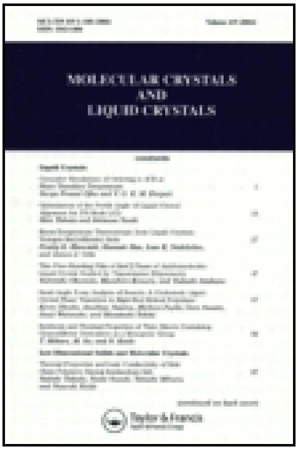

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A conventional liquid crystal display consists of a liquid crystal cell between two crossed polarizers. By applying a voltage, the liquid crystal can be switched and the transmission of light can be manipulated. For thick devices, the transmission shows a strong wavelength dependency and this can be used to construct a tunable Lyot-Öhman filter. Such a filter consists of several liquid crystal cells with polarizers in between with a narrow transmission band that can be shifted over a certain wavelength range. Instead of aiming for a narrow transmission peak, in this work the aim is to achieve a wide transmission wavelength range. In this way the transmission band can be switched, for example, from the visible wavelength range to the near-infrared range. Because the device needs only two different states, bistable surface-stabilized ferroelectric liquid crystal devices can be used which offer short switching times in the order of 100 μs. Numerical optimization of this switch reveals that high contrast ratios can be achieved by using 2 fixed and 2 switchable retarders.

Keywords: ferroelectric liquid crystals; Lyot-Öhman filter; wavelength tunable filter

1. INTRODUCTION

A conventional liquid crystal device as it is used in display applications consists of two crossed polarizers and a liquid crystal cell in between.

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The liquid crystal cell is made of two glass plates with a transparent electrode and a thin layer of liquid crystal in between. Such a device displays a transmission spectrum with different minima and maxima. By changing the applied voltage, these minima and maxima will shift to other wavelengths. For application in tunable filters, the liquid crystal between the glass plates usually has planar alignment with a uniform director in the bulk for zero applied voltage. By putting a number of these devices in series, with each step a different retardation (typically in each stage, the retardation doubles) a Liquid Crystal Tuneable Filter (LCTF) of the Lyot-Öhman type can be fabricated [1–6]. In such a Lyot-Öhman filter, all the polarizers are parallel and the liquid crystal is aligned at 45° with the polarizers. Other types of configurations exist, such as the Solc filter in which only two polarizers are used [7]. In a Solc filter, a large number of birefringent plates are placed between the polarizers with increasing angle of the optic axis with respect to the polarizer. Such a multistage filter (of the Lyot-Öhman or Solc type) shows a narrow transmission peak in function of wavelength. By changing the voltages over the different liquid crystal cells, the transmission peak shifts to other wavelengths. Such filters can have a large area as the technological processes involved are used mainly in the display industry. This makes them ideal for use in combination with a CCD camera. By tuning the transmission wavelength, multiple pictures can be taken over the desired wavelength range. Such filters are mainly used in astronomy [4,8] for imaging stars at different wavelengths. In optical telecommunication, tunable filters can be used for filtering or for protection [6,9]. These tunable filters are commercially available. Applications are fluorescence microscopy, absorption microscopy, human skin scanning and product inspection in the food industry. With 4 stages in the Lyot-Öhman filter one can achieve a spectral range of 400 to 700 nm and 20 nm FWHM, and recently also polarization selection of a LCTF has been demonstrated [10].

All of the reported work on LCTFs focuses on the reduction of the FWHM of the transmission peak and the reduction of unwanted side peaks. In this work, instead of aiming at a narrow transmission peak, we fabricate a filter that switches rapidly between two broad wavelength ranges. More specific for this article, we switch between the visible spectrum (limited to $450\,\text{nm} < \lambda < 700\,\text{nm}$) and the near infrared spectrum ($700\,\text{nm} < \lambda < 950\,\text{nm}$). The aim is to maximize the contrast between the transmission and the stop band. The filter can be used in combination with a CCD-imaging system to take alternating pictures in the visible and near-infrared. The fast switching speed of about $100\,\mu s$ of the ferroelectric liquid crystal cell allows taking alternating frames of visible and near-infrared images, canceling out the need for two separate CCD cameras. Applications of such a filter lie in the field of surveillance and inspection.

