

This article was downloaded by:

On: 25 January 2011

Access details: *Access Details: Free Access*

Publisher *Taylor & Francis*

Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK



Liquid Crystals

Publication details, including instructions for authors and subscription information:

<http://www.informaworld.com/smpp/title~content=t713926090>

Active broadband polymer stabilized liquid crystals

H. Guillard; P. Sixou

Online publication date: 06 August 2010

To cite this Article Guillard, H. and Sixou, P.(2011) 'Active broadband polymer stabilized liquid crystals', *Liquid Crystals*, 38: 6, 933 – 944

To link to this Article: DOI: 10.1080/02678290010028753

URL: <http://dx.doi.org/10.1080/02678290010028753>

PLEASE SCROLL DOWN FOR ARTICLE

Full terms and conditions of use: <http://www.informaworld.com/terms-and-conditions-of-access.pdf>

This article may be used for research, teaching and private study purposes. Any substantial or systematic reproduction, re-distribution, re-selling, loan or sub-licensing, systematic supply or distribution in any form to anyone is expressly forbidden.

The publisher does not give any warranty express or implied or make any representation that the contents will be complete or accurate or up to date. The accuracy of any instructions, formulae and drug doses should be independently verified with primary sources. The publisher shall not be liable for any loss, actions, claims, proceedings, demand or costs or damages whatsoever or howsoever caused arising directly or indirectly in connection with or arising out of the use of this material.

Active broadband polymer stabilized liquid crystals

H. GUILLARD

Polymage 7, rue Verdi, 06000 Nice, France

and P. SIXOU*

LPMC, UMR6622, UNSA, Parc Valrose, 06018 Nice Cedex 02, France

(Received 3 July 2000; in final form 3 October 2000; accepted 13 November 2000)

We consider the realization and the electro-optical behaviour of a polymer network stabilized liquid crystal whose reflection band has been broadened. We particularly emphasize the reflective properties (mean value of the selective reflection and bandwidth, and the parameters of broadening) and their evolution with voltage. Broadband active films can be obtained under special conditions of polymerization. A mechanism concerning the broadening of the reflection band is put forward based on inhomogeneous consumption of a chiral monomer within the samples.

1. Introduction

Reflective displays are being intensively studied as they do not require a back light, making possible more compact displays. Some of these use a polymer stabilized cholesteric texture (PSCT). In a PSCT, a small amount of a monomer is incorporated in the mixture to create a polymeric network through the sample [1–3]. With such displays, in direct–direct vision, there is only one colour in the reflective state because the width of the planar cholesteric selective reflection is generally small (between 50 and 100 nm in the visible spectrum).

Broadband passive films were first successfully made by Broer *et al.* [4–6]. The broadening of the reflection band is obtained thanks to diffusion of the monomer perpendicular to the film plane which leads to the existence of a pitch gradient. A UV gradient within the sample is necessary to induce that diffusion and a dye is added to the monomers to absorb UV radiation. Decreasing the UV intensity leads to a more broadened reflection band [4–6].

Broadband active films would react to an applied voltage and would therefore have many advantages. They would become scattering with an applied voltage and even homeotropic textures and displays with black/white grey scale can be expected. Moreover, considering light flux control, energy gains could be achieved thanks to these three possible states [7].

A broadband two-stage active film (reflective-scattering) has been obtained [8] thanks to an inhomogeneous

distribution of a chiral monomer concentration arising through the process of polymerization: it is assumed that there is an overlap of reflected spectra from a two-pitch region due to the creation of a greater chiral concentration around the polymer network than in the bulk.

Hikmet and Kemperman obtained broadband active films [9, 10] by applying to gels the method used by Broer for passive films. A mixture of two monomers was used, one being nematic and the other chiral. The monomer concentration seems high: an example is given with 40% monomer [10]. During polymerization, there is an inhomogeneous distribution of the chiral monomer within the system which determines the cholesteric pitch. A dye is used to create a more significant UV gradient and therefore to obtain a more broadened reflection band. A transparent state is reached for such films.

A broadband active film can also be achieved by means of a temperature gradient: the pitch of a suitable material depends on the temperature and it has been shown that if the cholesteric liquid crystal is cured at a certain temperature, the pitch is fixed even if the material is afterwards cooled [10, 11].

Active broadband films are also obtained with a method apparently close to the one originally used by Hikmet and Kemperman [9]. In our studies, only one monomer is used and at a low concentration (only a few per cent). The influence of parameters affecting the broadening is studied in detail. Experiments clarifying the broadening phenomenon are described and a mechanism is proposed. The electro-optical behaviour of the films is also investigated.

* Author for correspondence e-mail: sixou@naxos.unice.fr

2. Experiments and discussion

2.1. Natural broadness of the reflection band

The pitch of the cholesteric helix depends on the composition of the mixture: if a cholesteric liquid crystal is obtained by adding chiral compounds to a nematic liquid crystal, the higher the concentration of the chiral compounds, the smaller is the reflection wavelength. The width of the reflection band depends on several parameters [12–16]:

$$\lambda = n_{co} \times \text{pitch} = 0.25(n_e^2 + n_o^2)^{1/2} \times \text{pitch}$$

$$\Delta n = n_e - n_o$$

$$\Delta\lambda = (\Delta n/n_{co})\lambda$$

where λ = ‘average’ wavelength, n_{co} = cholesteric ordinary refractive index [16], Δn = birefringence, n_e = liquid crystal extraordinary index, n_o = liquid crystal ordinary index and $\Delta\lambda$ = width of the reflection band. The width of the reflection band is thus proportional to the reflection wavelength. Consequently, for the same liquid crystal and the same chiral dopants, the higher the pitch of the cholesteric liquid crystal, the broader is the reflection band. But if the liquid crystal is changed, the birefringence will be different and therefore the bandwidth will change as well.

A nematic liquid crystal was taken, and chiral compounds were added as well as 3 wt% of a monomer (to create a polymeric network through the sample to stabilize the textures). The concentration of the chiral compounds was changed in order to modify the wavelength of the reflection band. The width of the reflection band for each sample was measured, giving the results in table 1.

In the visible range, the ‘natural’ width of the reflection band is not broad enough to give a white reflective display and the reflection band has to be broadened.

