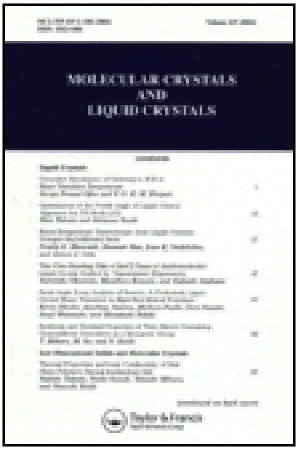

Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl20

Polarization Selective Wavelength Tunable Filter

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Version of record first published: 01 Jun 2009

To cite this article: Jeroen Beeckman, Tian Hui, Pieter J. M. Vanbrabant, Robert Zmijan & Kristiaan Neyts (2009): Polarization Selective Wavelength Tunable Filter, Molecular Crystals and Liquid Crystals, 502:1, 19-28

To link to this article: http://dx.doi.org/10.1080/15421400902813626

Mol. Cryst. Liq. Cryst., Vol. 502, pp. 19–28, 2009

ISSN: 1542-1406 print/1563-5287 online
DOI: 10.1080/15421400902813626

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Polarization Selective Wavelength Tunable Filter

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In conventional color CCD cameras, each color pixel consists of different pixels that record the red, green or blue light. However, for special applications such as in astronomy, it is desirable to take pictures at a number of specific wavelengths. In this work, we present the design and fabrication of a liquid crystal wavelength tunable filter which is also able to detect the polarization state of the light. The design consists of a 4-stage Lyot–Öhman filter with an additional liquid crystal cell in front of the filter. By applying the right voltage on the first cell, one can choose the polarization component of the transmitted light.

Keywords: Lyot–Öhman filter; nematic liquid crystals; polarization detection

1. INTRODUCTION

When taking pictures with a CCD-based camera, it is sufficient to record the intensity in the red, green and blue spectrum region to obtain a color image (trichromatic principle). In special applications however, it is not sufficient to record intensity profiles for three wavelength intervals, but more detailed data is required for a larger number of specific wavelengths. For example, it is desired in astronomy to obtain detailed information about the spectral properties of constellations of stars [1,2]. In even more specialized cases spectral information is not sufficient, but also polarization properties of the recorded image are important. This is the case in e.g. gaining

Jeroen Beeckman is postdoctoral fellow and Pieter J. M. Vanbrabant is Ph.D. fellow of the Research Foundation – Flanders (FWO). This work was supported by the Photonics@be IAP network of the Belgian Science Policy.

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information of the atmosphere of planets, where it is required to distinguish polarization states without any mechanical switches.

The most common used liquid crystal tunable filter (LCTF) is of the Lyot–Öhman type [3–6]. This is a multistage filter in which each stage contains a pair of parallel polarizers with in between a planarly oriented nematic liquid crystal layer between glass substrates coated with Indium Tin Oxide electrodes. Figure 1 shows the configuration for a 4-stage LCTF. The liquid crystal molecules are aligned at an angle of 45° with respect to the direction of the polarizers. The retardation of each liquid crystal cell can be tuned by applying a voltage over the cell. In order to filter out a certain wavelength with a narrow peak, the retardation of each stage must be twice the value of the preceding one, so the retardation of the k_{th} plate Γ_k is

$$\Gamma_k = 2 \cdot \Gamma_{k-1} = 2^{k-1}\Gamma_1$$

The transmission of the entire filter is

$$T = T_0 \prod_{k=1}^{4} \cos^2\left(\frac{\Gamma_k}{2}\right)$$

with T_0 the energy losses due to the absorption and reflection. If no voltage is applied, the retardation of each cell is given by

$$\Gamma = \frac{2\pi}{\lambda} \Delta n \cdot d,$$

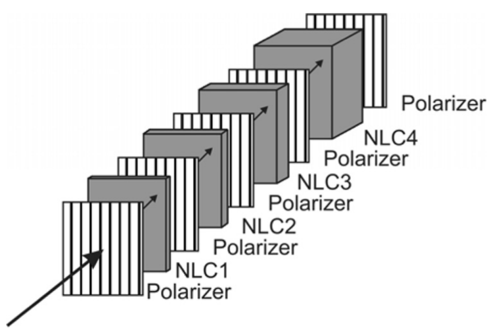


FIGURE 1 Configuration for a classical Lyot–Öhman type wavelength tunable filter with liquid crystal cells. Four stages are shown in the figure.

