell can be used to fabricate a bistable fluorescent LC device.

## Funding

We thank Samsung Display Company and Merck Company for providing materials and financial support for this study. This work was also supported by the National Research Foundation of Korea (NRF), and grant funded by the Korea government (MSIP) (No. 2012R1A1A1012167) and by the IT R&D program of MKE/KEIT (No.10041596).

## References

[1] Kim, K.-H., & Song, J.-K. (2009). *NPG Asia Mater.*, *1*, 29.
[2] Born, M., & Wolf, E. (1999). *Priciples of Optics*, Cambridge University Press: UK.
[3] Stalder, M., & Schadt, M. (1996). *Opt. Lett.*, *21*, 1948.
[4] Sariciftci, N. S., Lemmer, U., Vacar, D., Heeger, A. J., & Janssen, R. A. J. (1996). *Adv. Mater.*, *8*, 651.
[5] Weder, C., Sarwa, C., Montali, A., Bastiaansen, G., & Smith, P. (1998). *Science*, *279*, 835.
[6] Chen, S. H., Katsis, D., Schmid, A. W., Mastrangelo, J. C., Tsutsui, T., & Blanton, T. N. (1999). *Nature*, *397*, 506.
[7] Grell, M., & Bradley, D. D. C. (1999). *Adv. Mater.*, *11*, 895.
[8] Contoret, A. E. A., Farrar, S. R., Jackson, P. O., Khan, S. M., May, L., O'Neill, M., Nicholls, J. E., Kelly, S. M., & Richards, G. J. (2000). *Adv. Mater.*, *12*, 971.
[9] O'Neill, M., & Kelly, S. M. (2003). *Adv. Mater.*, *15*, 1135.
[10] Woon, K. L., O'Neill, M., Richards, G. J., Aldred, M. P., Kelly, S. M., & Fox, A. M. (2003). *Adv. Mater.*, *15*, 1555.
[11] Yamaguchi, R., Nagato, H., Hafiz, H., & Sato, S. (2004). *Mol. Cryst. Liq. Cryst.*, *410*, 495.
[12] Sagara, Y., & Kato, T. (2008). *Angew. Chem. Int. Ed.*, *47*, 5175.
[13] Tong, X., Zhao, Y., An, B.-K., & Park, S. Y. (2006). *Adv. Funct. Mater.*, *16*, 1799.
[14] Salamonczyk, M., Kovarova, A., Svoboda, J., Pociecha, D., & Gorecka, E. (2009). *Appl. Phys. Lett.*, *95*, 171901.
[15] Montali, A., Bastiaansen, G., Smith, P., & Weder, C. (1998). *Nature*, *392*, 261.
[16] Joo, S.-H., Kim, J.-K., & Song, J.-K. (2013). *J. Appl. Phys.*, *114*, 083508.
[17] Wang, C.-T., Wang, W.-Y., & Lin, T.-H. (2011). *Appl. Phys. Lett.*, *99*, 041108.
[18] Kim, J.-K., Joo, S.-H., & Song, J.-K. (2013). *Opt. Express*, *21*, 6243.
[19] Blinov, L. M., & Chigrinov, V. G. (1994). *Electrooptic Effects in Liquid Crystal Materials*, Springer: New York.