2.2. Broadening of the reflection band

2.2.1. By changing the liquid crystal birefringence

The width of the reflection band can be modified by changing the nematic liquid crystal. Figure 1 represents the evolution of the reflection bandwidth with the wave-

Table 1. Reflection band width.

| Spectral range | Mean reflection band wavelength λ /nm | Reflection band width $\Delta\lambda$ /nm |
|----------------|---|---|
| Green | 510 | 70 |
| Red | 630 | 90 |
| Near infrared | 950 | 130 |
| | 1550 | 230 |
| Mid infrared | 1725 | 240 |
| | 2065 | 300 |
| | 3200 | 450 |

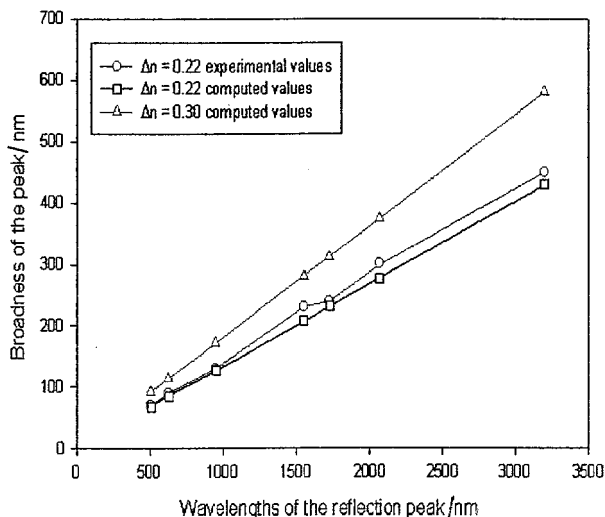


Figure 1. Variation of the broadness of the reflection band with the reflection wavelength and the birefringence.

length for liquid crystals with a birefringence between 0.22 and 0.3. We have included the experimental points obtained from table 1 which are in agreement with the computed points using a birefringence equal to 0.22 for the mixture experimentally tested. However, the birefringence cannot be modified over a wide range: the maximum values known for Δn are less than 0.4.

2.2.2. By modifying the polymerization conditions

We have recently carried out AFM studies on a polymer network grown in a polymer stabilized cholesteric liquid crystal with 3 wt% of a chiral monomer [17]. The monomer consisted of a siloxane backbone with both reactive acrylate and liquid crystal side groups. The UV intensity used was 0.6 mW cm^{-2} . It appeared that the network is denser on the surface strip closest to the UV source suggesting that the monomer is heterogeneously consumed, probably because of the existence of a UV gradient across the sample.

2.2.2.1. First mechanism. To have a broadband film, it is necessary to create a pitch gradient across the sample. The previous observations were used to create a broadband reflection. If a UV gradient exists within the sample, there will be a gradient of consumption of the monomer. In the areas close to the UV lamp, the UV intensity is stronger than in the areas close to the other surface. The consumption of the monomer is therefore higher in the areas close to the UV lamp. There ensues a diffusion of the monomer from the areas where the irradiation is low (low consumption of the monomer) to the areas closer to the lamp where the irradiation is higher and thus the consumption of the monomer is greater. A representation of the profiles of the UV

gradient and monomer diffusion within the sample is given in figure 2. Hikmet and Kemperman [9] also explain the origin of the broadening by an inhomogeneous distribution of the chiral monomer within the sample.

A liquid crystal whose pitch strongly depends on the monomer concentration has to be used so that the inhomogeneous consumption of the monomer across the sample leads to the creation of the pitch gradient. Such a diffusion of the chiral monomer is necessary to broaden the reflection band but there is another condition to the existence of a pitch gradient: the diffusion of the monomer modifies the pitch of the liquid crystal but it has to be blocked by the polymerization process. The mechanism is explained in more detail in §2.2.2.2.

2.2.2.2. Experiments and observations

First attempts. A liquid crystal whose pitch strongly depends on the monomer concentration has to be used. That requirement can be achieved by using a chiral monomer with a reverse rotation sense to that of one of the chiral dopants. The materials for the experiments are a nematic liquid crystal with positive dielectric anisotropy, a mixture of chiral dopants, a chiral monomer and a photoinitiator (Irgacure 907, 2% of the monomer weight). The wavelength of the mixtures was measured before and after a relatively strong (5 mW cm^{-2}) and long irradiation (1 h) in order not to have a UV gradient through the sample and to have complete consumption of the monomer. The results are given in the table 2, and show that the higher the monomer concentration, the higher is the wavelength.

A striking feature is that, except for the sample with 10 wt% monomer, the wavelength before and after irradiation is the same. Since all the chiral monomer is consumed, the wavelength after irradiation should be 400 nm (case without monomer). An explanation maybe

Table 2. Reflection wavelength versus monomer concentration.

| wt % Monomer | λ Before irradiation/nm | λ After irradiation/nm |
|-----------------|------------------------------------|-----------------------------------|
| 0 | 400 | / |
| 3 | 440 | 445 |
| 6 | 490 | 490 |
| 10 | 540 | Broadening |

that mesogenic networks have strong interactions with the surrounding liquid crystal molecules. The network formed by the cholesteric monomer could have a very strong influence on the cholesteric mixture, so that although the monomer is consumed, the pitch remains the same.

What happens for the 10 wt% monomer sample is interesting. The sample has a greyish aspect after irradiation. The peak corresponding to the reflected intensity is much larger after irradiation (figure 3). If the reflected intensity is analysed from the side exposed to the UV radiation, the reflected intensity for the highest wavelengths is stronger than that observed in the spectrum obtained from the other side (figure 3). The highest wavelengths can only be obtained in areas that became richer in monomer; this therefore means that the polymer network is denser close to the UV source. A diffusion of the monomer towards the areas closest to the UV source seems to occur. These two observations suggest the existence of a pitch gradient even for a very strong intensity. The hypothesis we suggest concerning the existence of such a pitch gradient seems to be correct.

The greyish metallic aspect is most obvious after an irradiation at 0.095 mW cm^{-2} for 6 h (see figure 4). On the edges, there seems to be an effect inhibiting polymerization due to oxygen (no metallic aspect). The interface between the two areas is shown in figure 5(a). The analysis of the reflected intensity shows that a large

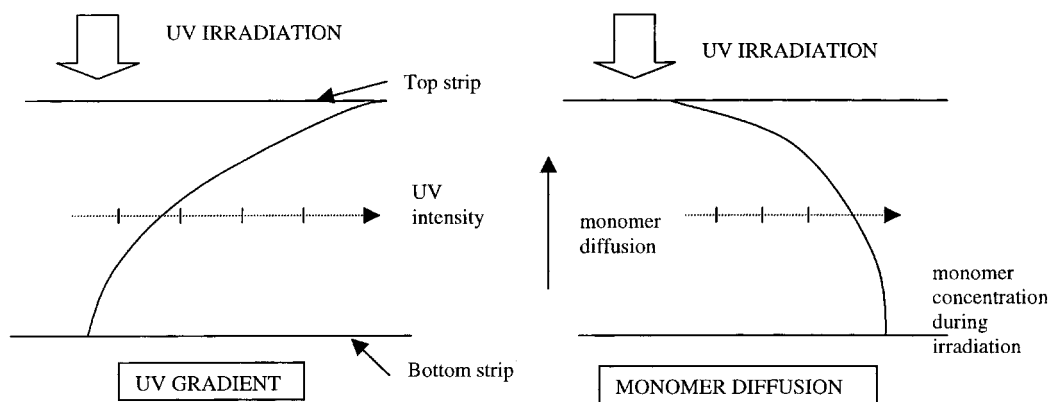


Figure 2. UV gradient and monomer diffusion during irradiation.

