XV Liquid Crystal Conference

OPTO-ELECTRONICS REVIEW **12**(3), 321–324 (2004)

Liquid crystal filter for polarization difference imaging

A. WALCZAK*[1], E. NOWINOWSKI-KRUSZELNICKI[1], and R. WAL[2]

[1]Institute of Applied Physics, Military University of Technology,
2 Kaliskiego Str., 00-908 Warsaw, Poland
[2]Institute of Automation and Robotics, Military University of Technology,
2 Kaliskiego Str., 00-908 Warsaw, Poland

The liquid crystal (LC) filters with hybrid, circular-planar, and circular-homeotropic alignments of the LC layer have been analysed in detail. The exploited alignment of the LC layer assures the uncommon polarizing properties of the filter. We manage to observe that transmissions in such a filter create an orthogonal set. This set may be joined with a spectral component of light by the unique way. It is exhibited in the presented work. We proved here that such an orthogonal set is created by means of light polarization as well as by means of the light wavelength. It has been shown that a liquid crystal which has a high birefringence improves sensitivity of transmission on the transmitted wavelength and polarization.

Keywords: polarization, filter, liquid crystal.

1. Introduction

Polarization effects are now perceived as a potential new source of information. Polarization analysis of the objects in a scene allows distinguishing the features according to their light, reflection properties or light scattering properties. The randomly scattered ambient light is likely to be unpolarized, whereas ambient light reflected from a smooth surface is likely to have a preferential polarization direction [1]. A difference between the scenes taken by two perpendicular polarizations removes the polarized light component from the resulting image. That way is known as a polarization-difference imaging (PDI) [2]. The liquid crystal (LC) micro polarizer array made by photolithography technology has been reported for that aim [3]. The efficiency of that micropolarizer array was very low and the polarizer seems to be far from being completed.

We describe here another kind of the LC device for polarization affected an object imaging. The reported device transmits the polarised component of an image. So, it also provides the data for the PDI procedure.

The authors partially described the considered filter construction earlier as a tool exploited for wavelet transform of an image while a circular-planar LC layer alignment has been applied in the filter [4]. A joined spectral and polarizing property of this filter has not been presented before this article.

Here, the most important features of the considered device have been characterised in detail. Especially, dependence of the filter parameters on the LC substance characteristics has been described. It is proved here that a transmission of the considered filter creates an orthogonal set of functions. Such a set may be obtained in reference to the incident light polarization as well as in reference to the wavelength of the transmitted light. We exhibit here also that the birefringence of an applied liquid crystal decides about the filter attributes.

2. Filter structure

The used LC layer alignment in the analysed filter is presented in Fig. 1. The LC filter with planar-circular alignment has been already described by Sato *et al.* [5,6]. They did not analyse a transmission dependency on LC properties. They also did not describe any spectral properties of such a filter.

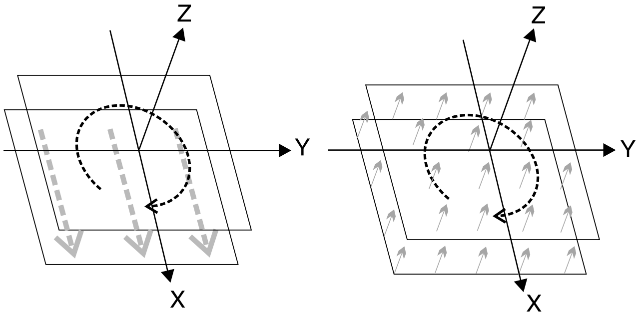
The light transmission in the filter is ruled by, so-called, adiabatic following in a twisted nematic LC layer. It appears that the electric field follows the twist of the director field in the LC layer, as optical path is long enough [7]. In such a situation, the resulted transmission in crossed polarizer is like in Fig. 2. Polarized direction in Fig. 2 has been placed along a sheet edge while a planar alignment is parallel to the arrow visible in the figure.

If the considered filter cooperates with the tuned half-wave liquid crystalline phase shifter, like in Fig. 3, then the area of transmission will rotate in the filter plane in accordance with the entrance light polarization.

When the spectral and polarizing scene acquisition is realized simultaneously, an optical system is like in Fig. 4.

---

*e-mail: awalczak@wat.edu.pl



$\vec{n} = [\cos\alpha, \sin\alpha, 0]$ $\quad$ $\vec{n} = [\cos\alpha, \sin\alpha, 0]$

$\vec{n} = [1, 0, 0]$ $\quad$ $\vec{n} = [0, 0, 1]$

Fig. 1. Schematic view of the LC alignment on both sides of LC layer inside investigated filter for two different LC layer arrangements. The arrows exhibit the director field orientation on both sides of the LC layer that is described for both surfaces below the picture.

Fig. 2. Light reflection on the filter when corners of the filter are not covered with the polarising sheet.

