Simulation of the Transmission Factor of Liquid Crystals Tuneable Filters (LCTFs)

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Lyot-Ohmann tuneable filters obtained from liquid crystalline layers for visible range are modelled by changing the intensity of an external electrostatic electric field applied to the glass cell containing liquid crystalline layer. The ordering action of the electric field on the optical birefringence of the liquid crystalline layers is considered in establishing the equations used for Java applications. The step by step changes in spectral composition of the emergent light are induced by modifying the electric field intensity and the thickness of the liquid crystalline layer.

Keywords: polymer liquid crystal, polarization interferential filters, tuneable filters, transmission factor

Tuneable polarization interferential filters made from liquid crystals (LCTFs) have multiple applications in different fields, such as: communications by optical fibres, astronomy, pollution monitoring, colour generation in displays, medical diagnosis [1] and so on. The great aperture and the large spectral range of LCTFs are distinct advantages compared with the conventional spectral analysis by dispersion. The benefits of the LCTFs compared to the tuneable opto-acustic filters include: low energy consumption, low control tensions, excellent image quality and high clarity even at great apertures [1-3].

LCTFs contain active elements as glass cells filled by liquid crystals whose birefringence is electrically controlled in order to select a given spectral range to be transmitted and to eliminate the rest of the radiations. This type of filters is ideal for electronic devices used in colour images capture, such as digital camera with sensors of the type charge-coupled devices, due to the excellent quality of the images. They have quite linear characteristics of the pathway difference in rapport with the electric applied tension [1-3].

There are two LCTFs: discrete and continue, classified after the adjustable procedure used to select the transmitted wavelengths. Both LCTF types are based on the interference of linearly polarized waves. The differences between the two types of filters are:

- the adjustable procedure for the continuous LCTFs utilises an electric tension continuously varied in order to obtain continuous modification of the selected wavelength;
- an electric tension varying in jumps is utilised in LCTFs with discrete adjustable procedure. They determine two complementary spectra at the exit of filter [4, 5].

By using more active elements in series, one can obtain transmission factors more and more narrower but this assemblage is characterized by low transmitted intensities and by increasing the filter complexity. LCTFs with continuous adjustment are devoted to the applications which do not ask for a high resolution.

Theoretical notions

Dispersion of the birefringence modelling

The optical properties of the liquid crystals correspond to those of the anisotropic crystals. The refractive index of the liquid crystals depends both on the propagation direction of the electromagnetic waves and on their polarization state. So, it is usually given by a 3 x 3 matrix. In the main system of coordinates O_{abc}, the matrix of refractive indices of the uniax liquid crystals, as well as that of uniax solid crystal, has only diagonal elements: $n_{aa} = n_{bb} = n_o$ and $n_{cc} = n_e$ [5-11]. The main values of the refractive index are measured with linearly polarized waves. The ordinary value n_o is measured with light having the electric field intensity parallel to the principal plane *aOb* (perpendicular to the optical axis O_c) and the extraordinary value n_e is measured with linearly polarized light having its electric field intensity parallel to the optical axis. The most obvious indication of the anisotropy of the liquid crystals is their birefringence. The main refractive indices of a uniax material determine the values of the birefringence [5-10]:

$$\Delta n = n_e - n_o \tag{1}$$

Usually, the main refractive indices and the birefringence of a liquid crystalline sample depend on its orientation degree. So, the birefringence is considered as a measure of the degree of order in liquid crystalline samples [5-9]. External mechanic, electric or magnetic fields can modify the order parameter and consequently, the birefringence of the liquid crystal. Like the main refractive indices, the birefringence shows dispersion in the visible range. The dispersion of ordinary and extraordinary refractive indices can be expressed by using the Cauchy formula [8, 9, 12, 13]:

$$n_{o,e}(\lambda) = A_{1o,e} + \frac{A_{2o,e}}{\lambda^2} + \frac{A_{3o,e}}{\lambda^4} \tag{2}$$

From relations (1) and (2) it results that the dispersion of the birefringence can be expressed by using the formula:

$$\Delta n(\lambda) = A_1 + \frac{A_2}{\lambda^2} + \frac{A_3}{\lambda^4} \text{ where: } A_i = A_{ie} - A_{io},\ (i = 1,3) \tag{3}$$

The fitting coefficients A_i usually depend of the electric field intensity. In a linear approximation, they can be calculated with the following relations:

$$A_i(E) = A_i(o) + \alpha_i \cdot E,\ i = 1,2,3 \tag{4}$$

From equations (2 - 4) it results that, in order to determine the fitting coefficients A_i and α_i, it is necessary to know the

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values of the refractive indices for three different wavelengths and correspondently for at least two values of the electric field intensity.