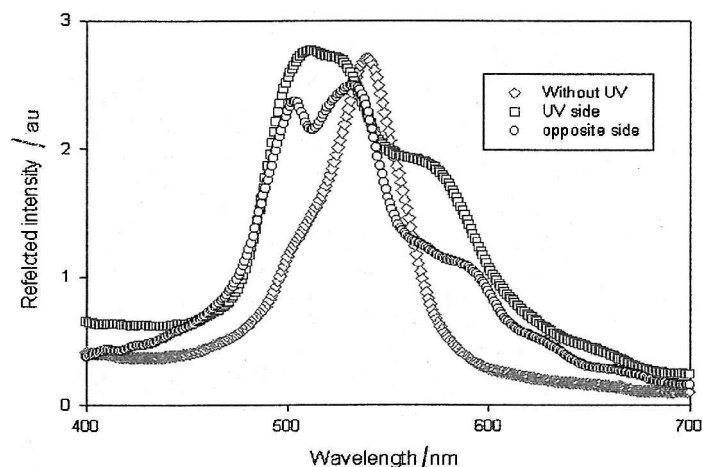


Figure 3. Broadened reflection band from the UV-exposed side and the opposite side.

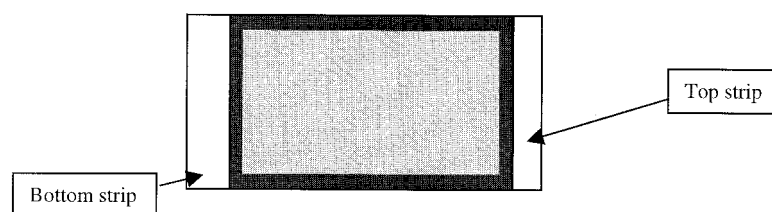


Figure 4. Top view of the sample after irradiation.

broadening occurs (figure 6): before irradiation, the width of the reflection band is 70 nm; after irradiation it increases 200 nm. It is therefore possible to have a reflection band more than three times broader than the initial band.

Other experiments and observations. Other experiments and observations were made to understand better the broadening process and confirm the process mechanism. The characteristics of each sample are given in table 3.

After irradiation, the cells were put in a container with acetone. The solvent completely replaced the liquid crystal after a few hours. The acetone was then evaporated at ambient temperature and the two strips were carefully split. The polymer network (10% monomer, 0.06 mW cm^{-2}) that stays on the strips was analysed by optic microscopy—figure 5(b) shows the strip close to the UV

source, figure 5(c) shows the strip on the opposite side. The polymer network is much denser on the strip close to the UV source.

Photographs taken from the exposed UV side or from the other side can show differences. The colour observed in reflection is different: the red colour observed on the exposed UV side, figure 5(d), is linked to a denser network; a less dense network leads to a green reflection colour; figure 5(e).

Diffusion of the monomer within the sample was also demonstrated by the following experiments. A sample was irradiated through a mask as shown in figure 7.

The mask was made of alternate black and transparent strips, the black strips preventing the UV radiation from reaching the sample. Polymerization therefore occurs preferentially in the areas exposed to the UV radiation, i.e. below the transparent areas of the mask (figure 7).

Table 3. Influence of parameters for broadening of the reflection band. The figures 11 to 15 correspond to a study of the broadening parameters; the parameter whose influence is studied in each figure is represented by the symbol /.

| Figure no. | Thickness/ μm | Irradiation time/h | Monomer concentration/wt % | UV intensity/ mW cm^{-2} | Polyimide layer |
|------------|--------------------------|--------------------|----------------------------|-----------------------------------|-----------------|
| 9 | 8.5 | 7 | 6.5 | 0.06 | yes |
| 11 | / | 7 | 6.5 | 0.06 | no |
| 12 | 8.5 | / | 6.5 | 0.06 | no |
| 13 | 8.5 | 7 | / | 0.18 | yes |
| 14 | 8.5 | 7 | 6.5 | / | yes |
| 15 | 8.5 | 7 | 5 | 0.18 | / |
| 16 | 15 | 7 | 10 | 0.095 | no |
| 17 to 20 | 15 | 7 | 6.5 | 0.06 | yes |