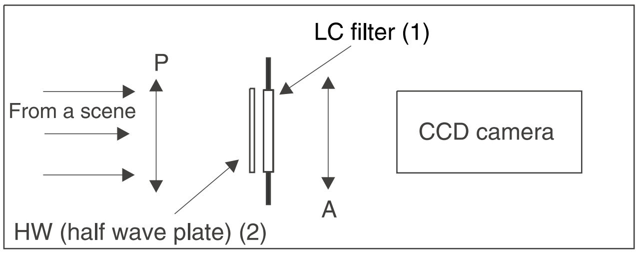


Fig. 3. Scheme of the measurement system.

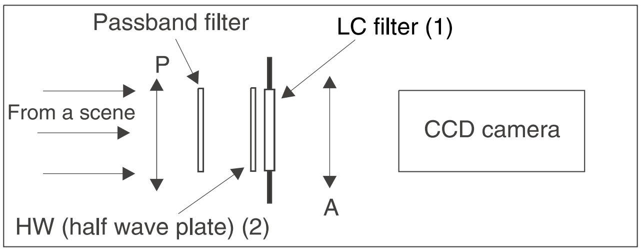


Fig. 4. Optical system for simultaneous spectral and polarizing acquisition of a scene.

3. Theoretical analysis of transmission

When the Jones vectors, says J, are used for description of the wave polarization, the transmission in the twisted LC medium should be treated as [7]

$$T = \left| J' M J \right|^2 . \tag{1}$$

The matrix M depends on the LC layer properties. The angle ϕ denotes the twist angle in the LC layer. In the examined filter, the twist angle depends on the position on the filter plane $\phi = \phi(x,y)$ or $\phi = \phi(x,y,z)$

$$M - \begin{pmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{pmatrix} \times \begin{pmatrix} \cos V - i\dfrac{\delta \sin V}{2V} & f\dfrac{\sin V}{V} \\ -f\dfrac{\sin V}{V} & \cos V + i\dfrac{\delta \sin V}{2V} \end{pmatrix} . \tag{2}$$

The item δ denotes the phase variation in a transmitted wave

$$\delta = \frac{2\pi}{\lambda} \Delta n d. \tag{3}$$

The sign V means

$$V = \sqrt{\phi^2 + \left(\frac{\delta}{2}\right)^2} . \tag{4}$$

The Δn is a birefringence of the LC medium and d is the LC layer thickness. The Jones vectors can be described in terms of polarizer and analyser angular position

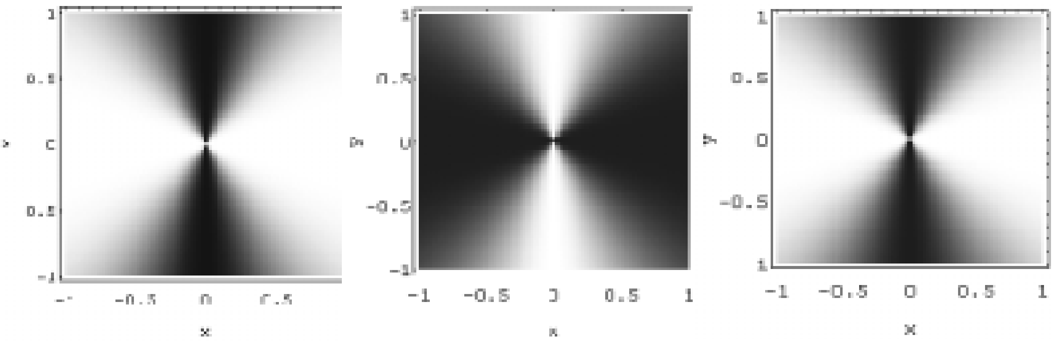
$$J = \begin{pmatrix} \cos\phi_{ent} \\ \sin\phi_{ent} \end{pmatrix}; \quad J' = \begin{pmatrix} \cos\phi_{exit} \\ \sin\phi_{exit} \end{pmatrix} . \tag{5}$$

The angles in Eq. (5) are orientations of the entrance and exit polarizer. We manage to notice that the twist angle distribution over the filter body may be characterised by means of the simple formulae

$$\phi(x,y) = \frac{\pi}{2} \cos\left(\arctan\left(\frac{y}{x} \right) \right), \tag{6}$$

$$\phi(x,y,z) = \frac{\pi}{2} \cos\left(\arctan\left(\frac{y}{x} \right) \right) \cos\left(\frac{z}{2d} \right) . \tag{7}$$

The co-ordinates are centred in the middle of the filter and they have been denoted as x and y. The coordinate z is directed as perpendicular to the filter body. The first twist angle distribution in Eq. (6) is for a circular-planar align-



Δn = 0.01
(a)

Δn = 0.15
(b)

Δn = 0.45
(c)

Fig. 5. Intensity transmission vs. LC birefringence (placed as *a*, *b*, *c*) at $\lambda = 700$ nm, *x* and *y* are the distances along a filter side.

ment and the angle described in Eq. (7) is for a circular-homeotropic alignment. The calculations in the second case have been done for a set of the "exit" Jones vector taken for each thin slice of the LC layer in which we assume

$$f_{exit|z_k} = \cos\left(\frac{z_k}{2d}\right). \tag{8}$$

Obviously, in the case of circular-homeotropic alignment we had to calculate the *T* matrix as

$$T = \prod_{k=1}^{L} T_k. \tag{9}$$

The number of the slices equal to $L - 1$ has been assumed arbitrary. The obtained dependence of the transmission on the lc birefringence has been calculated in accordance with Eqs. (1–6) and illustrated in Fig. 5. When the LC layer thickness remains fixed, polarization of the transmitted light may be selected in dependence on a given LC substance birefringence.