Transmission factor computation

Polarization interference filters are typically grouped into two main classes: Solc and Lyot structures. These two types of filters have competing advantages and disadvantages, and therefore a third type, the Evans split-element filter, is presented as a compromise [1].

The structures considered here are based on the work of Lyot and Ohmann [1-4]. These filters are made up of a cascade of filter units, or stages, each stage requiring two linear polarizers (parallel or crossed) bounding a linear multiple-order retarder oriented at 45° and consisting from one or two liquid-crystalline sheets combination (figs. 1 (a) and (b)).

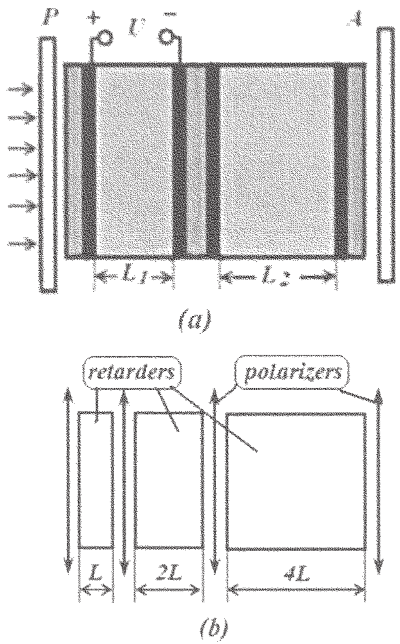


Fig. 1. (a) A single Lyot stage of LCTF system; (b) Three stages Lyot polarizing interference filter

The spectral region of the radiations passing the LCTFs is dependent upon the choice of polarizers, optical coatings and the liquid crystal layers characteristics (thicknesses, relative orientation, birefringence, dispersion of birefringence, etc.). Devices of this type usually perform quite well in the visible range.

Retardation in the anisotropic crystals is dependent upon the anisotropic layer thickness (L) and on its birefringence at a given wavelength [3-5]:

$$\Delta = L \cdot (n_e - n_o) \tag{5}$$

The extraordinary and ordinary radiations have different velocities in the anisotropic layer. Consequently, at the exit from the anisotropic layer (of a thickness L), the phase difference between the two components is expressed by relation (6):

$$\Delta\varphi = \frac{2\pi \cdot L \cdot (n_e - n_o)}{\lambda} \tag{6}$$

In order to avoid the use of not very thin layers and for a rigorous controlling of the filter optical characteristics, the achieving of tuneable elements having two liquid crystalline layers is convenient. The two layers, one from which has electrically controlled birefringence, can be oriented with their optical axes in parallel figures 2 (a) and (b) or perpendicular figures 3 (a) and (b).

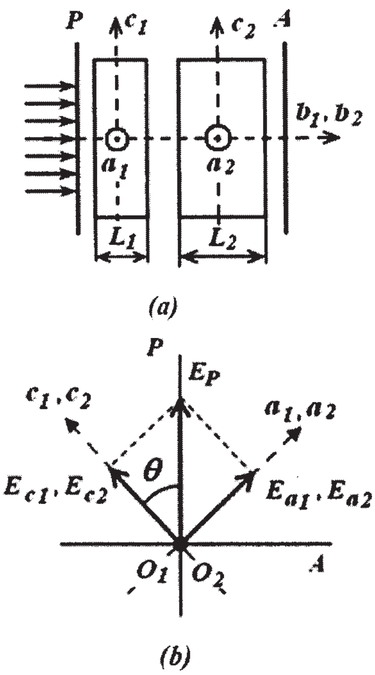


Fig. 2. (a) The slow axes of the two layers are parallel; (b) Reciprocal orientation of the polarizer's transmission directions and of the anisotropic layers' basic directions

