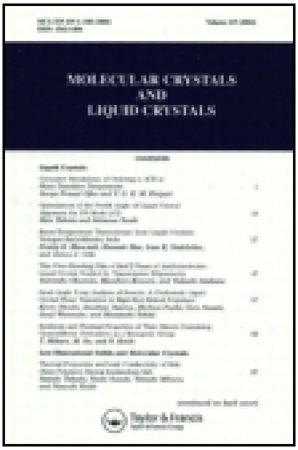

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Colour Rendering of Polymer Network Cholesteric Liquid Crystal: Model and Experimental Results

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Colour Rendering of Polymer Network Cholesteric Liquid Crystal: Model and Experimental Results

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We present a model of the colour rendering of the Cholesteric Polymer Network Liquid Crystal and a comparison with experimental results. The active medium was considered as a pile of stacked layers with continuous variable optical properties. The computation considers the optics of stratified mediums (matrix formalism) and in the complementary case analytical spectra were computed using theory of cholesterics. The spectral band and the corresponding point on the CIE (x,y) chromaticity diagram (Both colour triangle (CIE 1931) and CIELAB colorimetric space L*a*b* or L*C*h) were computed or experimentally measured. The influence of several parameters was studied such as sample thickness, pitch value, material birefringence, bandwidth broadening and modification with applied voltage.

Keywords: colour rendering; PNLC; model; chromaticity diagram

INTRODUCTION

The cholesteric reflective liquid crystal display (Ch-LCD) technology is under development to provide a low power display with high brightness in direct-direct vision. Cholesteric materials have the property of self reflection a pre-selected colour of incident white light.

In suitably prepared display cell, they also exhibit bi-stability and, as such, can present a high resolution image.

Furthermore, colour rendering is an essential parameter, determining for many applications. With this aim, several research institutions and companies have purposed reflective colour LCDs [1,2]. LCD technology can also be associated with a broad band polarizer, which improves substantially the brightness [3,4]. The limited capability was also improved by the incorporation of a metal-insulator-metal active matrix [5] or using double polarizers [6].

In this paper, we present a model of the colour rendering of the polymer network cholesteric liquid crystal and a comparison with experimental results. We study the influence of several parameters on the spectral band, such as birefringence of the liquid crystal (LC), distribution of the LC pitches, sample thickness, modification with applied voltage... In each case, the representation of the spectral band (theoretically computed or experimentally measured) and the corresponding point on the CIE (x,y) chromaticity diagram are given.

EXPERIMENTAL

Polymer network cholesteric liquid crystal (PNCLC) films were made using a liquid crystal with positive dielectric anisotropy and a photo-polymerisable cholesteric monomer. The absorption wavelength is adjusted by adding various chiral agents to the liquid crystal. The display is made with two glass plates with ITO coating and the cell gap is controlled by glass spacers. The polymerisation of the mixture was initiated by UV irradiation. By this procedure, densely cross-linked networks with a helical structure are obtained. Measurements were performed through a motor-driven Jobin-Yvon monochromator mounted with a phot-multiplier. The photo-multiplier response is monitored by a HP34401A multimeter. The whole system is computer driven and all measurements corrected to an ideally flat spectrum light source.

MODEL AND COLOUR REPRESENTATION

The process used for the active film modelling is described below. The analytical spectra were computed considering the active film as a pile of stacked layers with continuous variable optical properties. The computation used here considers the optics of stratified mediums and a matrix formalism is applied [7].

The quantitative representation of the active film colour rendering is obtained with different representation of chromaticity diagrams. The description of the visual feeling of colour is characterised by three parameters, which are the hue, the lightness and chroma or saturation [8]. The quantitative characterisation of colour depends on the triplet light source, the object observed and the observatory. Concerning the source, the calculation is performed using the D65 illumining. Moreover, we chose the standard 2° observatory of CIE 1931 system with the three associated x, y, z colorimetric functions.

Regarding the result representations, both colour triangle (CIE 1931) and CIELAB colorimetric spaces L*a*b* and L*c*h were used. However, we principally focused on the XYZ CIE 1931 representation in order to reduce the description of the aspect colour rendering. The periphery of the "colour triangle" is relative to pure colours and the centre of the diagram is associated to the achromatic point. Then, all the other colours can be represented by a point in the diagram.