2. MAXIMIZING THE CONTRAST RATIO

The bistable nature of the application we envisage, favors the use of surface stabilized ferroelectric liquid crystal (SSFLC) cells [11]. The switching speed of these type of cells is in the microsecond range and when the cone angle of the ferroelectric liquid crystal is 22.5°, the cells acts as a switchable wave plate where the angle between the optical axis in the two states is 45°. Figure 1 shows the configuration that we want to optimize. The configuration consists of multiple stages (two are drawn in the figure) of a nematic liquid crystal (NLC) cell and a ferroelectric liquid crystal cell in between crossed or parallel polarizers. The nematic liquid crystal cell is a planar oriented cell where the optical axis makes an angle of 45° with respect to the polarizers. This NLC cell is used as a fixed retarder. This means that once the necessary retardation and voltage is determined, the applied voltage is kept constant (in practice, an AC voltage is used to avoid ionic effects). By switching the SSFLC cell to one of the two states, the retardation added to the NLC cell becomes either zero (when the director is parallel or perpendicular to the polarizers) or not zero (when the director is at 45°). In this way, one can achieve two values for the retardation by switching only the SSFLC cell. A long pass filter can be used to block all the light with wavelength below a given value.

The transmission of a singe stage (polarizer, NLC cell, FLC cell and polarizer) is given by:

$$T(\lambda) = \sin^2\left(\frac{\pi \Delta n d}{\lambda}\right) \tag{1}$$

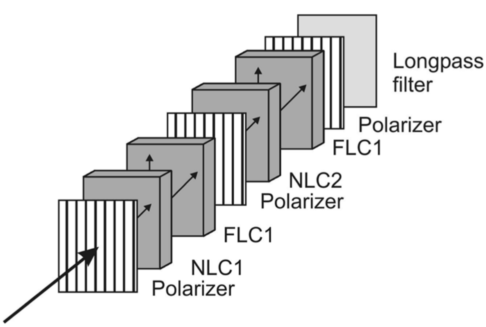

FIGURE 1 Schematic drawing of the switchable filter.

for crossed polarizers. For parallel polarizers, the sine is replaced by a cosine. If there are several stages, the transmission is just a multiplication of the transmissions of the individual stages. The birefringence of the liquid crystal can be modeled by the extended Cauchy model [12], given by:

$$\Delta n(\lambda) \approx A + \frac{B}{\lambda^2} + \frac{C}{\lambda^4} \tag{2}$$

In first approximation, we can ignore the wavelength dependence of the birefringence and write the total transmission of multiple stages in the following form:

$$T(\lambda) = \prod_{n=1}^{N} \sin^2\left(\frac{\pi\Gamma_n}{\lambda}\right) \tag{3}$$

with Γ_n the retardation in stage n. In order to optimize the filter characteristic, the total transmission over the pass band ($\lambda_1 < \lambda < \lambda_2$) should be maximized, while the transmission of the blocked wavelength band ($\lambda_2 < \lambda < \lambda_3$) should be minimized. Therefore, we have chosen to maximize the contrast ratios defined as:

$$C_{\mathrm{VIS}} = \frac{\int_{\lambda_1}^{\lambda_2} [\Pi_{n=1}^{N} \sin^2(\frac{\pi\Gamma_n}{\lambda})] d\lambda}{\int_{\lambda_2}^{\lambda_3} [\Pi_{n=1}^{N} \sin^2(\frac{\pi\Gamma_n}{\lambda})] d\lambda} \tag{4}$$

and its inverse,

$$C_{\mathrm{NIR}} = \frac{\int_{\lambda_2}^{\lambda_3} [\Pi_{n=1}^{N} \sin^2(\frac{\pi\Gamma_n}{\lambda})] d\lambda}{\int_{\lambda_1}^{\lambda_2} [\Pi_{n=1}^{N} \sin^2(\frac{\pi\Gamma_n}{\lambda})] d\lambda} \tag{5}$$

For the following calculations, $\lambda_1 = 450\,\mathrm{nm}$, $\lambda_2 = 700\,\mathrm{nm}$ and $\lambda_3 = 950\,\mathrm{nm}$.

2.1. One-Stage Filter

The contrast functions (4) and (5) are plotted in Figure 2 for one stage. The parallel polarizer setup gives similar values for the contrast, but the total transmission of the filter in the maximum points is much lower. Also for the two-stage design, the crossed polarizer configuration gives better results. Therefor, for the rest of the calculations we continue with a crossed polarizer configuration.