The phase difference for the device illustrated in figures 2 (a) and 3 (a) can be calculated with the following equation [8-10]:

$$\Delta\varphi = \frac{2\pi\left(L_1 \cdot \Delta n_1 \cdot (\lambda, E) \pm L_2 \cdot \Delta n_2(\lambda)\right)}{\lambda} \tag{7}$$

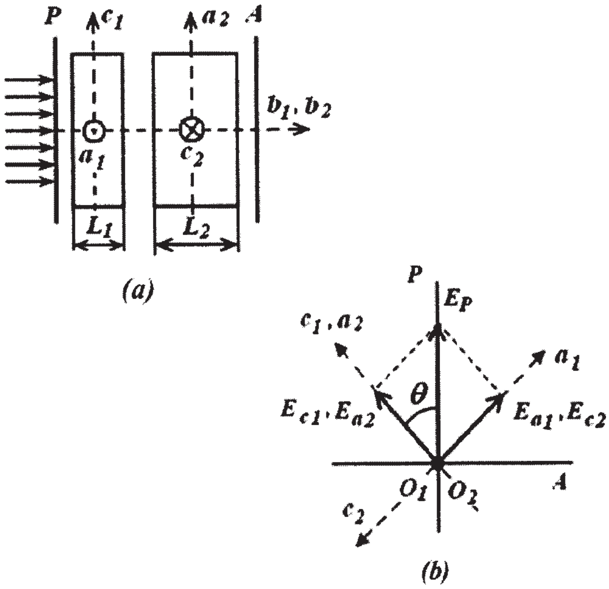


Fig. 3. (a) The slow axes of the two layers are perpendicularly; (b) Reciprocal orientation of the polarizer's transmission directions and of the anisotropic layers' basic directions

The transmission factor (T) through the devices shown in figures 2 (a) and 3 (a) is dependent on the value of Δφ, and it is given by the following equation [3, 10]:

$$T = \frac{1}{2}\sin^2\left(\frac{\Delta\varphi}{2}\right) = \frac{1}{2}\sin^2\left(\frac{\pi\left(L_1 \cdot \Delta n_1(\lambda, E) \pm L_2 \cdot \Delta n_2(\lambda, E)\right)}{\lambda}\right) \tag{8}$$

Both the wavelength corresponding to the maxim and the band-pass of the tuneable filter can be calculated with the relations [9-11]:
and

$$\lambda_{max} = \frac{L_1 \cdot \Delta n_1 \pm L_2 \cdot \Delta n_2}{k} \quad \text{and} \quad \Delta\lambda = \frac{\lambda^2}{2(L_1 \cdot \Delta n_1 \pm L_2 \cdot \Delta n_2)} \tag{9}$$

Crystalline layers in a typical Lyot filter are often selected for a binary sequence of retardation so that the transmission value is maxim at the wavelength determined by the thickest anisotropic retarder. Other stages in the filter serve to block the transmission of unwanted wavelengths. By cascading a series of these filter stages, a desired band-pass filter can be synthesized. For the computational modelling presented below the retardation values were chosen in binary steps of the crystalline thickness layers: (L_1, L_2), ($2L_1$, $2L_2$) and ($4L_1$, $4L_2$).

The global transmission factor of light through the three stages Lyot polarizing interference filter is given by the following equation [3-5]:

$$T = \frac{1}{2} sin^2\left(\frac{\Delta\varphi}{2}\right) sin^2\left(2 \cdot \frac{\Delta\varphi}{2}\right) sin^2\left(4 \cdot \frac{\Delta\varphi}{2}\right) \tag{10}$$

Tuning the wavelength of the peak transmission in a Lyot polarization interference filter (PIF) requires changing the path-length difference, or retardance of each filter stage. An external electric field applied to the lyotropic device produces an analogue variable retardation [12]. It is therefore quite obvious how a passive polarization interference filter (PIF) can be retrofitted to be active with nematic LC [13].

Experimental part

The experimental data used in this simulation were obtained from [14-16].