RESULTS AND DISCUSSION

It is well known that the cholesteric reflection must be performed with a sample having a sufficient number of cholesteric pitches in order to have its maximum of intensity. This aspect is illustrated in Figure 1 where the spectrum is calculated for a reflection around the green colour (500 nm) and with a birefringence of 0.1.

For a thickness of 5 μm, 95% of the reflected intensity is obtained. This intensity reaches its maximum for 10 μm and does not vary when the thickness further increased. Small and predictive modifications of the point representing the spectrum are observed in the CIE (x,y) chromaticity diagram (Figure 1b).

Another expected fact is related to the shape of the spectrum with oscillations happening when the frequency strongly differs from the central frequency of the band.

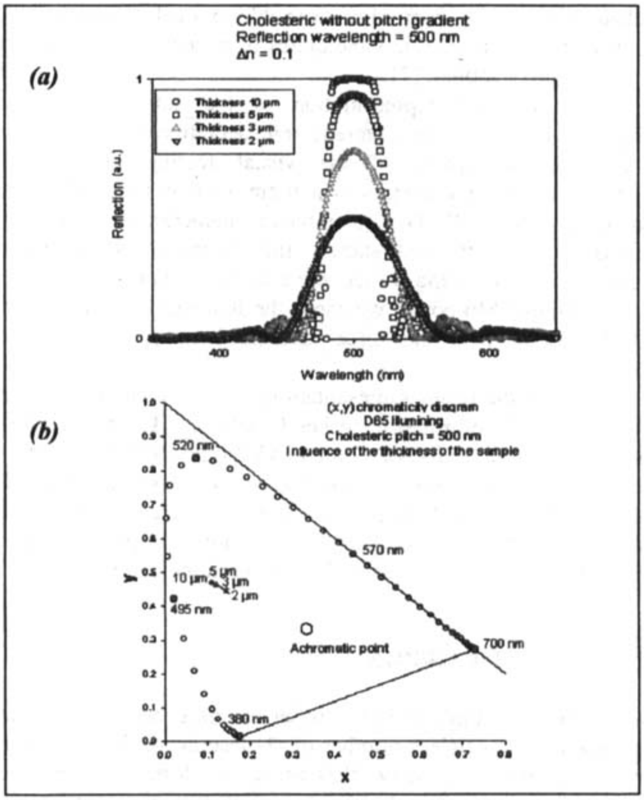

FIGURE 1 Influence of sample thickness : (a) on the calculated spectral band and (b) on the colour rendering represented by the (x,y) chromaticity diagram. See Color Plate XXXI at the back of this issue.

Considering a film having a sufficiently big thickness (20 µm) and always a birefringence of 0.1 value, the spectra were calculated when the pitch value was changed : Figure 2a is relative to the computed spectra and Figure 2b to the CIE diagram. In Figure 2a, we can notice an expected increase of the bandwidth with the pitch value. In Figure 2b, the representative points associated to the corresponding spectra are not located on the periphery of the triangle but inside, near by this periphery because of the finite value of the bandwidth.