with d the thickness of each cell and $\Delta n = n_e - n_o$ the birefringence of the liquid crystal where n_e and n_o represent the extraordinary and ordinary refractive index, respectively. In case a voltage is applied across the cell the birefringence becomes $\Delta n = n_{e,avg} - n_o$, where *avg* denotes the average value of the extraordinary refractive index over the thickness of the cell:

$$n_{e,avg} = \int_0^d n_e(x)dx = \int_0^d \frac{n_e n_o}{\sqrt{n_e^2 \cos^2\theta(x) + n_0^2 \sin^2\theta(x)}} dx$$

In this equation $\theta(x)$ represents the tilt of the molecules along the thickness of the cell, which is determined by the applied voltage and the material parameters such as the elastic constants K_{11} and K_{33} and the dielectric properties $\varepsilon_\perp$ and $\varepsilon_{//}$.

By changing these simple design rules, one can improve one or more characteristics of such devices and numerical analysis leads to design rules for devices which reduce side peaks in the transmission [7,8] or flat top transmission profile [9,10]. In Section 2 this article will focus on the fabrication and design of a classical tunable filter and in Section 3 some adaptations to this filter are discussed to achieve a polarization selective device.

2. FABRICATION OF A LIQUID CRYSTAL LYOT-ÖHMAN TUNABLE FILTER

The LCTF we have implemented is a 4-stage filter. For the cell in the first stage, the liquid crystal E7 was used (Merck), which is characterized by a moderate value of Δn (see Table 1 for material properties).

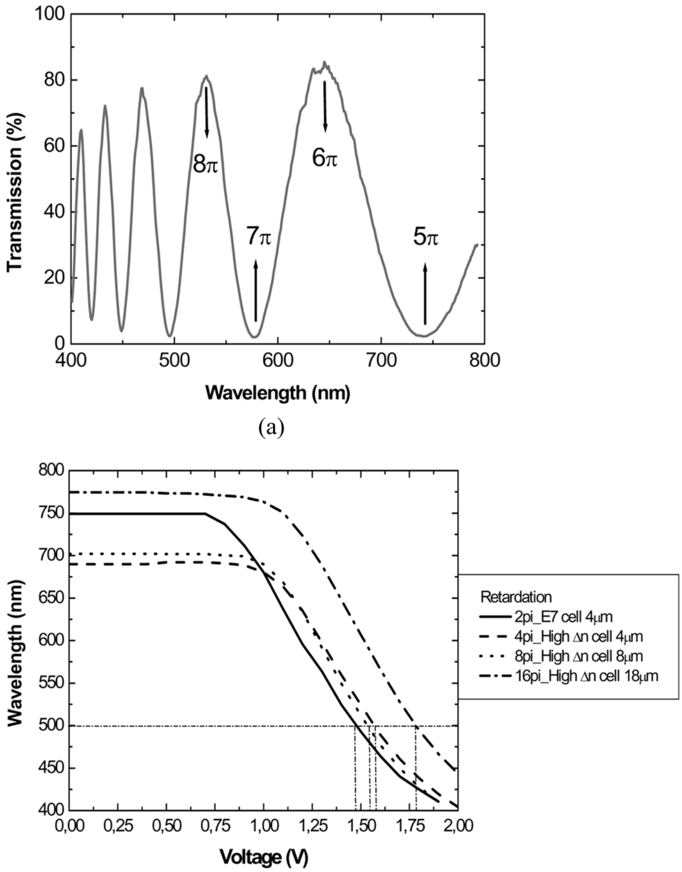
TABLE 1 Parameter Values for E7 and High Δn Liquid Crystal Materials

