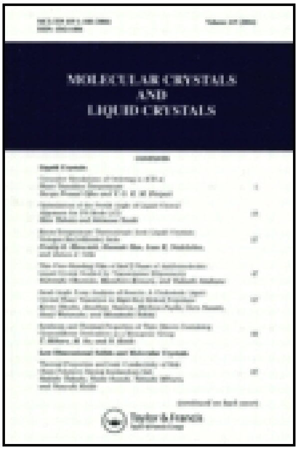

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Polarization Imaging Components Based on Patterned Photoalignment

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The photoalignment technique was used for creating liquid crystal (LC) and LC polymer based polarization imaging components comprising areas of different orientation of optical axis. We discuss applications of such components for visualization of the state of polarization of a light beam and for producing microlens arrays. We used the technique also for producing patterns of cholesteric LCs (CLCs) with different azimuthal anchoring angle at the cell boundaries. The interface between different orientation states prove visible when viewed from the side of patterned orientation and they are invisible from the side of homogeneous planar orientation of the CLC.

Keywords: imaging; liquid crystals; microlens arrays; patterned cholesterics; photoalignment; spectral polarizers

1. INTRODUCTION

The photoalignment technique [1–6] developed with the main purpose of replacing mechanical buffing of liquid crystal display (LCD) substrates has found important applications in photonics due to the opportunity it provides for producing micropatterned orientation structures [7–12]. In the present work we have used commercially available photoaligning materials for producing optical components that could present interest for polarization imaging applications. Unique opportunities provided by the photoalignment technique for such applications were explored by the pioneers in this field still in the early stages of developments [13–15].

In this work we used linear photopolymerizable polymer (LPP) ROP-203 (Rolic Ltd.). It was spin coated on glass substrates at

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3000 rpm during 60 sec. The substrates were then dried for 10 min at $T = 150$–180°C to remove residual solvent. Finally, the substrates were exposed to linearly polarized UV light ($\lambda = 365$ nm) with 10–100 mJ/cm^2 exposure energy density before being used for LC prepolymer (LCP) coatings or for making LC cells.

2. OPTICAL COMPONENTS COMPRISING AREAS OF TRANSMISSION MODULATION

In case the photoalignment layer is not treated by a polarized UV radiation, the LCP coating becomes randomly oriented [16] and forms diffuse light scattering layer allowing recording of transmission modulation patterns with high spatial resolution. Figure 1 shows a photo of such a polymer film with the imprint of a resolution target. The imprint was obtained by exposing the photoalignment layer to polarized UV radiation through the resolution target positioned on the glass substrate. It was then coated with LCP ROF-5102 and photopolymerized under Nitrogen atmosphere for 10 min. This procedure allowed transforming the patterned structure of the original resolution target onto the polymer film. The dark areas in Figure 1 correspond to aligned and transparent areas of LCP observed through crossed polarizers. The surrounding white areas correspond to diffuse light scattering areas of nonaligned LCP.

Orientation patterns on homogeneous transparent background are obtained using azodye photoalignment materials [17]. Light scattering material structures in conjunction with photoalignment processes

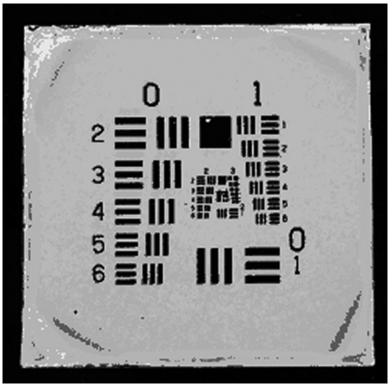


FIGURE 1 LCP film obtained on a photoalignment layer treated by a linear polarized UV light through a resolution target. The photo is taken with the substrate between crossed polarizers.

were studied earlier in [18,19]. As shown in [19], light scattering from CLC textures on photoalignment layers with different radiation treatment conditions exhibit a contrast between untreated areas and areas subject to UV radiation, however, for CLCs, strong light scattering is present in all cases reducing the contrast.

3. POLARIZATION IMAGING COMPONENT COMPRISING AREAS OF DIFFERENT OPTICAL AXIS ORIENTATION

The patterns of LC orientation were obtained by exposing different areas of substrates to UV light polarized at different angles. Figure 2(a) shows the schematic of a cell made of two substrates each treated with a photoalignment layer. One of them, the input substrate of the cell for a light beam, induces spatially homogeneous planar orientation, while the second substrate is split into three areas inducing different orientation directions of LC.