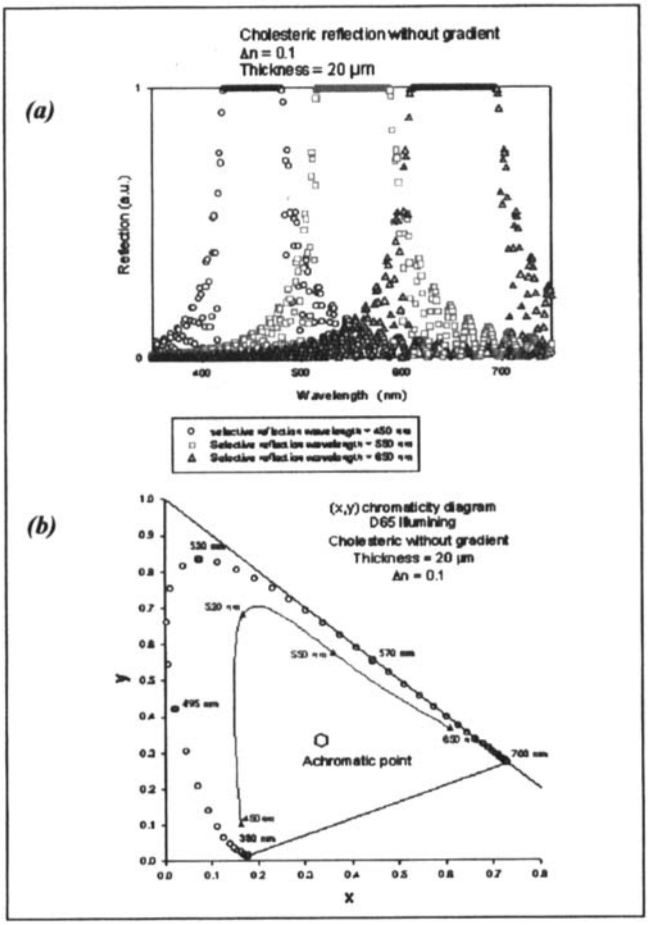

FIGURE 2 Influence of the pitch value : (a) on the calculated spectral band and (b) on the colour rendering represented by the (x,y) chromaticity diagram. See Color Plate XXXII at the back of this issue.

The measured spectra are shown in Figure 3a. Using these spectra, the corresponding representation in the (x,y) chromaticity diagram was obtained (Figure 3b). As expected, the results are close by the periphery (owing to the bandwidth if the spectra) and around the achromatic point (because of the modification of the pitch). This figure could be compared with the theoretical one (Figure 2).

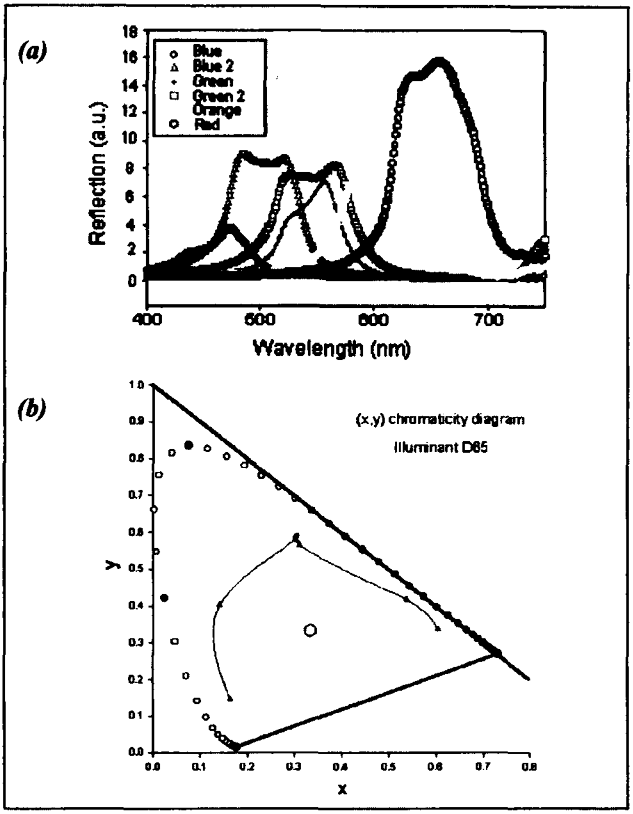

FIGURE 3 Influence of the pitch value : (a) on the measured spectral band and (b) on the colour rendering represented by the (x,y) chromaticity diagram. See Color Plate XXXIII at the back of this issue.

For a thickness of 20 μm and a reflection wavelength chosen in the green (550 nm), the band shape can be calculated for different values of birefringence. The Figure 4a illustrates the spectrum obtained and the corresponding points in the CIE diagram (Figure 4c).