	E7 (for $\lambda = 577$ nm)	High Δn (for $\lambda = 633$ nm)
n_e	1.75	1.9045
n_o	1.6231	1.5390
Δn	0.2269	0.3655
K_{11}	12 pN	16.2 pN
K_{33}	19.5 pN	10.8 pN
$\varepsilon_\perp$	5.1	5.4
$\varepsilon_{//}$	19.6	16.5
$\Delta\varepsilon$	14.5	10.1

For the other three cells we have used a special mixture with high birefringence, provided by Prof. Dabrowski (Military University of Technology, Poland). This material was used to keep the thickness of the liquid crystal layers at the stages with high birefringence at acceptable levels. The resulting thicknesses of the liquid crystal layer in the different stages are respectively 4 μm, 4 μm, 8 μm and 18 μm, while the substrates are 5 by 5 cm. The total useful surface area of the cell is smaller due to the dimensions of the glue lines near the edges of the cell. Note that the thicknesses are rough values which are related to the dimensions of the spacer balls that were used, so the actual thickness of the cells can be slightly different. This is not a problem because the required retardation can be obtained by applying a voltage on the cell.

In order to measure the transmission as a function of wavelength, an experimental setup containing a white light source (Xenon lamp) and spectrometer was used. The individual cells were placed between parallel polarizers and their transmission spectrum was measured. As an example, Figure 2(a) shows the experimental transmission spectrum for the third cell at 1.5 V (high birefringence, 8 μm). One can see different minima and maxima in the transmission spectrum. The minima correspond to a retardation of an odd multiple of π, while the maxima in the spectrum correspond to an even multiple of π. When higher voltages are applied, the spectrum shifts to the left. As this cell is used for the third stage of the filter, the required retardation for this cell is 8π. In case 1.5 V is applied, this retardation is achieved for 530 nm (see Fig. 2(a)). For each stage the wavelength corresponding to the desired 2π multiple birefringence value was recorded as a function of voltage. Figure 2(b) shows the resulting voltage-wavelength plots for all four stages. Note that in the ideal case, i.e. when all the cells would have the same liquid crystal and the thicknesses are exactly the doubled, all plots in Figure 2(b) should coincide. Due to technological issues this is however very difficult to achieve. If a horizontal line is drawn at the desired wavelength in Figure 2(b), the intersections with the four curves show which voltages need to be applied to the subsequent stages to filter the light with the desired wavelength. For 500 nm this results in respectively 1.47, 1.52, 1.59, and 1.76 V. For these voltages, the measured maximum transmission peaks of all four cells coincide at the desired wavelength (see Fig. 3) and hence when all four transmission spectra are combined, the single transmission peak at the desired wavelength is obtained.

The four cells are glued together with sheet polarizers in between and the measured transmission of the combined cells is shown in Figure 4 for three selected wavelengths (450, 550, and 587 nm).



(a)

(b)

FIGURE 2 (a) Measured transmission spectrum for high Δn cell (8 μm) at 1.5 volt. (b) The relation between wavelength and applied voltage for the required retardation for each cell.

The three peaks are clearly visible at the selected wavelength in Figure 4. Unfortunately, also side-peaks are visible at wavelengths different from the selected wavelength. These side peaks are larger than expected from theoretical analysis. The reason obviously lies in the non-ideality of the components that were used, mainly due to misalignments between the rubbing direction and the polarizers and due to reflections. The FWHM of the three peaks are respectively 11.6, 22.6, and 25.3 nm and these values are roughly equal to the expected theoretical values. The FWHM increases for larger wavelengths.