A LC cell made of such substrates contains areas with planar, 45° twist, and with 90° twist orientation. The polarization of a light beam linearly polarized along the LC orientation at the input substrate does not change when propagating through the planar area. It rotates by 45° when propagating through the 45° twist area, and rotates by 90° when propagating through the 90° twist area, Figure 2(b).

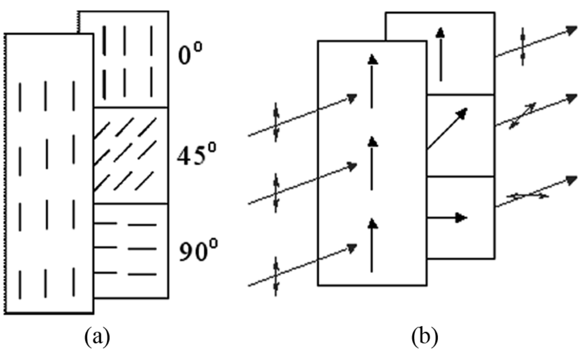


FIGURE 2 (a) Schematic presentation of the substrates of a LC cell treated with a photoalignment layer for inducing spatially homogeneous planar alignment on one of the substrates and LC orientation at 0°, 45°, and 90° on the second substrate. (b) Propagation of a light beam through a LC cell with three different states of orientation. The incident beam is linearly polarized along the LC orientation at the input substrate. The polarization of the output beam may have three different states.

Attaching a polarizer at the output substrate transforms such a cell into an optical component that allows to easily determine the state of polarization of a light beam. In case the input polarization is parallel to the polarizer axis which, for certainty, we may assume to be parallel to the LC orientation at the input substrate, we obtain high transmission in the area of planar orientation of the LC, lower transmission in the 45° twist area, and no transmission in the 90° twist area, Figure 3(a). In case the input polarization is perpendicular to the polarizer axis, we obtain high transmission in the 90° twist area and no transmission in the planar orientation of the LC (0° twist), Figure 3(b). The transmission is homogeneous over the whole area of the cell in case of unpolarized or circularly polarized beams. This system can straightforwardly be modified for distinguishing between the unpolarized and circularly polarized beams as well, and for quantitative characterization of the state of polarization of light beams in a single image acquired, particularly, by a CCD camera [20].

Figure 4 shows a realization of the polarization test device discussed in Figure 3. Large variety of phase modulating LC structures can be produced for different polarization imaging needs using substrates capable of enforcing different orientation patterns, stepwise or smoothly varying along the LC cell [7,11]. A two or multidomain cell could be used for this application as well. Note that similar functionality could

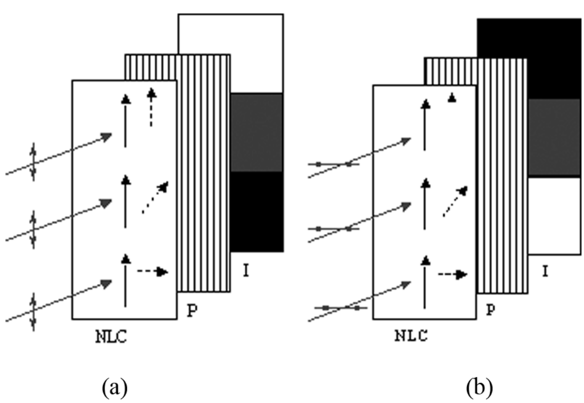


FIGURE 3 Schematic representation of polarimetric function of a LC cell with different polarization rotating sections and a polarizer at its output. Solid and dashed arrows show the nematic LC (NLC) orientation at the input and output substrate, correspondingly; P is the polarizer; I – the image obtained at the output of the cell; (a) and (b) correspond to vertical and horizontal input polarizations of the light.