The main refractive indices of PPMAECOBA in TCM for three different values of wavelength are given in figures 4 (a) and 4 (b).

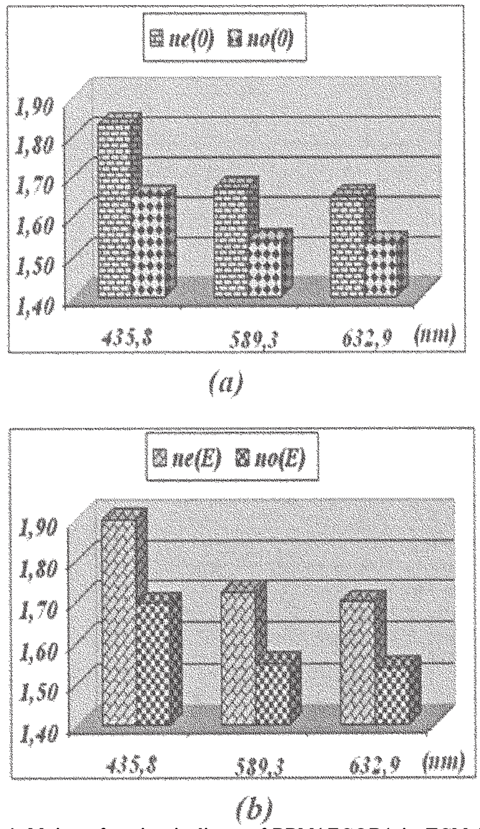


Fig. 4. Main refractive indices of PPMAECOBA in TCM (a) in absence and (b) in presence of the electrostatic field

The Cauchy fitting coefficients for PPMAECOBA in TCM were calculated by using the equations (2-4) and they are shown in the table 1.

Application interface description

The applet frame is composed by four regions (fig. 5):

- (Top–left) - displaying zone of the transmission factor of the device versus light wavelength and the image of the visible transmitted spectrum;

- (Bottom-left) - displaying zone of the image of the visible spectrum in the absence of the device (for comparison);

Table 1
CAUCHY FITTING COEFFICIENTS FOR THE ORDINARY AND EXTRAORDINARY REFRACTIVE INDICES

	Ordinary index			Extraordinary index		
i	$A_{io}(0)$	$A_{io}(E)$	α_{io}	$A_{ie}(0)$	$A_{ie}(E)$	α_{ie}
1	1,5638	1,5579	$-5,5068\cdot10^{-8}$	1,5339	1,5787	$4,1814\cdot10^{-7}$
2	$-3,6899\cdot10^{-14}$	$-3,7622\cdot10^{-14}$	$-6,7482\cdot10^{-21}$	$3,7385\cdot10^{-14}$	$3,3321\cdot10^{-14}$	$-3,7932\cdot10^{-20}$
3	$1,0165\cdot10^{-26}$	$1,2097\cdot10^{-26}$	$1,8032\cdot10^{-32}$	$3,6800\cdot10^{-27}$	$5,8926\cdot10^{-27}$	$2,0651\cdot10^{-32}$