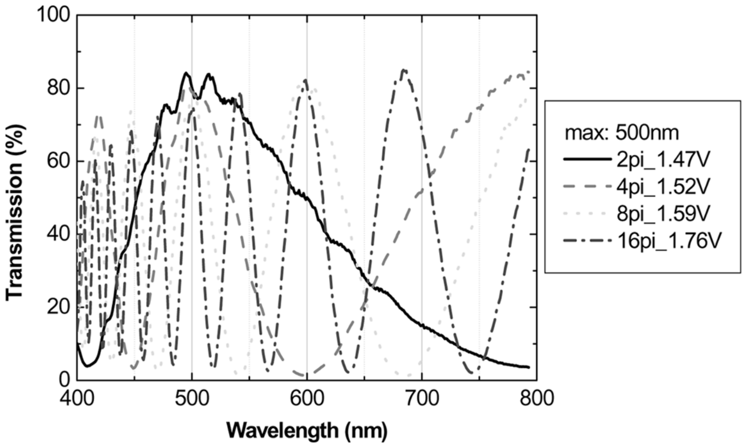


FIGURE 3 Measured transmission spectrum of the four individual cells. The applied voltage is chosen so maximum transmission peaks all coincide at 500 nm.

If necessary, these values can be reduced by a factor 2 by adding an extra stage to the filter. However, the total transmission which is already quite low (ranging from 10 to 25%) will be even more reduced by adding this extra stage. This low overall transmission is mainly due to absorption of light in the polarizers, which is larger for smaller wavelengths.

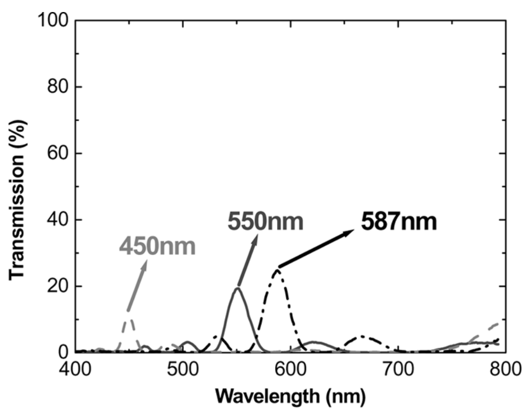


FIGURE 4 Measured transmission spectrum of the four cells in series for three different selected wavelengths.

3. POLARIZATION SELECTIVE TUNABLE FILTER

The LCTF only works for light with polarization parallel to the initial polarizer, but for some applications it is also required to record the intensity pattern for different polarizations.

In principle, there are several ways to realize polarization sensing for this filter. The first one is to use the Mauguin-regime for a twisted nematic cell [11]. In this regime, the ordinary and the extraordinary waves follow the rotation of the optical axis of the cell and the polarization of light also rotates with this rotation. If a high voltage is applied on the cell, all molecules tend to align along the electric field and the light passes through the cell without changes. For cells with a total twist angle of $\pi/2$, the condition for the Mauguin-regime is $\Delta nd/\lambda >> 0.5$. However, we have not chosen this option because the retardation can never be exactly zero. A high voltage orients the molecules perpendicularly to the substrates, but close to the substrate there will always be a transition region.

As an alternative, we choose to place an additional planarly oriented nematic liquid crystal cell in front of the filter with the director at 45° with respect to the initial polarizer direction. No polarizer is placed in front of this additional cell. In order to understand the working principle of this first cell, the measured transmission of this retarder is plotted as a function of voltage in Figure 5 for a single wavelength (585 nm). One curve is measured between parallel polarizers while the other curve is measured between crossed polarizers.

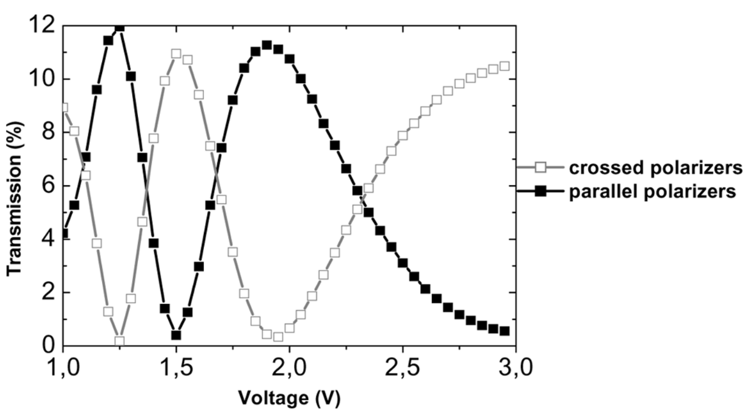


FIGURE 5 Measured transmission of a nematic liquid crystal cell in function of voltage when the cell is either placed between crossed of parallel polarizers ($\lambda = 585$ nm).