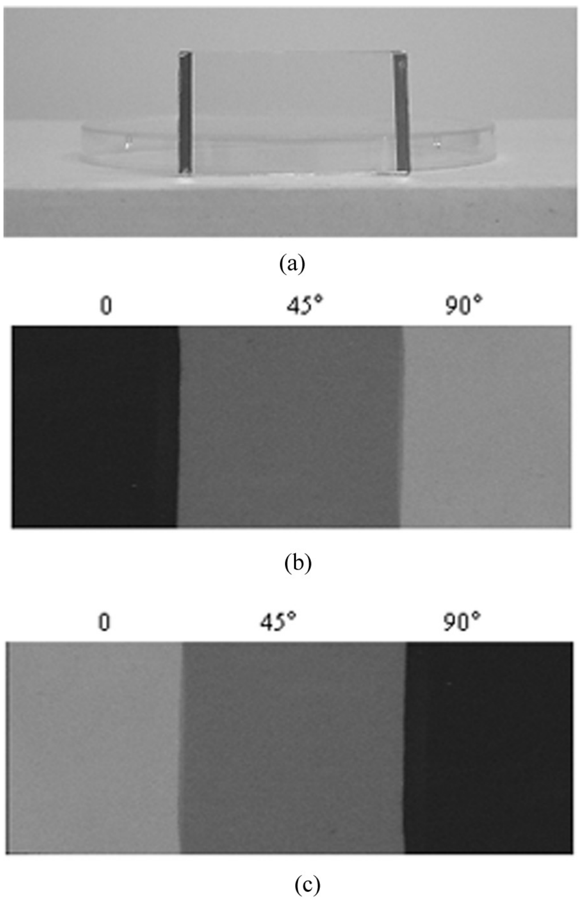


FIGURE 4 Photos of the LC cell containing areas with different twist angles, 0°, 45°, and 90°: (a) no polarizers; (b) between crossed polarizers and polarization of a beam parallel to the LC orientation at the input substrate; (c) between crossed polarizers and polarization of a beam perpendicular to the LC orientation at the input substrate.

be obtained with LCP instead of a LC cell, by producing areas with different orientation of the optical axis of the LCP [11]. The polarization images obtained in such a structure will depend, however, on wavelength. More complex orientation structures that allow to convert a linearly polarized light into axially symmetric distribution [13] may provide additional opportunities for the purposes of detection and characterization of polarization state of light beams.

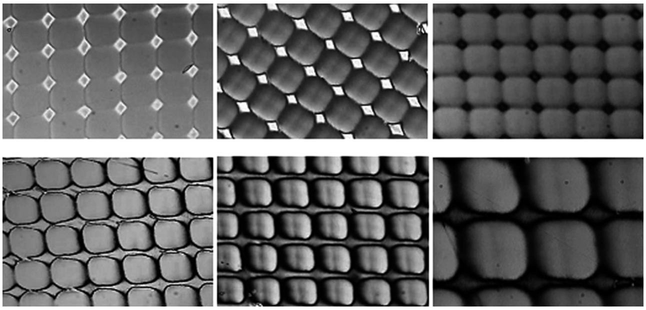


FIGURE 5 Microlens arrays recorded in a photoaligned LC cell. Photos are taken under microscope in-between crossed polarizers, under differing imaging conditions. The approximate size of a microlens is $\sim 40\,\mu m$.

4. RECORDING OF LC MICROLENS ARRAYS

The technique of photoaligning could be used to produce microlens arrays in LC cells as shown in Figure 5. The array was made by preparing a LC cell using a nematic LC between substrates containing photoalignment layers and subjecting the cell to a polarized UV radiation through a mask of $40\,\mu m$ mesh size. This results in spatial modulation of orientation condition and smooth periodic modulation of the LC orientation seen in Figure 5.

5. SPECTRALLY SELECTIVE POLARIZERS

A thin layer of highly dichroic LC oriented between glass substrates that enforces homogeneous planar orientation of the LC acts as a polarizer. Showing contrast ratio as high as conventional polymer polarizers, Figure 6, the LC cell has the advantage of being switchable between polarizing and non-polarizing optical states. For the red wavelength of a He–Ne laser beam, $\lambda = 633\,nm$, the contrast ratio of the LC polarizer proves to be 153.

Using a highly dichroic LC one can produce a polarizer patterned to comprise different directions of optical axis orientation. Such polarizers appear very promising for imaging applications [21]. Figure 7 shows photos of such a patterned polarizer. Patterned broadband polarizers were demonstrated in [22,23] using photoalignment of chromonic lyotropic LC dyes. *In situ* photopolymerization of reactive LC was used in [24] for producing thin high efficiency guest-host polarizers and patterning them using photoalignment techniques.

