Thin film polarizer and color filter based on photo-polymerizable nematic liquid crystal

Mohammad Mohammadimasoudi*[a,b], Kristiaan Neyts[a,b], Jeroen Beeckman [a,b]
[a] ELIS Department, Ghent University, Gent, Belgium [b] Center for Nano- and Bio-photonics, Ghent University, Ghent, Belgium

ABSTRACT

We present a method to fabricate a thin film color filter based on a mixture of photo-polymerizable liquid crystal and chiral dopant. A chiral nematic liquid crystal layer reflects light for a certain wavelength interval Δλ (= Δ*n*.*P*) with the period and Δn the birefringence of the liquid crystal. The reflection band is determined by the chiral dopant concentration. The bandwidth is limited to 80nm and the reflectance is at most 50% for unpolarized incident light. The thin color filter is interesting for innovative applications like polarizer-free reflective displays, polarization-independent devices, stealth technologies, or smart switchable reflective windows to control solar light and heat. The reflected light has strong color saturation without absorption because of the sharp band edges. A thin film polarizer is developed by using a mixture of photo-polymerizable liquid crystal and color-neutral dye. The fabricated thin film absorbs light that is polarized parallel to the *c* axis of the LC. The obtained polarization ratio is 80% for a film of only 12 µm. The thin film polarizer and the color filter feature excellent film characteristics without domains and can be detached from the substrate which is useful for e.g. flexible substrates.

Keywords: Liquid Crystal, UV curing, polymerization, polarizer, optical filter

1. INTRODUCTION

Photo-polymerisation of aligned liquid crystalline mono(di)acrylate monomers is an elegant and versatile method to form oriented and structured liquid crystal (LC) polymers. The liquid crystalline mono(di)acrylates can be aligned easily, similar to non-reactive nematic LCs. The photo-polymerisation process freezes the orientation of the liquid crystals and keeps the anisotropic optical properties of the films. Homogeneous and birefringent optical films based on liquid crystalline mono(di)acrylate monomer can be applied to improve the performance and properties of optical devices such as displays, lasers, color filters, retarders and polarizers. The optical function can be optimized by tuning the anisotropic properties and by controlling the orientation and order of these compounds before photo-polymerization. The optimized optical functions are stabilized by the formation of a cross-linked network through photo-polymerization of these compounds. In addition, chiral nematic liquid crystals (CLC) are well-known for their spontaneous arrangement into helical structures with corresponding periodic refractive index profile.[1] The periodicity of a CLC, possesses a 1D photonic band gap (PBG).The photonic band gap is determined by: $\Delta\lambda = \Delta n P$ with $\Delta n = n_e - n_o$ the LC birefringence and P the distance of one 360° rotation of the nematic director. When an unpolarized light beam propagates towards the planar CLC cell along the helical axis, the CLC layer reflects circularly polarized light of the same handedness as the chiral helix and light with a different handedness than the CLC helix can propagate in the PBG wavelength range.[1, 2] This is an interesting feature which can be used to fabricate color filters, polarizers and lasers.[3-10] We are able to make thin films of these color filters using the photo-polymerization method and by adding appropriate chiral dopant to the liquid crystalline mono(di)acrylate monomers. The bandwidth of reflection is limited to 80nm and the reflectance is at most 50% for unpolarized incident light. It is possible to drastically increase the wavelength range of the reflection.[11, 12] The thin color filter is interesting for innovative applications and stealth technologies like polarizer-free reflective displays

*Mohammad.Mohammadimasoudi@elis.ugent.be; phone +32 9264 8952; fax +32 9264 3594; lcp.elis.ugent.be

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and polarization-independent devices. The thin color filter can also be used in smart switchable reflective windows to control solar light and heat.