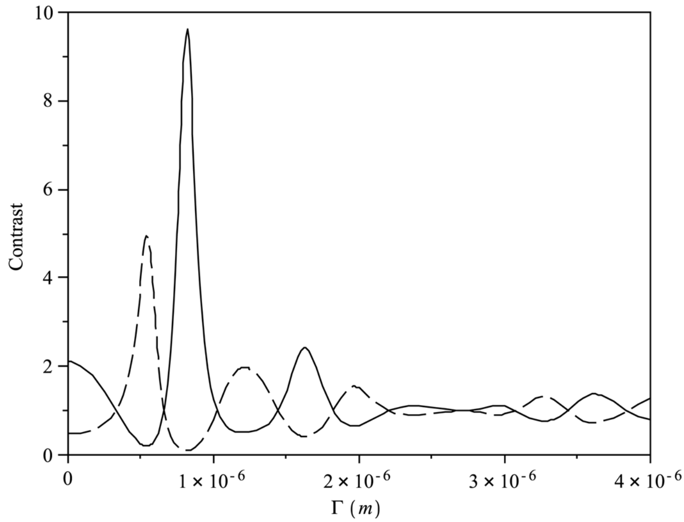

FIGURE 2 Contrast as a function of retardation for a one-stage filter. The solid curve shows the contrast when the visible wavelength band is selected, the dashed line shows the contrast for the near-infrared pass band.

The two curves show different maxima in function of the retardation. The highest values however are achieved for small values of retardation. For the visible selected wavelength band, the maximum contrast is 9.6 for a retardation of 830 nm. For the NIR selected wavelength band, the maximum contrast is 5.0 for a retardation of 550 nm. If we take a nematic liquid crystal cell as a fixed retarder with an average birefringence of 0.22, the thickness should be at least 2.5 μm. The switchable ferroelectric cell with a typical birefringence of 0.17 must have a thickness of 1.65 μm. These values for the thickness are achievable with standard liquid crystal display technology.

Figure 3 shows the transmission of the device in function of wavelength for the selected retardation. As expected, the maximum contrast is achieved when the minimum transmission lies approximately in the middle of a blocked wavelength band. Due to the sinusoidal nature of the transmission however, the transmission in the blocked wavelength band is still considerable. To reduce this unwanted transmission, it is necessary to include additional stages.

2.2. Two-Stage Filter

In order to find the necessary retardation for the two stages, as a first proposal, we take the retardation of the first stage as it was obtained

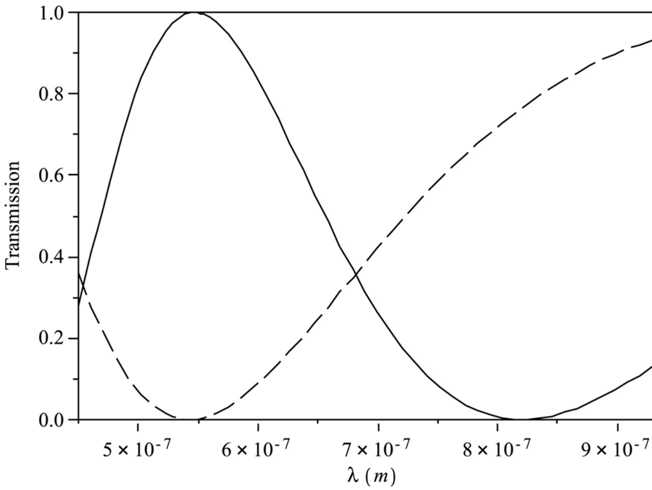

FIGURE 3 Transmission of the one-stage filter for maximized contrast. The solid line denotes the visible pass band while the dashed line denotes the near-infrared pass band.

in the previous paragraph. Then we plot the contrast as function of the retardation of the second stage. The resulting contrast is shown in Figure 4. The maximum contrast increases with respect to the

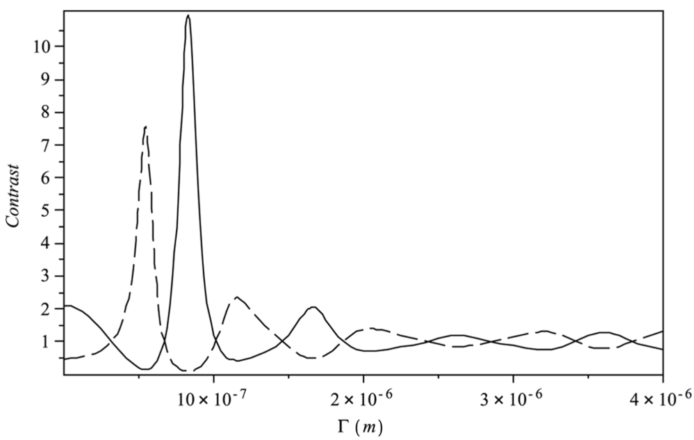

FIGURE 4 Contrast as a function of the retardation of the second stage for a two-stage filter, using a retardation of 830 nm or 550 nm. The solid curve shows the contrast when the visible wavelength band is selected, the dashed line shows the contrast for the near-infrared pass band.

one-stage filter from 9.6 to 11 (for the visible band) and from 5.0 to 7.5 (for the near-infrared band). The transmission improves as the unwanted transmission in the blocked wavelength bands are reduced.