Dyes with high dichroic ratio can be used as dopants to the LCP material for obtaining polarizing action in different parts of the

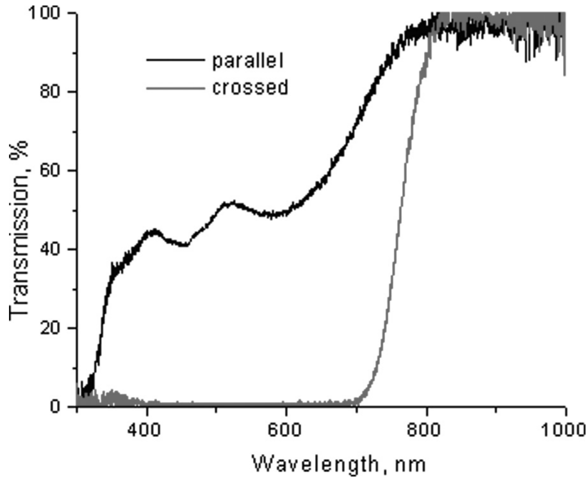
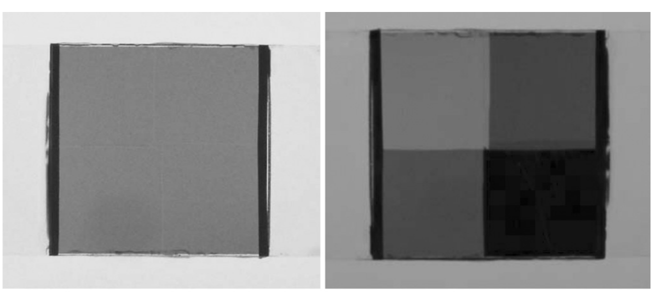


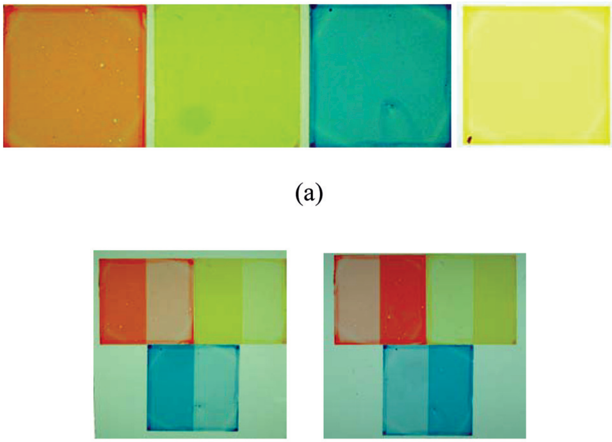
FIGURE 6 Transmission of LC polarizer for parallel and crossed polarization.

spectrum [7,25]. Photos of polarizing films based on different dichroic antraquinone dyes are shown in Figure 8(a). Each film consists of two areas with orientation of the optical axis orthogonal to each other, Figures 8(b) and (c). The contrast of the films could be enhanced by multiple coatings of the LCP material, however, at the expense of reduced transmission. Similar polarizing color films were prepared using luminescent dyes. Transmission spectra of several spectrally selective polarizers for different states of light polarization along with the spectra of their polarization ratio are shown in Figure 9.



(a) (b)

FIGURE 7 A liquid crystal polarizer comprising four sections with polarizer axis directions at 0°, 45°, 90°, and −45°. Photos are taken (a) without a polarizer and (b) with a polarizer.



(a) (b) (c)

FIGURE 8 Photos of spectrally selective polarizer films: orange, yellow, blue, and luminescent yellow. Images are taken with no polarizer (a), and with a polarizer parallel (b) and perpendicular (c) to the optical axis.

6. PHOTOPATTERNED CLC CELLS

Patterning with the aid of photoalignment was used for CLCs in [11] for producing security devices. Photoalignment of commercial cholesteric mixtures on photosensitive polymer materials was studied in detail in [19] with the main purpose of characterizing the effect of the exposure dose and polarization of radiation. The quality of CLC alignment was found to be noticeably different in non-irradiated areas compared to radiated with polarized as well as with unpolarized light. Periodic-planar and homeotropic anchoring conditions were used for obtaining a uniform lying helix alignment for short pitch CLCs [26]. The photoalignment technique using oblique illumination with nonpolarized light was shown to produce homogeneous alignment of CLC axis in the fingerprint textures [27,28]. Spatial modulation of the helical twisting power by subjecting chiral photoisomerizable nematic LCs to spatially modulated UV radiation was suggested as a method of producing patterned birefringent films and color filters [29,30].