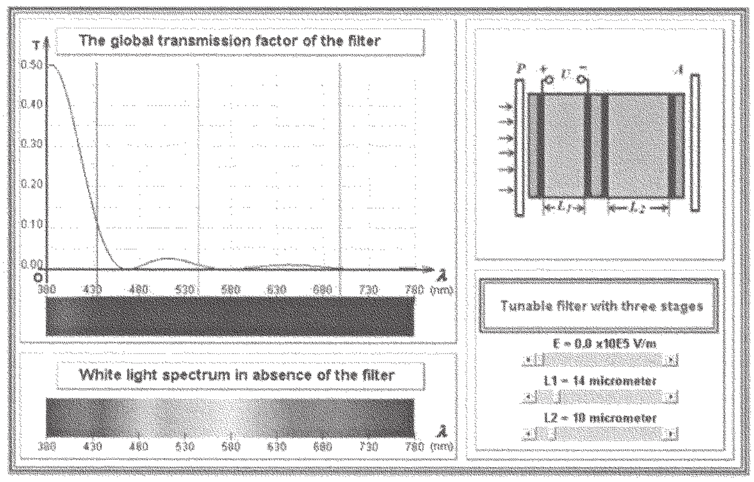
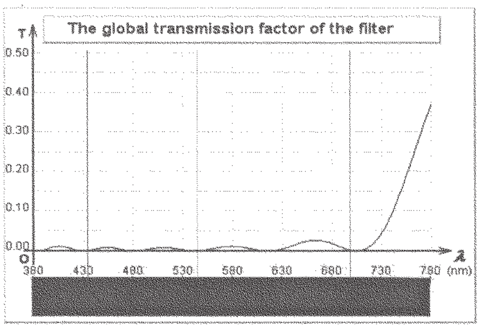
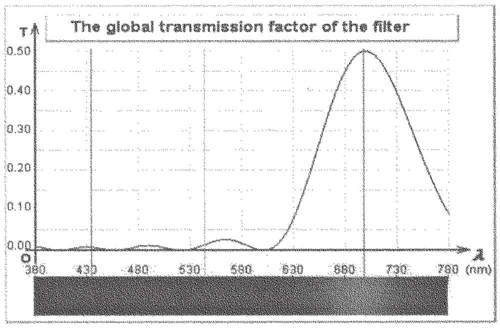


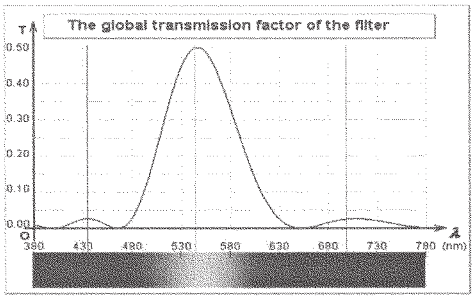
Fig.5. Image of the applet frame



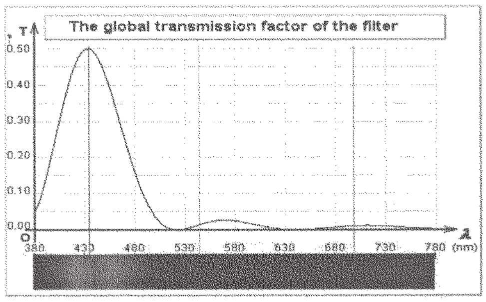
$E = 0$ or $E = 1{,}4 \cdot 10^5\ V/m$



$\lambda_R = 700nm$ for $E = 0{,}32 \cdot 10^5\ V/m$



$\lambda_G = 550nm$ for $E = 0{,}75 \cdot 10^5\ V/m$



$\lambda_B = 435{,}8nm$ for $E = 1{,}05 \cdot 10^5\ V/m$

Fig. 6. Electric field intensities for some important cases (blocked and RGB colours)

- (Top–right) - displaying zone for the first stage of the filter;
- (Bottom–right) - displaying zone for controlling scrollbars of the application.

There are three scrollbars controls labelled for the electric field intensity (E) and for the two thicknesses ($L_1$and L_2) of the lyotropic liquid crystalline layers corresponding to a first stage filter.

Results and discussions

The simulation permits a continuous modification of the wavelength corresponding to the maximum of the transmission band by modifying both the electric field intensity and the thicknesses of the used liquid crystalline layers.

When L_1 and L_2 thicknesses increase, the number of the transmission bands, obtained in the visible range, increases and their band pass decreases.

In figure 6 one can see the transmission factor of the Lyot tuneable for some value of the transmitted wavelength.

Similar simulations for a multiple stage tuneable filter made by lyotropic liquid crystal were previously published [17] by us.

Conclusions

Our work demonstrates the possibility of using the PPMAECOBA in TCM to design optoelectronic devices such a Lyot polarizing interference filter.

The simulations demonstrate that the continuously tuned filters are, generally, best suited to low resolution applications. To obtain a higher resolution it is necessary to increase the number of the stages.

The simulation may be used in studying and designing the electrically controlled tuneable polarization interference filters. The conditions in which the interference filters are working, such as external field intensity, thickness or optical characteristics of the layers can be easily established by simulation. The simulation avoids a great number of experimental trials conducting to the same results.

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