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The Effect of Accelerated Post-Curing on Haze and Switching Voltages of a UV-Cured PDLC Film Formulation

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Abstract

The influence of accelerated ultraviolet (UV) post-curing on the electro-optical (EO) performance of an industrial polymer-dispersed liquid crystal (PDLC) formulation was systematically investigated under production-relevant conditions. Primary curing intensity was varied within 40–200 mW/cm² range to establish baseline relationships between curing kinetics, morphology, haze (Hon), and switching voltages (V_{10} and V_{90}). Subsequently, accelerated post-curing treatments were applied on samples cured at 43.2, 106.5, and 162.8 mW/cm². Increasing primary curing intensity resulted in a near-linear decrease in haze and switching voltages, indicating improved polymer network homogeneity and refractive index matching. In contrast, accelerated post-curing consistently increased normal haze and produced minor but systematic variations in switching voltages.

Keywords: Polymer-dispersed liquid crystal (PDLC), UV curing, accelerated post-curing, haze, switching voltage, morphology, phase separation.

1. Introduction

Polymer Dispersed Liquid Crystals (PDLCs) have been extensively studied for smart glazing and optical modulation applications. The electro-optical performance of PDLC depends strongly on polymerization-induced phase separation (PIPS), which governs droplet size distribution, interfacial anchoring strength, and refractive index matching. The curing intensity, temperature, exposure time, and formulation composition collectively determine polymer network architecture and resulting electro-optical behavior.

The effect of material and process parameters on electro-optical properties of industrial-scale PDLC films are essential for manufacturing of high-quality products. Among the material parameters, such as chemical and physical properties and composition, as well as process parameters, such as curing intensity, temperature and time; thickness; natural aging; phase separation and curing kinetics are important factors influencing the electro-optical properties of PDLC films [1-17]. In particular, the effect of material composition on morphology and electro-optical properties in various PDLC film formulations have been also reported in some recent literature [18-26]. More specifically, the process parameter such as curing UV intensity have also shown to be dominant contributing factors on the kinetics of phase separation and polymerization, morphology and electro-optical properties of PDLC films [27-32].

Other recent studies and review showed that higher cure temperature or longer cure times tend to increase polymer crosslinking and can change droplet size/distribution, transmissions and switching voltages. Multiple experimental datasets confirm higher UV dose and longer exposure tends to accelerate phase separation, yielding to various droplet morphologies with predictable effects on electro-optical performances of PDLC [13-15, 33-36].

Although primary UV curing conditions have been widely investigated, the influence of accelerated post-curing on already-formed PDLC morphology remains less reported in the literature. Secondary UV exposure may induce additional crosslinking, polymer shrinkage, interfacial stress redistribution and droplet morphology evolution, where understanding these mechanisms is critical for production-line optimization.

The present work is the continuation of our previous studies [10-15, 24-26] regarding the effect of material and process parameters on the morphology, optical transmissions, switching voltage and response times of industrial-scale flexible PDLC films for product manufacturing. Consequently, in continuation of those reports, here we focused on the effect of accelerated UV post-curing on the normal haze and switching voltages of a PDLC formulation to understand if it would be appropriate for industrial scale up and production. The detailed results of this work are described in the following sections.

2. Materials and Methods

The utilized PDLC materials consisted of commercial QYPDLC142 (QY142) liquid crystal mixture (Qingdao), NOA65 (N65) pre-polymer resin (Norland Optical Adhesive), acrylic acid (AA) index-matching additive (Kaitai), Tinuvin TV-400 (TN400) UV absorber (BASF) Irga-cure 819 (Irg819) and 184 (Irg814) photo-initiators (Ciba), 25μm Nano (NM) Micro micro-spacers (Suzhou) and 175 μm ITO-PET transparent conductive films (Eastman). The material compositions (weight%) of PDLC formulation were:

Q142/N65/AA/TV400/Irg819/Irga184/ micro-spacer25um (40%/51%/4%/4%/0.5%/1%/0.6%).

The uncured PDLC mixture was pre-heated at 45°C for 10 minutes and then was poured between the vertical gap of two ITO-PET rolls on a custom-made coater/laminator system (Sigma Sivo). Under the coating rolls, the uncured coated films were passed through a pressure roll to insure the uniformity of the PDLC film thickness. The uncured PDLC film was then cured through a custom-made UV-IR conveyor system at UV intensity of 165 mW/cm^2 and 0.15 meter/minute line speed. The thickness homogeneity of PDLC layers were further insured by micro-spacers. Further details on effects of other process parameters, such as UV intensity, cure temperature, cure time, film thickness and liquid crystal concentration on morphology and electro-optical properties of PDLC films have been mentioned elsewhere [10-15, 24-26].

The electro-optical properties of the PDLC film was measured on the as-made samples. The threshold voltage (V_{10}) and saturation voltage (V_{90}) were measured from transmission-voltage curves on a specially constructed photometric system consisting of a white light source, sample chamber, a photometer, an amplifier, a function generator and electronic data acquisition network with VAC square wave at 100 Hz frequency. The on-state haze (H_{on}) of PDLC films was measured by BYK-Gardner model XL835 haze-meter. Further details of these experimental setups and measurements have been mentioned elsewhere [10-15, 24-26].