A second possibility is to use non-chiral LC. In addition, absorbing dye molecules can be mixed with the LC to further increase light absorption. The fabricated thin film polarizer absorbs light that is polarized parallel to the *c* axis of the LC. The obtained contrast is 9 for a film with thickness of only 12 μm. The thin film polarizer and color filter feature excellent film characteristics without domains. The application of such thin film polarizers can be interesting for applications which require very small thicknesses of the final device. One example are electro-active contact lenses.[13 14]

All these films are mechanically, thermally and chemically (apolar solvents) stable and therefore very suitable to be processed in optical devices as additional films or as in-cell optical components. The films are very thin and can be detached from the substrate and applied inside the cell or they can be used in flexible optical devices such as flexible displays or electro-active contact lenses. It is also possible to photopattern the color filter and polarizer by using selective photo irradiation through a photomask, which is required for the realization of 3D displays. Compared to previously reported polymerized thin films,[11, 15] the new method provides a mono domain thin film. Hence the incident light does not scatter. In case of a color filter, the reflected light exhibits strong color saturation without absorption because of the sharp band edges.

2. FABRICATION

The photo polymerizable mixture is prepared by mixing liquid crystalline monoacrylate monomers (RM105, Merck) and two liquid crystalline diacrylate monomers (RM257 and RM82, Merck). The physical properties of the liquid crystalline diacrylate monomer (RM257) given by the material supplier, indicate that the refractive indices for ordinary and extraordinary light are $n_o = 1{,}508$, $n_e = 1{,}687$ and the melting and clearing points are 66°C and 127°C, respectively. To increase the nematic range down to room temperature, other liquid crystalline monomers (RM82-RM105) are added to the mixture. The photo initiator (Irgacure 819, BASF) is added to the mixture and an inhibitor (tert-Butylhydroquinone, Sigma-Aldrich) is added to inhibit thermal polymerization reactions. To obtain color filter material, the right handed chiral dopant (BDH1305, Merck) is added to the mixture. The photonic band gap of the color filter is tunable by selecting the appropriate chiral dopant concentration. The chemical structure of the above materials is shown in figure 1. For the thin film polarizer, a black dichroic dye is added to the mixture instead of chiral dopant.

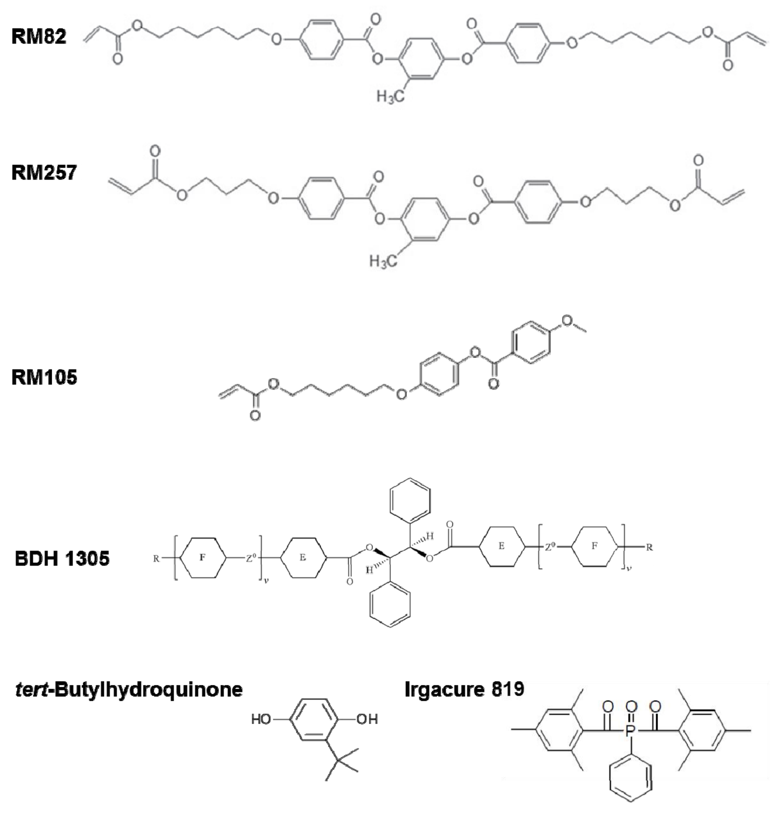

Figure 1: Chemical structure of two liquid crystalline diacrylate monomers having side groups of different lengths (6-carbon spacers for RM82 and 3- carbon spacers for RM-257), liquid crystalline monoacrylate monomer (RM105), chiral dopant (BDH 1305), inhibitor (tert-Butylhydroquinone) and initiator (Irgacure 819).