The dependence of transmission on reference orientation of the polarizer and analyser has been shown in Fig. 6. It can be seen that a reference position of entrance and exit polarizer results, to some extent, in improvement in light polarization selection.

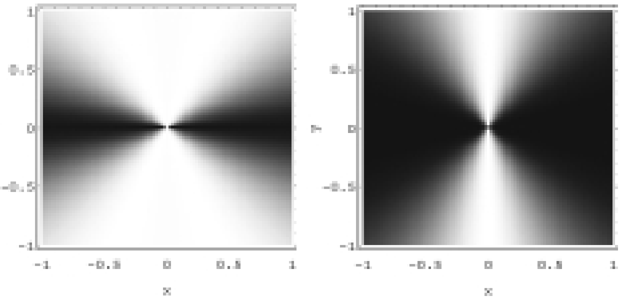
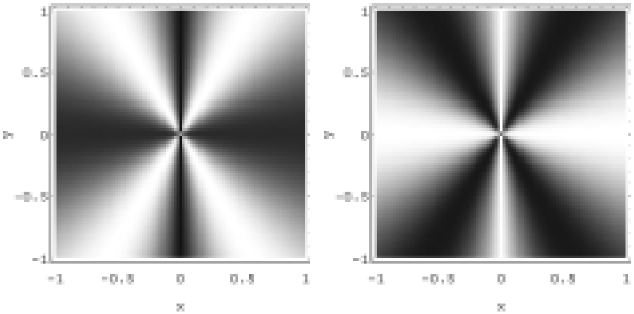


Fig. 6. Transmission when polarizer and analyser are parallel (on the left) and crossed (on the right).



λ = 740 nm, Δn = 0.45
(a)

λ = 640 nm, Δn = 0.45
(b)

Fig. 7. Dependence of the transmission on the transmitted wavelength for the entrance and exit polarizer twisted on 45°.

The transmission in the analysed device is sensitive to light colour as well. It is shown in Fig. 7. Such an effect is especially strong in the case when an angle between the entrance and the exit polarizer is equal to 45°. The orthogonal character of the both transmitted intensities can be easily seen.

4. Conclusions

Very useful perceive about twist angle distribution over the LC layer in the filter allow us to simulate optical properties of the filter. Intensity transmission in the figures with mixed, circular-planar LC, and circular-homeotropic alignment has been analysed in detail theoretically and illustrated experimentally. The obtained theoretical and experimental transmissions are very similar.

The transmission in the analysed filter occurs polarisation sensitive. A final shape of the transmission depends on a reference orientation of the entrance and exit polarizer. The influence of the entrance and exit polarizer has been shown as a way to obtain higher sensitivity of the filter on the transmitted wavelength. An exhibition of the spectral sensitivity of the filter proves that one can apply such a filter for polarization difference imaging in different ranges of the spectrum. The presented figures prove also that transmission of the filter creates an orthogonal set, which can be joined with polarization and/or with the spectrum of the transmitted wave.

So, as a component of an optical system that filter may be optimised, and the main decisive factors of an optimisation are collected in here. The details of the theoretical model have been also given.

Acknowledgements

We acknowledge the support of the Military University of Technology, Warsaw, Poland under the projects PBS705.

References

1. G.P. Können, *Polarized Light in Nature*, Cambridge, 1985.
2. J.S. Tyo, E.N. Pugh, and N. Engheta, "Colorimetric representations for polarization difference imaging of objects in scattering media", *J. Opt. Soc. Am. A* **15**, 367 (1998).
3. C.K. Harnett and H.G. Craighead, "Liquid-crystal micropolarizer array for polarization-difference imaging", *Appl. Optics* **41**, 1291 (2002).
4. A. Walczak, E. Nowinowski-Kruszelnicki, L.R. Jaroszewicz, and R Wal, "Edge detection with liquid crystal polarizing filter", *Mol. Cryst. Liquid Cryst.* **413**, 407 (2004).
5. R. Yamaguchi, T. Nose, and S. Sato, "Liquid crystal polarizer with axially symmetrical properties", *Jap .J. Appl. Phys.* **28**, 1730 (1989).
6. S. Masuda, T. Nose, and S. Sato, "Optical properties of a polarization converting device using a nematic liquid crystal cell", *Opt. Rev.* **2**, 211 (1995).
7. P. Yeh. and C. Gu, *Optics of Liquid Crystal Displays*, Wiley & Sons, Inc., New York, 1998.