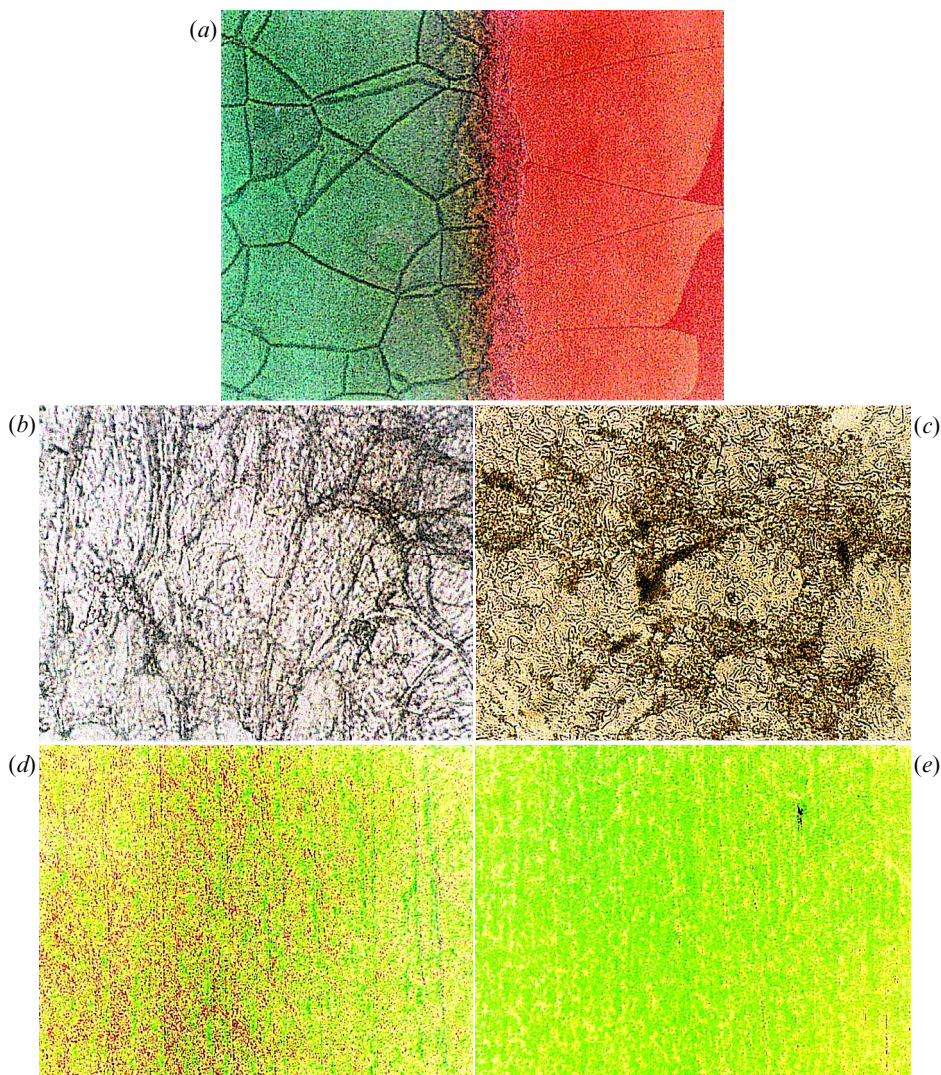


Figure 5. (a) 6.5 wt % monomer: left—reflection view, creation of a gradient after irradiation; right—reflection view, no polymerization due to oxygen inhibition. (b) 10 wt % monomer: polymer network, strip close to the UV side. (c) 10 wt % monomer, the same sample as that in (b): polymer network, strip opposite side. (d) 5 wt % monomer: reflection view, UV irradiation side. (e) 5 wt % monomer: the same sample as in (d): reflection view, opposite side.

After polymerization, the sample's appearance and the liquid crystal texture were different in the exposed and non-exposed areas (figure 8). The exposed areas were more polymerized, as is obvious around the oily-streaks; almost no polymerization occurred around the oily streaks in the non-exposed areas.

Each area was analysed in reflection (figure 9), showing that (1) the reflection wavelength in the non-exposed areas (area 1) is lower than the initial reflection wavelength of the liquid crystal before irradiation; (2) a significant broadening of the reflection band takes place in the exposed areas (area 3); (3) at the intersection of the exposed and non exposed areas, both phenomena occur (area 2).

We can conclude from these experiments that there is a diffusion process of the chiral monomer from the non-exposed areas towards the exposed areas. In the non-exposed areas, the decrease of the reflection wavelength shows that there is an impoverishment of chiral monomer which has therefore diffused towards the areas of polymerization. Two phenomena occur in the exposed areas: on the one hand there is an enrichment in monomer diffusing from the non-exposed areas (lateral diffusion) and on the other, there is also a vertical diffusion in the exposed areas, as described by the mechanism in figure 10. The areas exposed to a low UV irradiation are distributed across the sample. Therefore there is a UV gradient and a consumption of monomer which is higher close

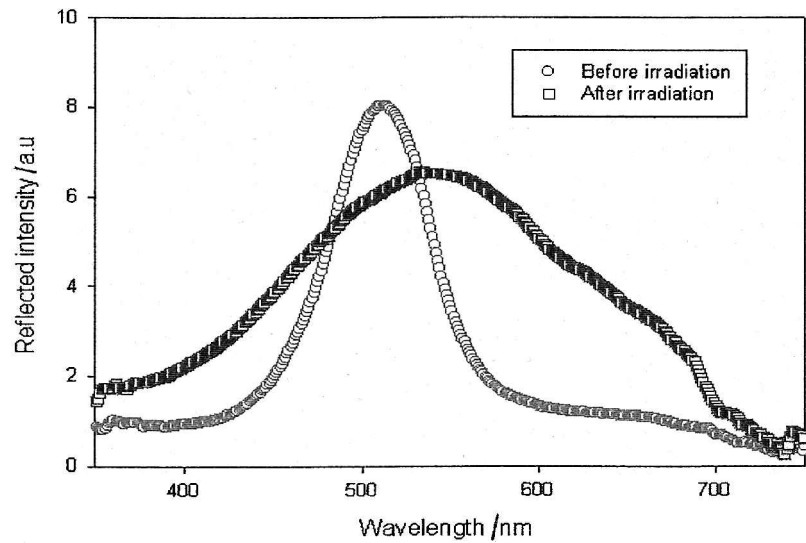


Figure 6. Example of broadening of the reflection band after irradiation.

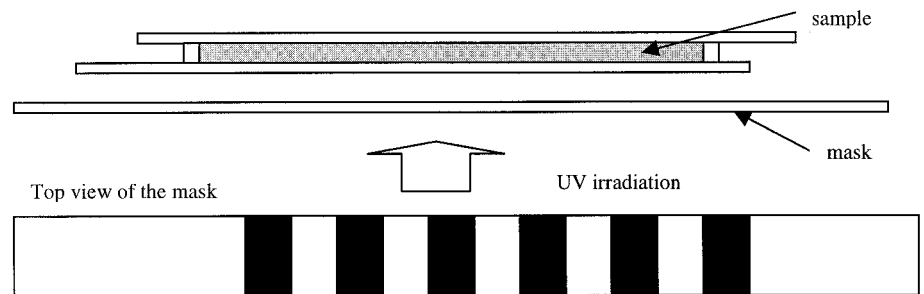


Figure 7. Diffusion experiment irradiation through a mask.

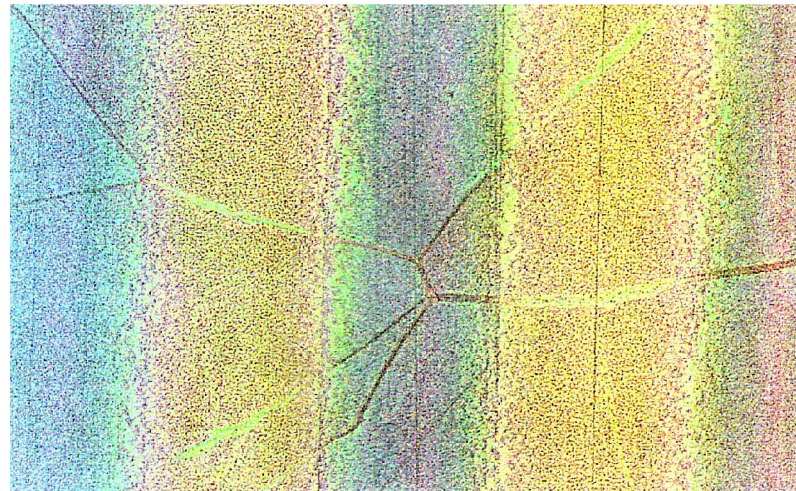


Figure 8. Reflection view of a sample after an irradiation through a mask.

to the lamp. This leads to a diffusion of monomer from the surface region remote from the UV towards the other surface.

This experiment confirms the hypothesis that we have put forward: there is a diffusion of the monomer towards the areas of consumption (close to the UV source). These

results are in agreement with experiments carried out by Broer *et al.* [6] for passive films and Hikmet and Poels [18] for active films with nematic liquid crystals: they observed a diffusion of the monomer (or of one of the monomers) of the mixture from the dark areas towards the illuminated areas.