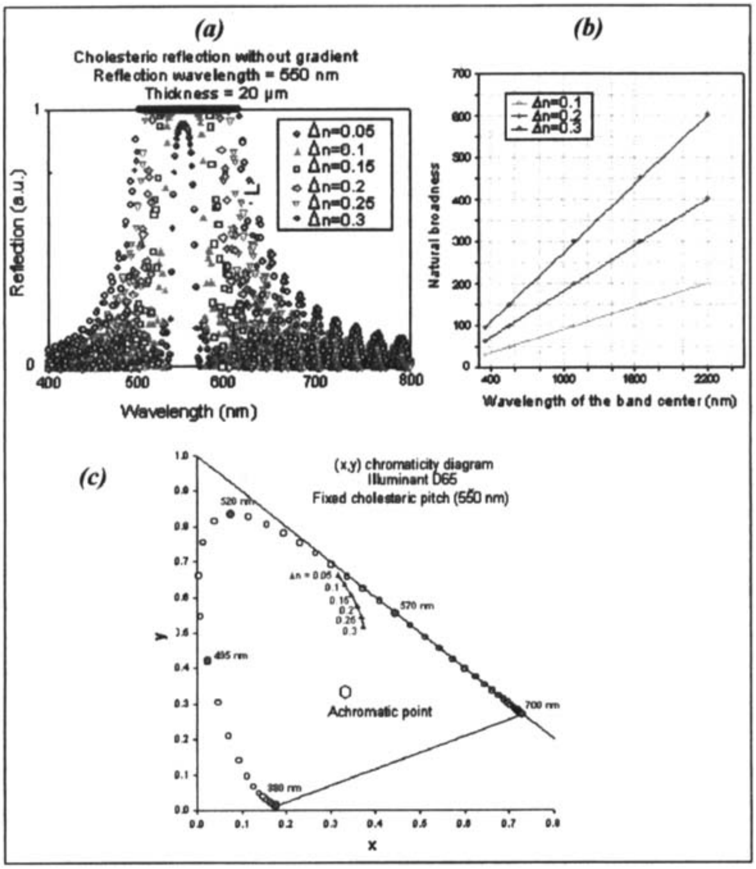

FIGURE 4 Influence of the LC birefringence (a) on the calculated spectral band, (b) on the natural broadness of the reflection band and (c) on the colour rendering represented by the (x,y) chromaticity diagram. See Color Plate XXXIV at the back of this issue.

As expected when the birefringence is increasing, the bandwidth increases in the same proportion. Moreover, the increase of this bandwidth induces a shift of the relevant point on the CIE (x,y) diagram from the periphery to the achromatic point. The same computation was performed for different pitches and allows to define a quantity very important that is the natural bandwidth broadening. Figure 4b expresses the evolution of the natural broadness as function of the wavelength of the reflection band centre for different values of the birefringence.

It is important to note that considerable broadening is expected for high birefringence ($\Delta n = 0.3$) and in the infrared wavelength range. This broadness corresponds to a single pitch sample and therefore must be distinguished from the induced broadening corresponding to a non uniform pitch in the sample. This last broadness is superposed to the first one and can multiply the bandwidth by a factor which is of several units and which precisely depends on: the shape of the pitch distribution (factors P_0 and α and thickness) when there is a pitch distribution and the shape of the intermediate area when the sample is constituted by the superposition of two layers having an individual pitch.

In the experimentally studied active films the birefringence of the liquid crystals is around 0.22 and the natural broadening between the blue and the near IR is around five or six times and the expected induced broadening is twice or three times the first broadening. At 400 nm the calculated natural spectral bandwidth is around 80 nm.

If we assume a distribution of pitch in the sample between an initial pitch P_{ini} and a final pitch P_{fin} given by $P = P_0 \exp^{-\alpha z}$ it is possible to calculate the broadening when P_{ini} and P_{fin} are modified. The shape of the bands are shown in Figure 5 for chosen values of P_{ini} and P_{fin}. In this figure, we can observe a broadening of the band and simultaneously the disappearance of oscillations.