The mixture is mixed with a magnetic stirrer. The cells are fabricated with two glass substrates with a 30 nm thick conductive Indium-Tin-Oxide (ITO) electrode coating. The substrates are coated with a nylon layer and rubbed anti-parallel in order to stabilize the CLC in the planar texture with the helical axis perpendicular to the glass substrates. The gap in the empty cell is determined by spacers balls mixed inside the glue. In this work different spacers (6µm-8µm) are used. The composite mixtures are injected into the empty cells using the capillary effect in vacuum on a hot stage in the isotropic phase (92°C) of the polymerizable LC mixture. The cells are cooled down such that the liquid crystal can orient itself into a helical structure (planar structure in case of polarizer) as a uniform film without domains. The dye molecules also align to the direction of LCs in the cell. Then the cell is exposed to UV light from a mercury lamp (with the main power at 365 nm and a blocking filter for short and long wavelengths) to polymerize the CLC mixture and polarizer mixture.

3. RESULTS AND DISCUSSION

3.1 Dye-doped thin film polarizer

A 6 µm polarizer is formed with mono-domain orientation of the LC. The structure of the dye-doped polarizer is schematically shown in figure 2(a). The dye-doped polarizer is placed onto a conventional polarizer with the LC director either perpendicular (figure 2(b)) or parallel (figure 2(c) to the conventional polarizer direction.

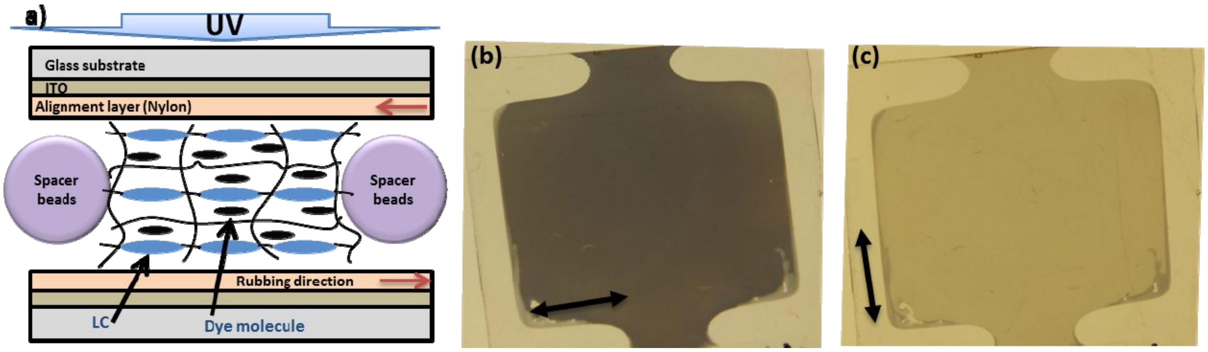

Figure 2. a) Structure of a polymerized dye-doped polarizer. b) A photograph of a 6 μm thin film dye-doped polarizer with a 2×2 cm^2 region placed on a polarizer which the direction of LC film b) perpendicular and c) parallel to the polarization of incident light.

To quantify the optical properties of dye-doped polarizer, the transmittance of the polarizer is measured by using a spectrophotometer (Perkin Elmer). The cell is place in the photospectrometer such that the LC direction is either parallel ($T_{//}$) or perpendicular ($T\perp$) to the incident polarized light. The resulting graphs are shown in figure 3. The films show a broad absorption ranging from 400 nm to 650 nm. The contrast of the polarizer is defined as the ratio of $T_{//}$ and $T\perp$. The maximum contrast of 9 is obtained around at a wavelength of 550-600 nm. These results confirm the fact that the long axis of the chromonic dyes are oriented along the LC direction. Its anisotropic orientation is maintained after the photo-polymerization process. The contrast ratio however is rather low compared to commercial film polarizers which easily reach contrasts of 5000 These commercial polarizers however are typically several tens or hundreds of micrometers thick. It is known that the nematic phase results in a rather low dichroic dye order parameter and a low dichroic ratio. Using smectic phases, the dichroic ration and hence the contrast of the film can be improved drastically.[16, 17] The film has good resistance for some solvents and is stable up to 100°C. The film can be detached from the substrate and can be used in flexible devices.