2.3. Two-Stage Filter – Optimized Design

A much better strategy to increase the contrast is to optimize the retardation of the two stages simultaneously. Therefore we have plotted the contrast of the two-stage device in function of the retardation of both the first and the second stage (see Fig. 5). Again, multiple maxima are visible in the graph but the achievable contrast is much higher than the previous case. For the visible pass band, a contrast of 82 can be achieved for a retardation of $\Gamma_1 = 7.67 \times 10^{-7}$ m and $\Gamma_2 = 8.73 \times 10^{-7}$ m. For the near-infrared pass band, two different

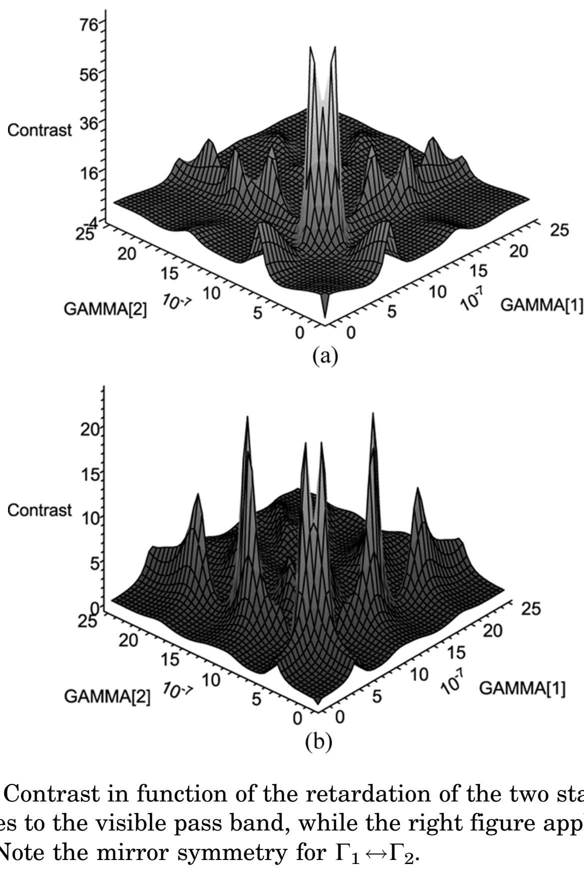

FIGURE 5 Contrast in function of the retardation of the two stages. The left figure applies to the visible pass band, while the right figure applies to the IR pass band. Note the mirror symmetry for $\Gamma_1 \leftrightarrow \Gamma_2$.

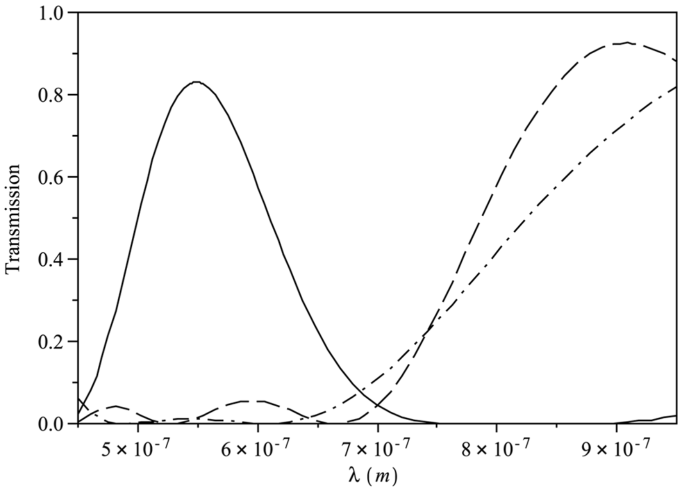

FIGURE 6 Transmission of the filter for the maximized contrast. The solid line denotes the visible pass band while the dashed and dash-dotted line denote the near-infrared pass band. The dashed and dash-dotted line are for the two different maxima in Figure 5.

possibilities arise with either a contrast of 25.2 $\Gamma_1 = 4.9 \times 10^{-7}$ m and $\Gamma_2 = 6.1 \times 10^{-7}$ m) or a contrast of 26.0 ($\Gamma_1 = 5.3 \times 10^{-7}$ m and $\Gamma_2 = 13.3 \times 10^{-7}$ m). The two give similar transmission curves (see Fig. 6), but the second possibility requires thicker cells. According to [11] the switching time of surface-stabilized FLC cells is inversely proportional to the electric field (compared to inversely proportional to the square of the electric field for nematic cells). For a certain voltage this means that the switching time scales proportional with the thickness. Hence it is better to keep the thickness as small as possible.