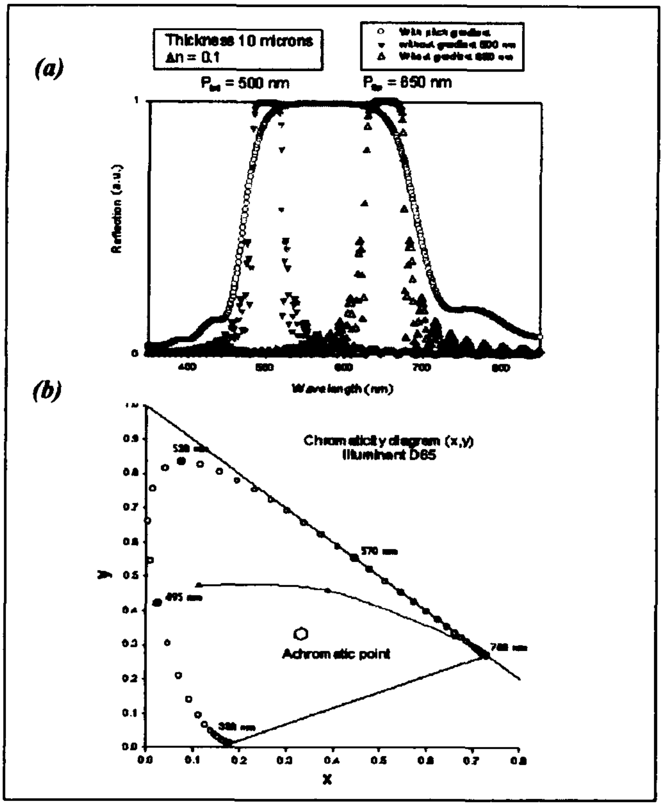

FIGURE 5 (a) Influence of the pitch gradient existence on spectral band and (b) Simulation of a pitch gradient on the colour rendering represented by the (x,y) chromaticity diagram.
See Color Plate XXXV at the back of this issue.

Superposed layers were also performed. The Figure 6a shows the spectra of the two layers (respectively reflecting in blue and green) and the spectra of the stacked layers. The Figure 6b indicates the representation in CIE 1931 diagram. The spectrum of the stacked layers is spread over a large wavelength range and the result is, as expected, a point near by the achromatic point. This effect is evidently also observed on the L*a*b* and L*C*h representations.

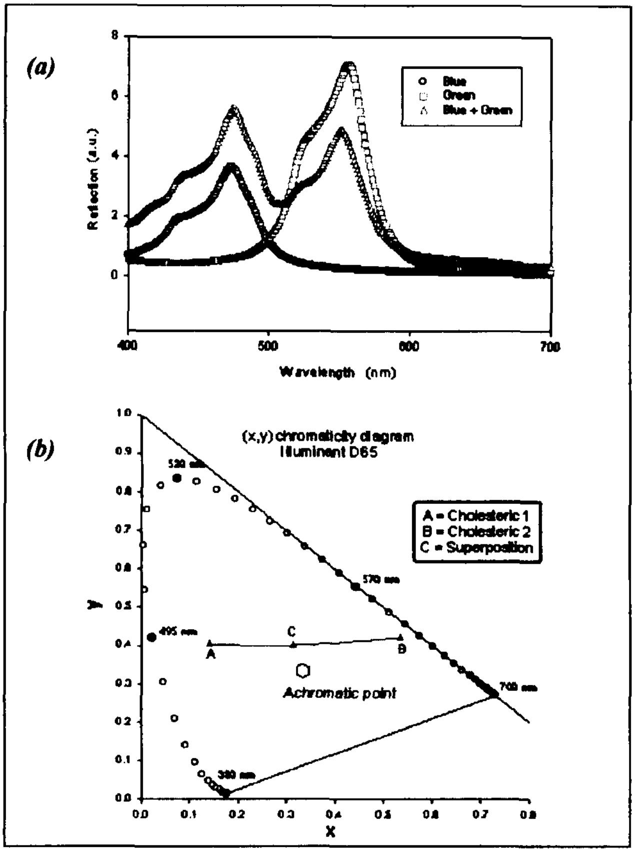

FIGURE 6 Influence of the cholesteric film superposition : (a) on the measured spectral band and (b) on the colour rendering represented by the (x,y) chromaticity diagram.
See Color Plate XXXVI at the back of this issue.

The modifications of the spectra with applied voltage were previously studied. The spectra strongly depends on the voltage application mode and it is important to distinguish the "quick cut-off voltage" and the "increasing maintained voltage". We only report here the results regarding the "quick cut-off voltage" mode.

Figure 7 presents the absorption spectra in reflection measurements as a function of wavelength and applied voltage for various cell characterised by three different reflective colours. These spectra were measured immediately after the cut-off voltage and after the refresh at high voltage. It appears that the liquid crystal molecules come back to the planar initial state for low and high applied voltage. The part between these two areas, from about 50 V to 100 V, corresponds to the diffusive state, which persists after the quick cut-off voltage.