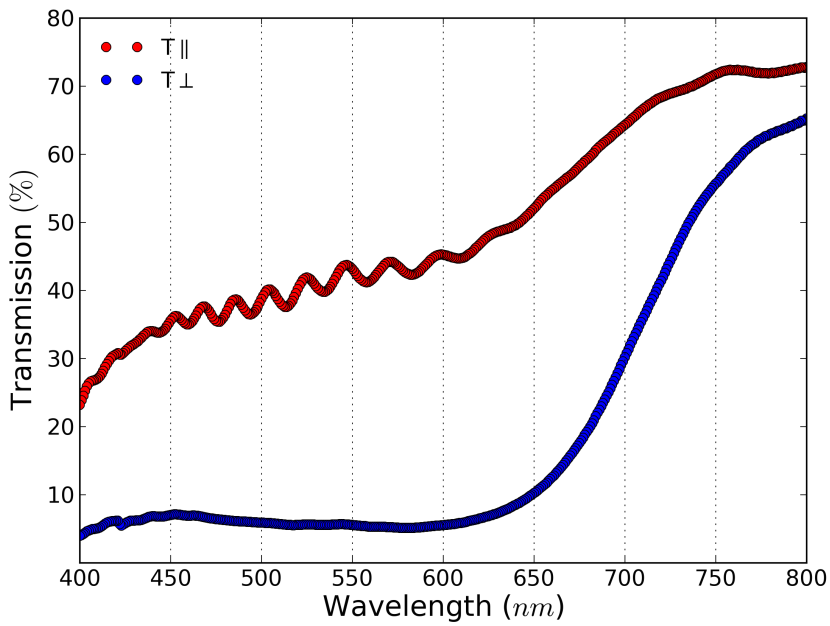

Figure 3. Optical properties of 12 μm thin films dye-doped polarizer. $T_{//}$ ($T\perp$) is the transmittance when the aligned LC direction is parallel (perpendicular) to the polarization of incident light.

3.2 CLC thin film Color filter

A CLC polymer film is formed exhibiting selective reflection of right handed circularly polarized light. The color filter film is otherwise transparent without observable scattering. The schematic structure and photograph of the CLC polymerized color filter are depicted in figure 4. The color filter is placed on a black background on which the UGent logo is printed in white. The image clearly indicates that the cell does not scatter light thanks to the mono domain structure. Obtaining a monodomain CLC layer is technologically quite challenging.