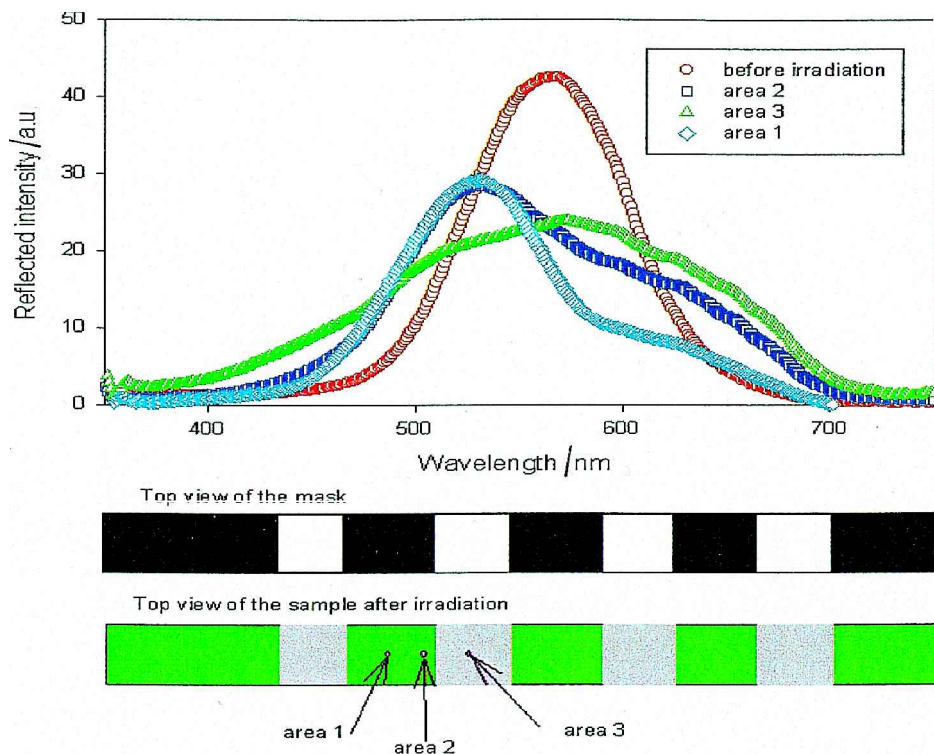


Figure 9. Diffusion experiment on the prepolymer. Irradiation through a mask, analysis of the reflected spectra in several areas.

2.2.2.3. Improved mechanism

By taking into account the foregoing results and observations, the following mechanism can be put forward. A relatively strong irradiation (more than 10 mW cm^{-2}) induces almost no change in the pitch of the cholesteric helix though all the monomer is consumed. Because of the very strong interactions between the polymer network and the surrounding liquid crystal molecules, there is no modification of the pitch. But, if the irradiation is very low (typically less than 0.1 mW cm^{-2}), the monomer will be consumed preferentially close to the UV source. Because of these strong interactions between polymer and active liquid crystal, the pitch is not changed, but there is a decrease in the concentration of the chiral monomer (figure 10—step 1).

Since the monomer is preferentially consumed close to the UV source, a diffusion phenomenon takes place (figure 10—step 2). The free monomer diffuses from the areas richest in monomer to the poorest areas (close to the UV source). In the areas poorest in monomer, the monomer supplied by the diffusion causes an increase in the pitch since it increases with the monomer concentration. Due to the diffusion process, the pitch decreases in the remotest areas from the UV source since the monomer concentration decreases.

However, at the same time, polymerization occurs: in the areas where the monomer is consumed, the pitch is fixed (figure 10—step 3). Then the process proceeds.

Of course, the three steps actually happen at the same time. This mechanism is based upon the following ideas. When the monomer is consumed, there is no modification of the pitch although the quantity of chiral monomer decreases; the pitch is fixed. On the other hand, if the chiral monomer concentration changes, not because of on-the-spot consumption of the monomer but due to a diffusion of the monomer, the pitch does change. If there is a supply of monomer, the pitch increases (this happens in the areas close to the UV source); then there is an on-the-spot consumption of the monomer by polymerization—the pitch is fixed. Again, the two mechanisms happen simultaneously. If there is an impoverishment in monomer, the pitch decreases (this happens in the remotest areas from the UV source); then there is an on the spot consumption of the monomer by polymerization—the pitch is fixed.

2.2.2.4. Parameters of the reflection band broadening

The parameters concerning the broadening of the reflection band were studied. To establish the influence of a given parameter, all the others were kept equal. All the characteristics of the samples are summarized in the table 3.

Influence of sample thickness. Three samples with different thicknesses were made (12, 20 and $50 \mu\text{m}$) and the reflection of each sample measured (figure 11) after