3. EXPERIMENTAL IMPLEMENTATION OF A ONE-STAGE FILTER

For the implementation of the one-stage filter, we have chosen to use the liquid crystal E7 from Merck [12] for the nematic cell that acts as a fixed retarder ($\Delta n \approx 0.22$). The thickness of the liquid crystal layer was chosen large enough (4 μm), so that the required retardation can be obtained by applying a voltage over the cell. For the surface-stabilized ferroelectric cell, we have used the material FELIX 017/000 from Merck and the thickness of the layer is 2 μm ($\Delta n \approx 0.17$). The main bottleneck for the maximum achievable spectral range are the polarizers.

For our implementation we have used the colorPol VIS BC4 polarizer from CODIXX, which has an acceptable contrast ratio in the wavelength range from 550 to 1000 nm, which means that it is not possible to span the whole visible region. Our device thus only works well for $550\,\text{nm} < \lambda < 950\,\text{nm}$. As a possible way to extend the range to smaller wavelengths, a combination of a visible and a near-infrared polarizer can be used, at the expense of extra losses due to polarizer absorption.

The switching time of the ferroelectric liquid crystal was measured using a polarizing microscope and a photodiode and a value of 150 μs was obtained for ±5 V driving voltage.

This value is in line with theoretical estimations [11]. After that, the transmission spectrum of the combination of polarizers, nematic liquid crystal cell and ferroelectric liquid crystal cell was measured using a spectrometer and the results are shown in Figure 7. Unfortunately, our spectrometer is limited to wavelengths below 800 nm. Therefore, we have included a theoretical fit, so the transmission at higher wavelengths is visible. The figure shows indeed that the filter switches from a state with a minimum transmission at around 625 nm to a state with a minimum at 760 nm. The measured spectrum is very similar to the optimized transmission of a one-stage device (Fig. 3).

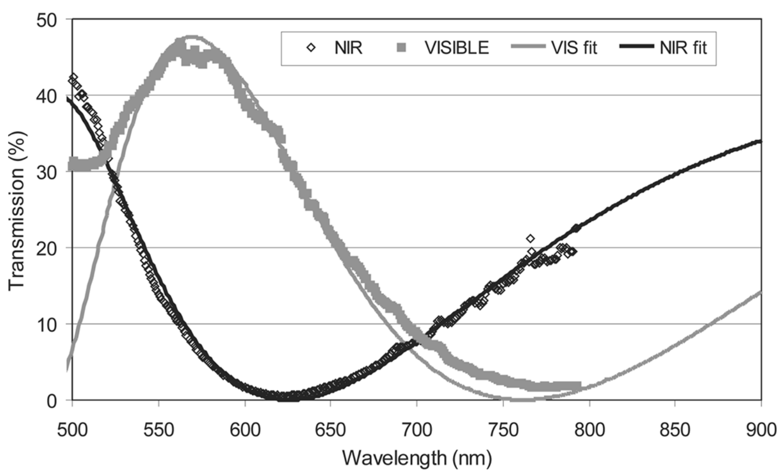

FIGURE 7 Measured transmission of the filter and a fit with the theoretical formula (1) including a wavelength dependent birefringence. The voltage applied on the nematic cell is 1.09 V. The voltage on the ferroelectric cell +5 V and −5 V.

4. DISCUSSIONS

The contrast of the filter can even be increased by adding more stages. The maximum contrast then cannot be found anymore via visual inspection of the contrast plot, and numerical methods must be used. Adding more stages however will reduce the overall transmission of the device because the transmission of parallel polarized light through a polarizer is often limited to 90% (with even lower transmission for the shorter wavelength range).

The same optimization procedure can be used for the design of tri-state and multi-state filers. For a tri-state filter, per stage, one nematic and two ferroelectric cells are required.

5. CONCLUSIONS

An optimization procedure was used to design multi-state wavelength tunable filters. A one-stage filter has been designed and experimentally implemented with a moderate contrast. A two-stage filter was designed with a much higher contrast by optimizing the necessary retardation of the two stages simultaneously.

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