We studied specifics of CLC cells made of substrates containing areas of orthogonal orientation patterns in at least one boundary, Figure 10. The Bragg wavelength of CLCs used in this study was 532 nm. Interestingly, such cells reveal the interface lines between areas of different orientation when viewed from the patterned side

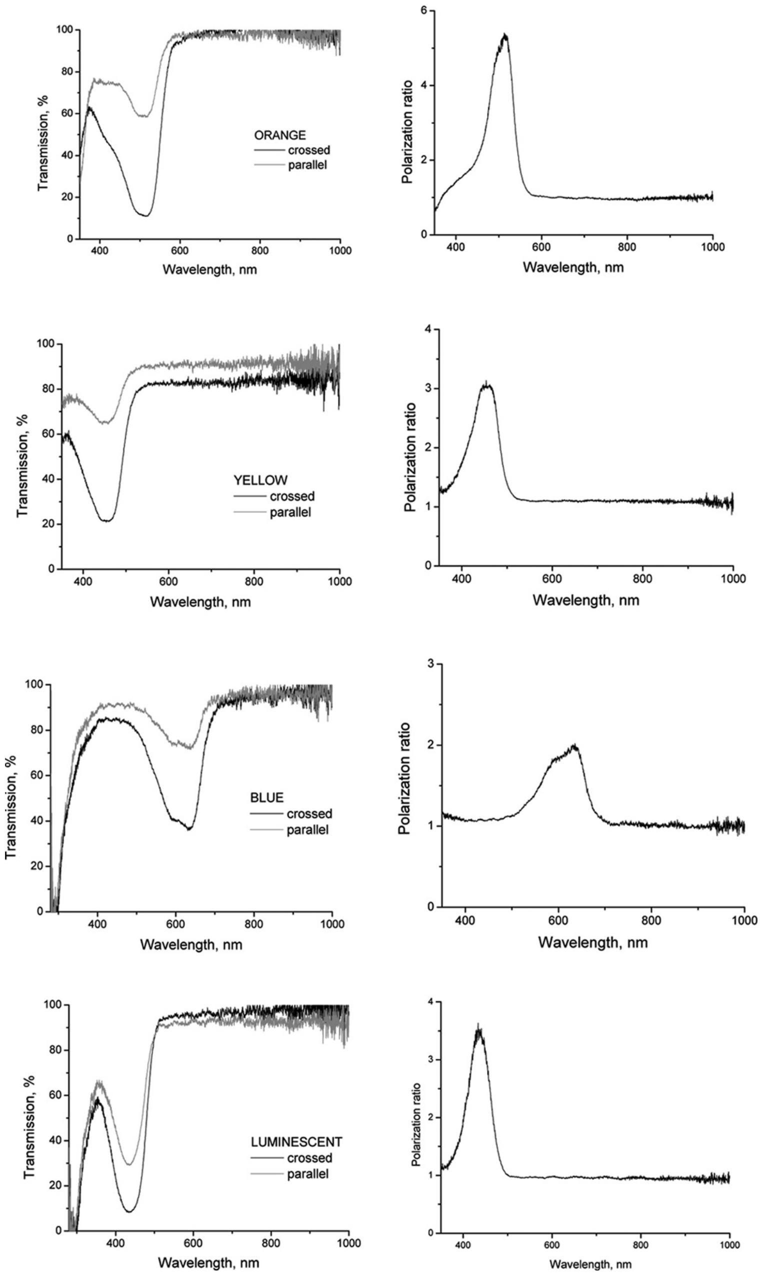


FIGURE 9 Transmission of spectrally selective polarizers for light polarized parallel and perpendicular to the optical axis of the film.