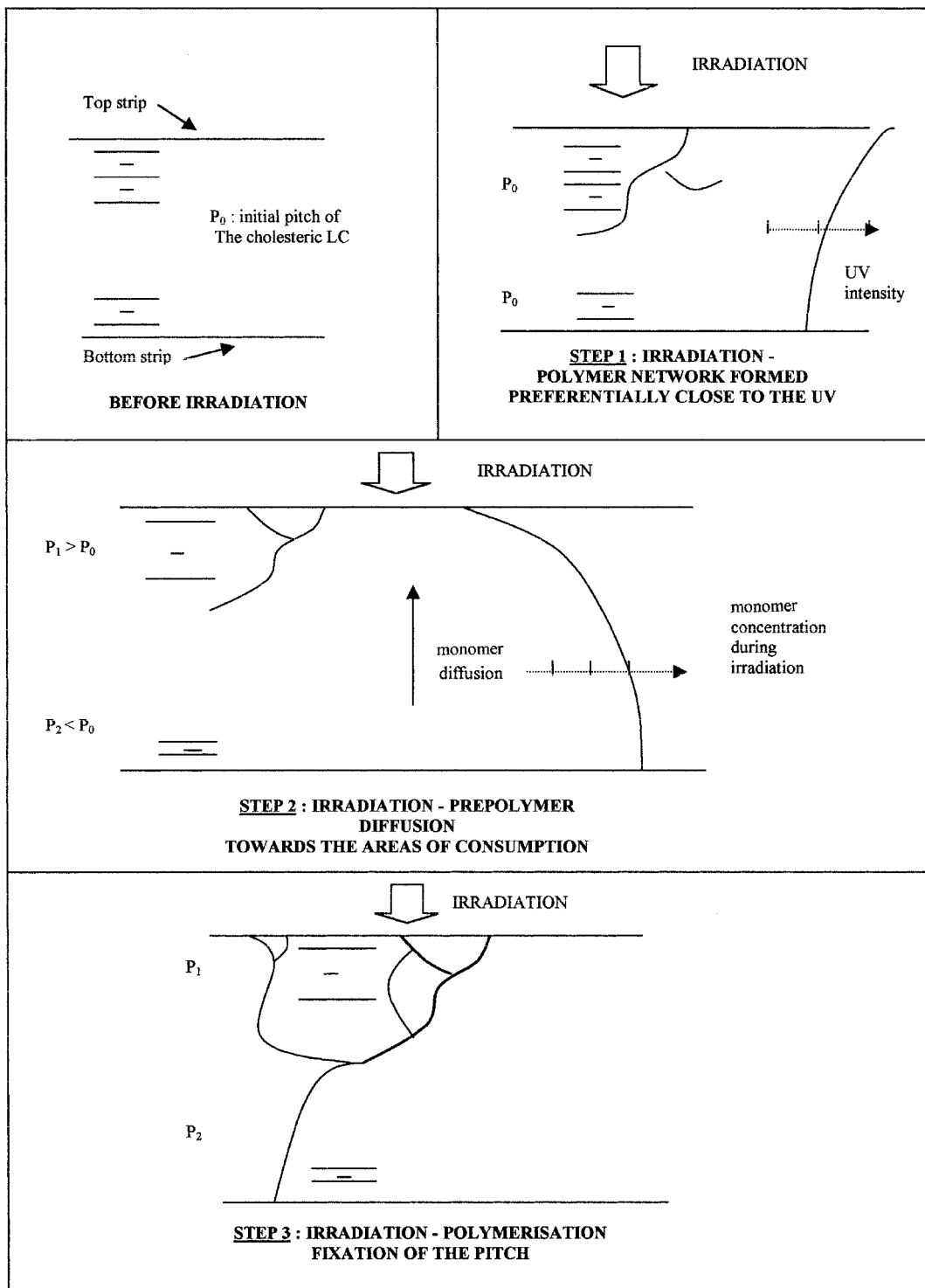


Figure 10. Steps in the creation of the pitch gradient: cross-section of a sample.

irradiation. The width of the reflection band is almost the same for the three samples. Changing the sample thickness induces no major changes in the reflection

broadening. The important consequence is that thin samples (10–15 μm) with a broad reflection band can be made in order to obtain low threshold voltages.

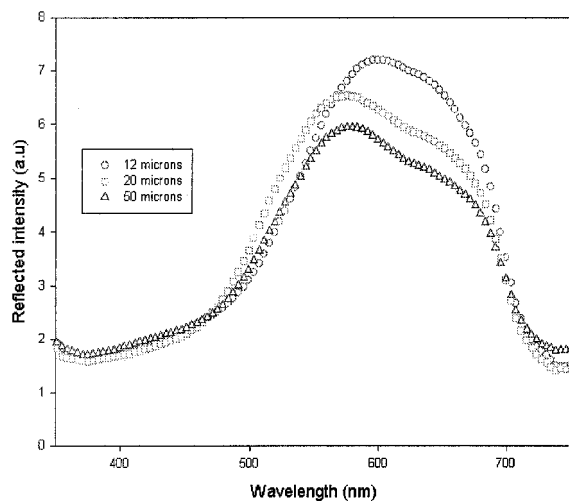


Figure 11. Influence of thickness.

Influence of irradiation time. Figure 12 shows the broadening of the reflection band with time of irradiation. After 15 min of irradiation, no broadening happens, but after 1 h, the reflection band is much broader. Longer irradiation times only slightly modify the broadening. We can therefore suppose that the polymerization mechanism is almost over after one hour. Irradiation times of typically a few hours or less allow a broad reflection band to be obtained.

Influence of monomer concentration. Since the pitch of the liquid crystal depends on the monomer concentration, a broader range of reflection wavelengths is expected after irradiation for high concentrations. Samples were made by modifying the concentration of the chiral monomer (figure 13). For 5% monomer, the reflection band is 140 nm in width, and for 6.5% monomer 180 nm in width. It appears that the width of the reflection

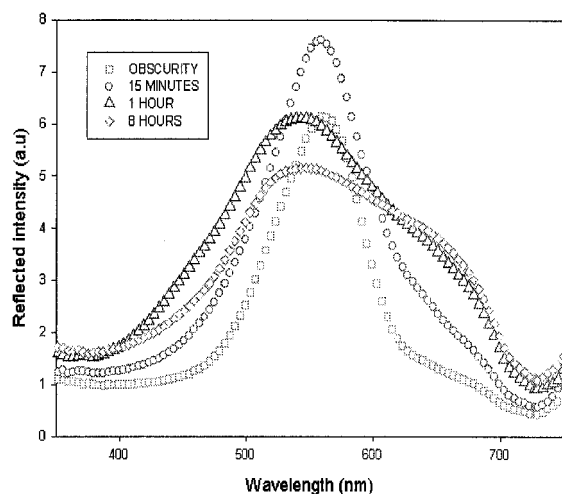


Figure 12. Influence of irradiation time.

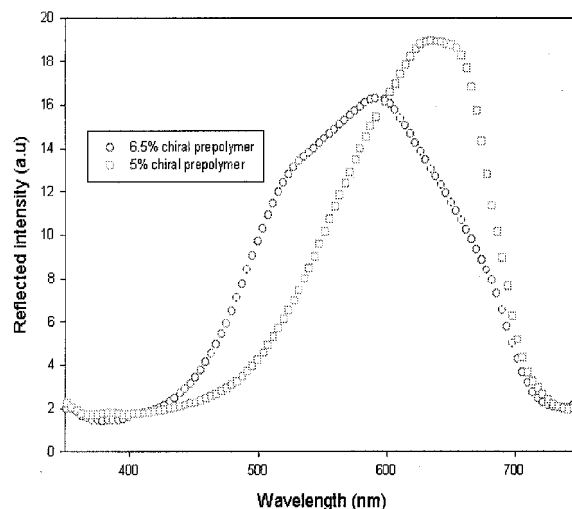


Figure 13. Influence of chiral monomer concentration.

band increases with increase of the chiral monomer concentration.

Influence of UV intensity. The broadening mechanism depends on UV irradiation; therefore we decided to study the influence of UV intensity on the broadening of the reflection. The samples were irradiated at four different UV intensities (figure 14) for 7 h. A broader reflection band is obtained for the 0.06 mW cm^{-2} UV intensity. For lower intensities, the polymerization mechanism is not complete. As observed by Broer *et al.* [4–6], for passive films, decreasing the UV intensity leads to a broader reflection band. Small intensities are suitable for achieving a broad reflection band. For very small intensities, longer irradiation times must be used.