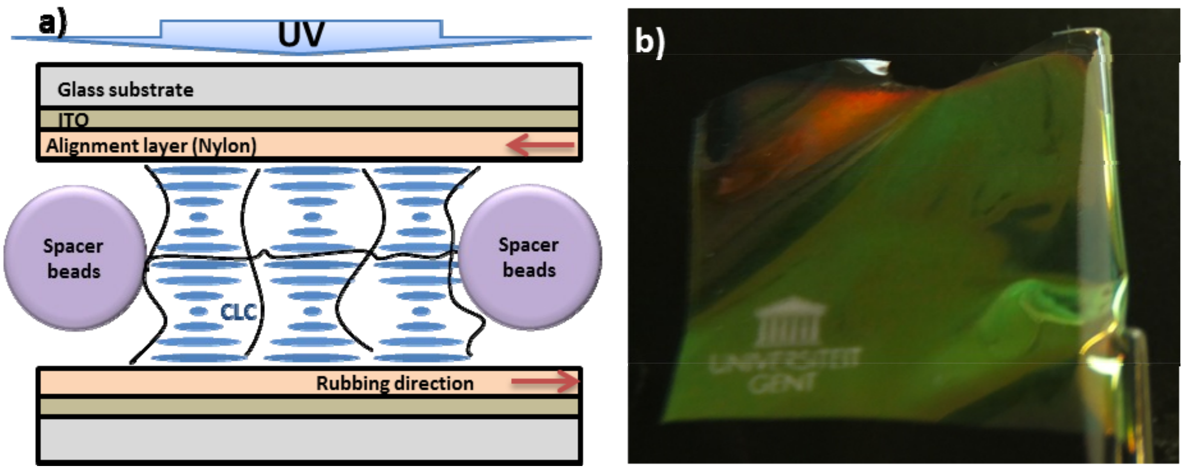

Figure 4. a) Structure of a polymerized CLC color filter. b) Photograph of an 8 µm thin film polymerized CLC color filter placed on a black background on which the UGent logo is printed in white to illustrate the lack of scattering.

A number of CLC color filters are made by using mixtures with different chiral dopant concentration. To investigate the quality of the photonic band gap, the transmission spectra of the cells for unpolarized light are measured by a spectrophotometer. The fabricated CLC films exhibit a broad PBG with a total bandwidth of approximately 80 nm and good reflectivity (almost 50%) in the PBG region as shown in figure 5. The photonic band gap of the devices shifts to the blue by increasing the concentration of the chiral dopant. The reflected light shows strong color saturation because of the sharp band edges.

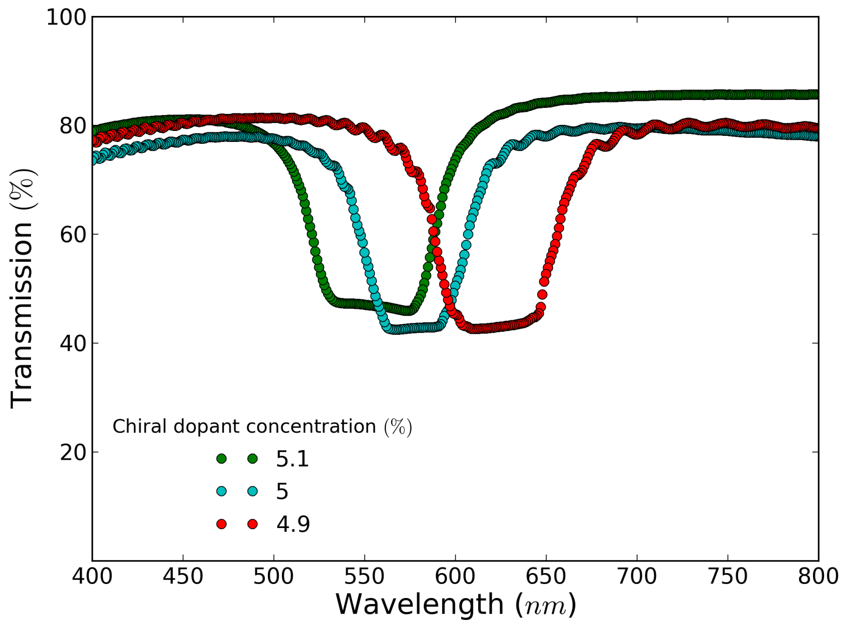

Figure 5. Transmission spectra (for unpolarized light) for 8 µm thin color filters with various concentrations of chiral dopant. Almost 50% of the incident light is reflected in the photonic band gap.

4. CONCLUSION

We have demonstrated a CLC thin film color filter and dye-doped polarizer with photo-polymerization of liquid crystalline mono (di)acrylate monomers. The PBG of the color filter is around 80 nm with high reflectivity. The thin film dye-doped polarizer has a broad absorption band between 400 nm and 650 nm and has a contrast ratio of 9 for a film of only 12 µm. Both thin films can detach from the substrate. These films have thermal stability and chemical resistivity (against apolar solvents) and are suitable to be processed in optical device manufacturing as additional films or as in-cell optical components.

5. ACKNOWLEDGMENTS

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