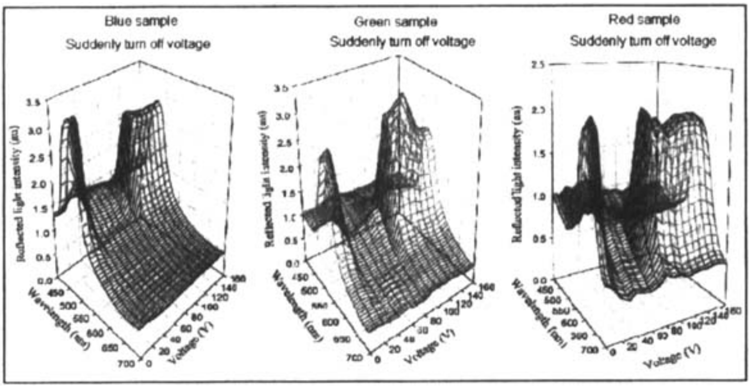

FIGURE 7 3D representation of the reflection measurements variation versus wavelength and applied voltage for three different colours of cholesteric PNLC. See Color Plate XXXVII at the back of this issue.

Figure 8a shows the representation in the (x,y) CIE 1931 diagram for a "quick cut-off voltage". Whatever the voltage application mode may be, the representation is similar: the initial colour of the sample (for all the studied samples) is modified and goes to the same scattering point. This point is not exactly the achromatic point. In the case of "quick cut-off voltage" and for the higher voltages, the representation of the spectra shows, as expected, a return of the initial colours. The same effect can also be observed in the L*C*h representations (Figures 8b).

Moreover, we could shown that the spectra strongly depends on the voltage application mode and then is different in the case of the "increasing maintained voltage".

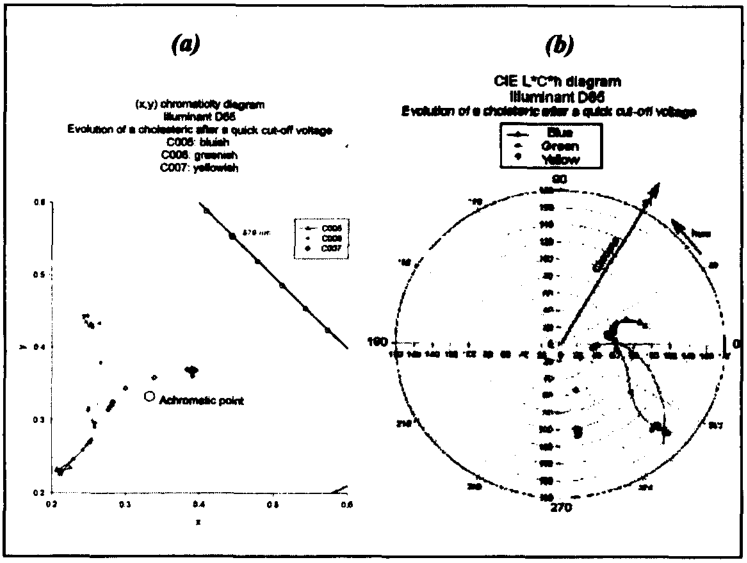

FIGURE 8 Evolution of a cholesteric PNLC after a quick cut-off voltage : colour rendering represented by (a) (x,y) chromaticity diagram and (b) CIE L*C*h diagram.
See Color Plate XXXVIII at the back of this issue.

CONCLUSION

From the whole results, we have shown that the spectral band can represented with the corresponding point on the CIE (x,y) chromaticity diagram. First, we studied the influence of various parameters in the case of one single film. The increase of sample thickness leads to small modification of the point in the CIE diagram. However, the representative points, located near the triangle periphery, shift around the achromatic point according to the pitch value. Regarding the liquid

crystal birefringence, its increase lead to a shift of the relevant point in the CIE diagram from the periphery to the achromatic point. In the case of pitch gradient in the layer, we observed a broadening of the band and the relevant point shifts nearer to the achromatic point. This same phenomenon is observed considering stacked layers. Furthermore, the experiments performed under applied voltage indicate that the representation in the (x,y) CIE diagram strongly depends on the voltage application mode and the achromatic point is never exactly reached with the samples used.

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