Influence of an orientation layer. Figure 15 shows the influence of the presence of an orientation layer on

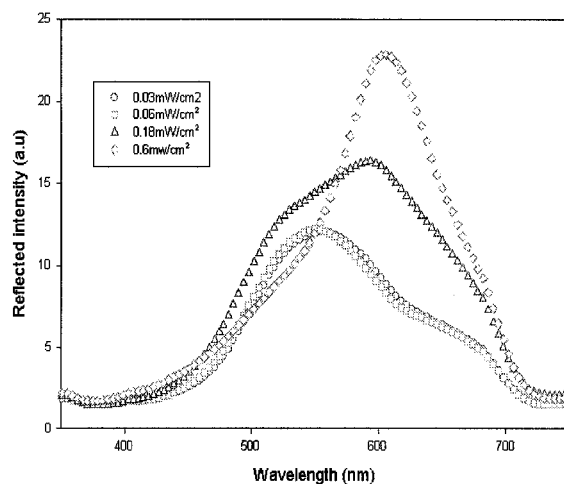


Figure 14. Influence of UV intensity.

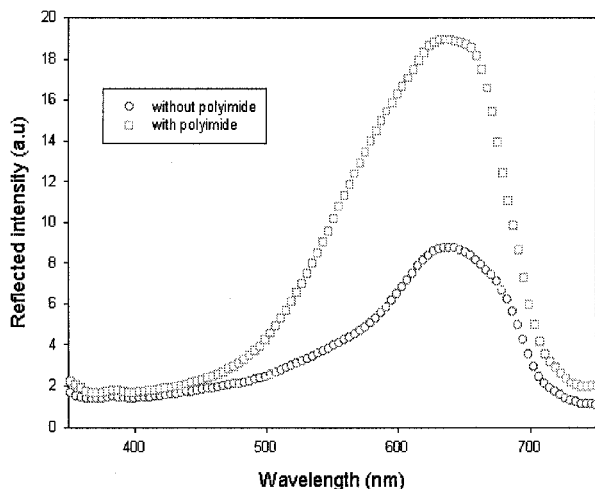


Figure 15. Influence of the use of an orientation layer.

the broadening of the reflection band. The width of the reflection band (measured at the mid-height of the band) is the same with or without a polyimide layer, but the reflected intensity is higher with an orientation layer. It is therefore better to have a polyimide layer.

Influence of other parameters. Other parameters such as the quantity of photoinitiator or the use of a photosensitizer (isopropyl thioxanthone ITX) induce no great changes in the broadening of the reflection band. Adding a UV absorber (Tinuvin 1130) to the mixture does not in our case give a broader reflection band, whereas a broadening was obtained by Broer *et al.* [4–6] for passive films and Hikmet and Kemperman [9] for active films.

2.2.2.5. Voltage behaviour

The voltage behaviour of a sample with 10% monomer was studied (table 3, figure 16). With an applied voltage (95 V), the sample loses its reflectivity and becomes scattering. When the field is cut off, the liquid crystal returns to its planar orientation (reflective state). A two-stage broadband active film can be achieved.

The stability of the voltage behaviour depends on monomer concentration. For lower concentrations, the return to the initial reflective state is less good. The sample remains partially scattering and the scattering becomes more significant as the monomer concentration becomes lower. For high concentrations of monomer, dense networks are created; there are therefore very strong interactions between the polymer network and the surrounding liquid crystal molecules. The return to the reflective state is therefore easier for samples with the highest monomer concentrations.

The threshold voltage depends on monomer concentration. In the latter case, the third state (transparent

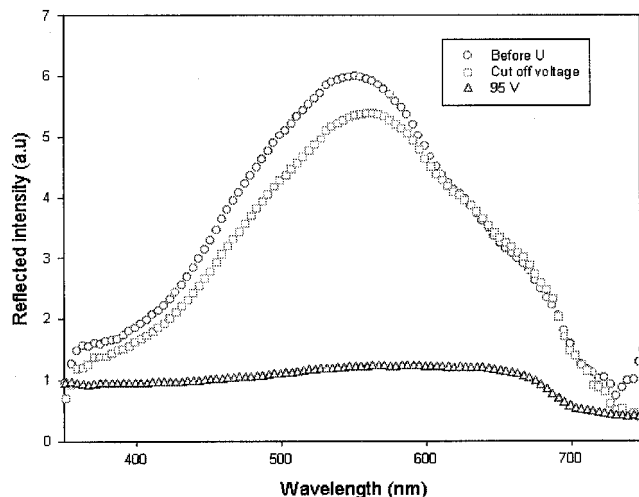


Figure 16. Two-stage broadband reflective/scattering (see table 3).

state) is not obtained because of the high monomer concentration. To reach the homeotropic state, a lower monomer concentration is necessary.

Figure 17 represents the absorbance of another sample with a lower monomer concentration (6.5%) without an applied voltage. The reflection band is 150 nm in width. When the voltage is increased, the sample becomes scattering; the absorbance then increases (figure 18). Then the sample begins to become transparent; the absorbance is then lowered (figure 18). If the voltage is further increased, the liquid crystal molecules become homeotropic and the sample completely transparent (figure 18). On that graph, there is also shown the reflection band without an applied voltage. If we compare them, we can conclude that the scattering of the

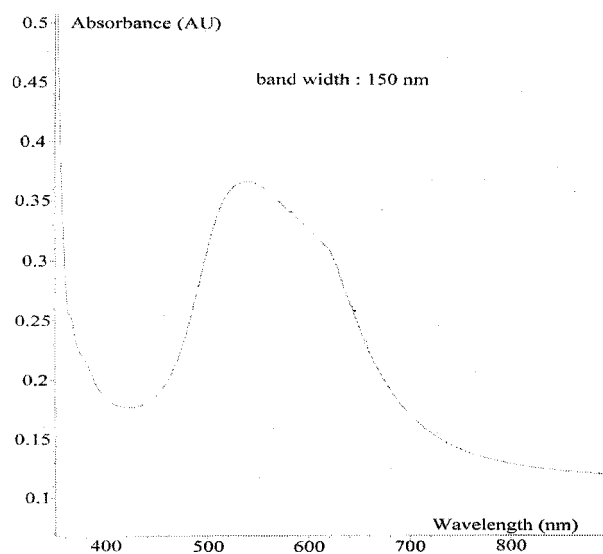


Figure 17. Reflection band before application of a voltage (see table 3).