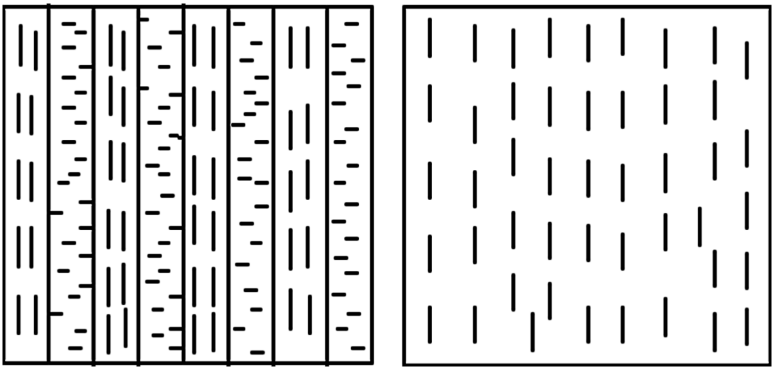
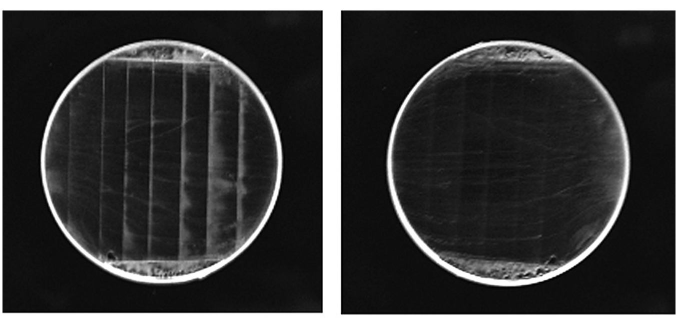


FIGURE 10 Top and bottom substrates of a CLC cell: dashed lines show the alignment conditions at the boundary obtained using patterned photoalignment technique.

while those lines are practically invisible when viewed from the side of homogeneous planar orientation, Figure 11. Another example of such a cell is shown in Figure 12. The reason for such an optical nonreciprocity could be attributed to polarization variation of the light propagating in the CLC. Namely, when the light is incident from the side of homogeneous planar orientation, it emerges from the patterned part of the CLC with spatially modulated polarization.

The photos of patterned CLC cell taken with one or two polarizers are shown in Figures 13 and 14. The polarizers make visible not only the interface between different states of orientation, but the areas of different orientation state as well.



(a) (b)

FIGURE 11 Photos of a CLC cell made of substrates shown in Figure 11 taken from the side of (a) patterned and (b) planar orientation.

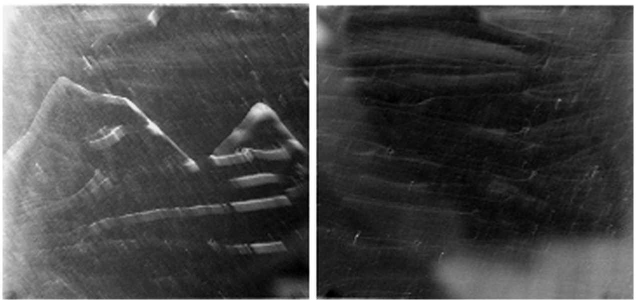


FIGURE 12 Photos of a cholesteric cell wherein one of the substrates induces homogeneous planar orientation while the second substrate is split into two areas of orthogonal orientation states using photoalignment technique, with a mountain-like interface profile. The interface is visible from the patterned side (a) and it is invisible from the homogeneous planar side.

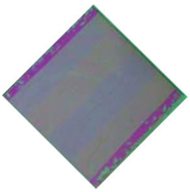
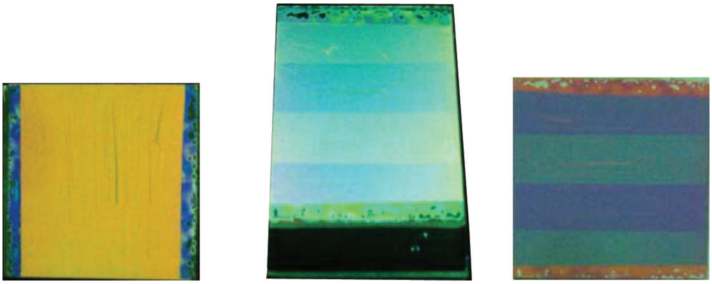


FIGURE 13 Photos of a cholesteric cell comprising areas of mutually orthogonal planar orientation. Photos are taken with one polarizer before the cell at different cell orientations.



(a) (b) (c)

FIGURE 14 Photos of the cholesteric cell comprising areas of mutually orthogonal planar orientation. Photos are taken with the cell in between two polarizers: (a) crossed polarizers; (b) the cell is between crossed polarizers viewed at a large angle tilt; (c) parallel polarizers.

SUMMARY

We have explored the opportunities provided by photoalignment technique for producing polarization imaging components. Combination of different orientation conditions and patterns on the substrates, the variety of LCs and dopants that can be used for functionalizing LCs and LCPs make the technique highly versatile and suitable for a large variety of applications.

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