Every maximum of one curve corresponds to a minimum of the other curve, and vice versa. The transmission for the crossed polarizers is maximum for voltage V_2, so the polarization of the incoming light will be rotated over 90°. For the applied voltage V_1, the transmission for parallel polarizers is maximum, which means that the polarization of the incoming light is not rotated. This means that we can actually choose the polarization component of the incoming light that is transmitted through the LCTF. For each wavelength of the LCTF, one of the two voltages V_1 and V_2 are used to select the desired polarization component. Obviously, these two voltages vary as a function of the selected wavelength.

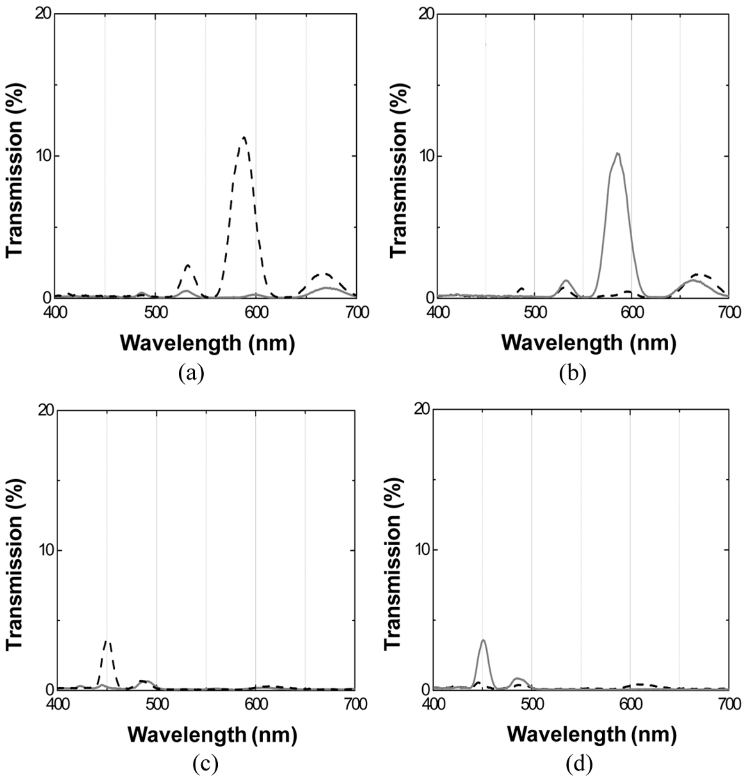


FIGURE 6 Measured transmission spectra for a selected wavelength of 585 nm (a) and (b) and 450 nm (c) and (d). The solid curves denote transmission of the polarization state perpendicular to the first polarizer of the LCTF and the dashed curves show the transmission of the polarization state parallel to the first polarizer or the LCTF.

Figure 6 shows the experimental transmission of linearly polarized light when either 585 nm or 450 nm is selected as the pass wavelength. For the figures on the left (a) and (c), the voltage $V_1(\lambda)$ is applied while for the figures on the right (b) and (d) the voltage $V_2(\lambda)$ is applied. One can see that indeed the right polarization component of the light is filtered out. The contrast ratio is calculated by integrating the visible parts of the two curves in the same graph and dividing the transmission of the unwanted polarization component by the selected one. The values for the contrast ratio are respectively for figures (a) to (d): 7.23, 3.16, 2.11 and 2.03. These values are quite low due to the detrimental influence of the side peaks. When comparing the maximum transmissions at the selected wavelength, the values for the contrast are a factor ten higher.

4. CONCLUSIONS

A four stage Lyot–Öhman type filter has been designed and fabricated. Experimental results show that the filter works well, except for the appearance of some unwanted side peaks in the transmission spectrum. We discussed and implemented a technique to extend the basic filter setup that only works for one polarization in order to achieve a polarization selective tunable filter. Measurements of this filter demonstrate the correct operation of the device although the polarization selective contrast can be low due to the detrimental effect of unwanted side peaks.

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