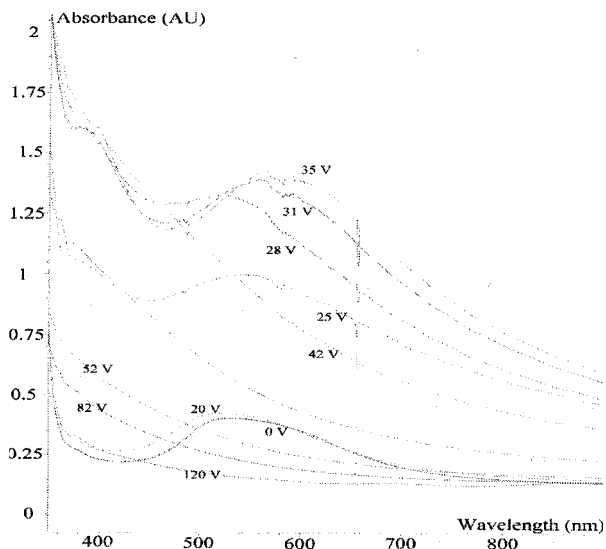


Figure 18. Voltage behaviour of the broadened sample (sample figure 16, see table 3).

sample before the application of the voltage is very low. When the voltage is suddenly cut off, the sample remains scattering but is still reflective (figure 19); the reflection band appears on the base line corresponding to the scattering state and showing that the sample is still reflective.

Another analysis was made to study only the reflection of the sample when the voltage is cut off (figure 20). When the voltage is cut off, the reflection band is measured again; the reflected intensity is lower since the sample is also scattering and the reflection band is 140 nm in width, that is a little lower than the initial breadth of the reflection band (before application of the voltage). The important point is that the reflection band is not destroyed by the application of the voltage.

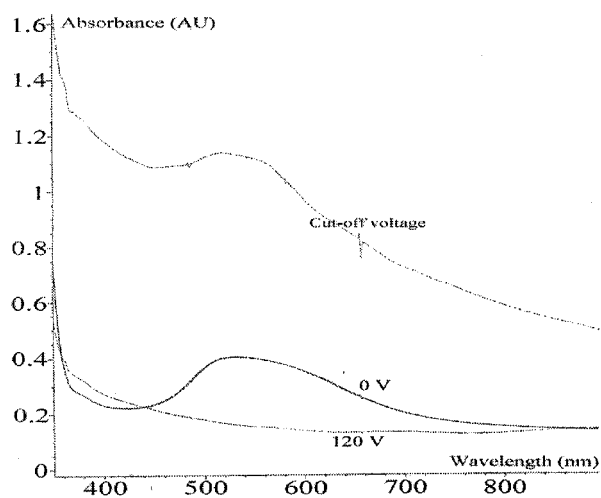


Figure 19. Return to the planar state when the voltage is cut off (sample figure 16).

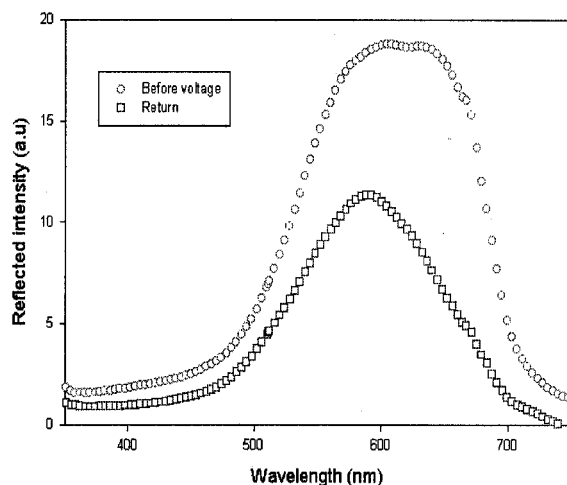


Figure 20. Comparison of the reflection band before/after application of a voltage.

The creation of an inhomogeneous polymer network throughout the sample can explain the existence of the scattering when the voltage is cut off. In the areas where the polymer network is denser, it is probably too dense, and the voids of the network are too small: this prevents the liquid crystal molecules from returning to their initial orientation. But to have a broadening of the reflection band, a rather high monomer concentration is necessary. A compromise has therefore to be found.

Ways of lowering the scattering will be discussed in a future article.

3. Conclusions

A broadening of the reflection band in PSCT has been obtained and a mechanism based on the creation of an inhomogeneous polymer network across the sample is put forward. We have identified the parameters of the broadening as:

- (1) UV intensity—low intensities are necessary;
- (2) irradiation time—rather short times are suitable (one or a few hours);
- (3) sample thickness—thin samples can be made;
- (4) monomer concentration—the broadening increases with concentration of the monomer.

A mechanism is put forward to explain the broadening: it is due to an inhomogeneous consumption of the chiral monomer within the sample.

The voltage behaviour of the samples was investigated. A two-stage sample can be made with a broadband reflection without voltage and with scattering when a voltage is applied. If the homeotropic state is reached, the sample recovers its broadband reflective state when the voltage is cut off, but is also scattering. Modifications of the liquid crystal mixtures are therefore necessary.

References

- [1] YANG, D. K., CHIEN, L. C., and DOANE, J. W., 1970, *International Display Research Conference Digest*, 49.
- [2] YANG, D. K., CHIEN, L. C., and DOANE, J. W., 1992, *Appl. Phys. Lett.*, **60**, 3102.
- [3] YANG, D. K., and DOANE, J. W., 1992, *SID Dig.*, **23**, 759.
- [4] BROER, D. J., LUB, J., and MOL, G. N., 1995, *Nature*, **378**, 467.
- [5] BROER, D. J., MOL, G. N., VAN HAAREN, J. A. M. M., and LUB, J., 1999, *Adv. Mater.*, **11**, 573.
- [6] BROER, D. J., LUB, J., VAN NOSTRUM, C. F., and WIENK, M. M., 1998, *Recent Res. Dev. Polym. Sci.*, **2**, 313.
- [7] SIXOU, P., 2000, Applied Photonics, SPIE conference, May 22/24 Glasgow.
- [8] LEROUX, N., FRITZ, W. J., DOANE, J. W., and CHIEN, L. C., 1995, *Mol. Cryst. liq. Cryst.*, **261**, 465.
- [9] HIKMET, R. A. M., and KEMPERMAN, H., 1998, *Nature*, **392**, 476.
- [10] HIKMET, R. A. M., and KEMPERMAN, H., 1999, *Liq. Cryst.*, **26**, 1645.
- [11] to be published
- [12] DE GENNES, P. G., and PROST, J., 1993, *The Physics of Liquid Crystals* (Oxford: Oxford University Press), Chap. 6.
- [13] KOZAWAGUCHI, H., and WADA, M., 1978, *Mol. Cryst. liq. Cryst.*, **45**, 55.
- [14] ST JOHN, W. D., FRITZ, W. J., LU, Z. J., and YANG, D. K., 1995, *Phys. Rev. E*, **51**, 1191.
- [15] ST JOHN, W. D., LU, Z. J., and DOANE, J. W., 1995, *J. appl. Phys.*, **78**, 5253.
- [16] HIKMET, R. A. M., and ZWERVER, B. H., 1992, *Liq. Cryst.*, **12**, 319.
- [17] GUILLARD, H., SIXOU, P., and TOTTEAU, D. *Macromolecules* (submitted).
- [18] HIKMET, R. A. M., and POELS, H. L. P., 2000, *Liq. Cryst.*, **27**, 17.