3. Results and Discussion

In order to provide a comparative background, the haze and switching voltages of PDLC film were first measured as a function of UV curing within 40-200 mW/cm^2 range. The results of the effect of UV curing intensity (IUV) on H_{on}, V_{10} and V_{90} are presented in Figure-1. The results clearly indicate that, by increasing the UV intensity, both haze and switching voltages decrease almost linearly. Increasing primary UV intensity reduced both haze and switching voltages. Faster polymerization likely produces finer droplet distributions and improved refractive index matching, thereby lowering scattering and electric-field requirements. Such correlation between haze and switching voltages indicates that lowering of V_{10} and V_{90} by increasing the UV intensity are due to favorable morphology, LC droplet alignments and anchoring energy that resulted to reduction of switching voltage consumptions.

Subsequently, the electro-optical properties of utilized PDLC film formulation were studied under various UV post-curing intensities. Accordingly, we studied the effect of post-curing on haze and switching voltages of PDLC film at three 43.2 mW/cm^2, 106.5 mW/cm^2 and 162.8 mW/cm^2 UV curing intensities. The results are presented in Figures 2-4, where at constant curing energy both haze and switching voltages increase by increasing post-curing intensity. While higher curing energy improves the haze and switching voltages (see Figure 1), post curing energy demonstrates opposite effect. Namely, the accelerated post-curing at all tested intensities increased the Hon, whereas the V_{10} and V_{90} exhibited minor but systematic variations depending on initial curing conditions. The trends of haze and switching voltages by accelerated post-curing are in contrast with our previous work on similar PDLC formulation, where both haze and switching voltages decreased upon natural aging process.

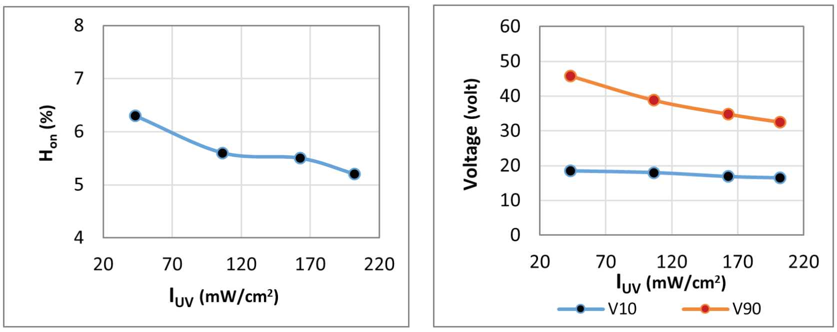

Figure-1: The haze and switching voltages of PDLC film as a function of UV curing intensity

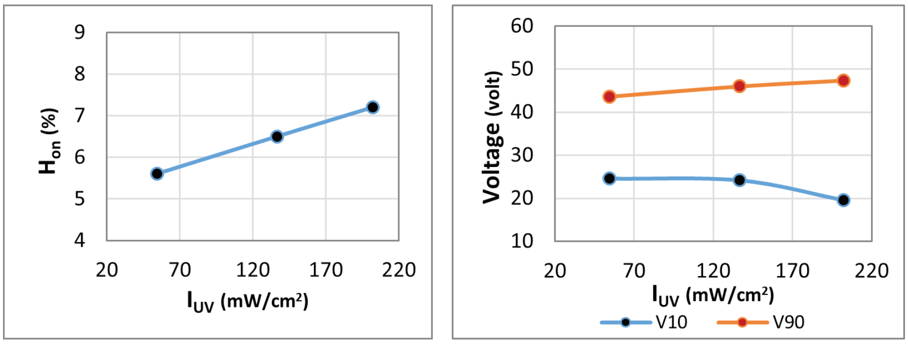

Figure-2: The effect of post-curing on haze and switching voltages of PDLC film cured at 43.2 mW/c

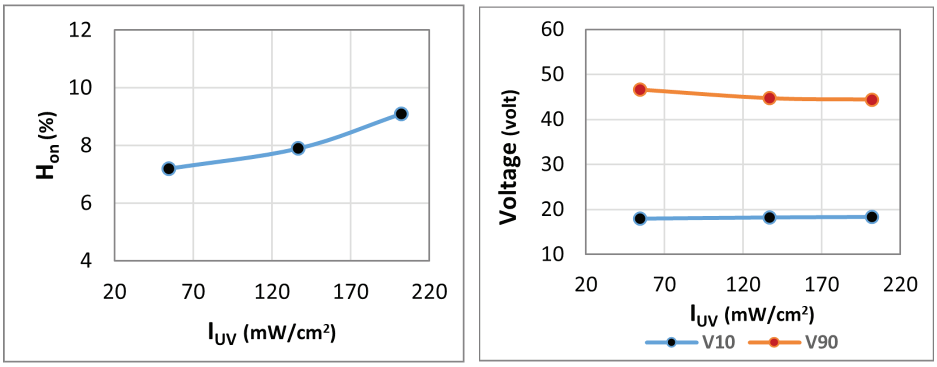

Figure-3: The effect of post-curing on haze and switching voltages of PDLC film cured at 106.5 mW/cm^2

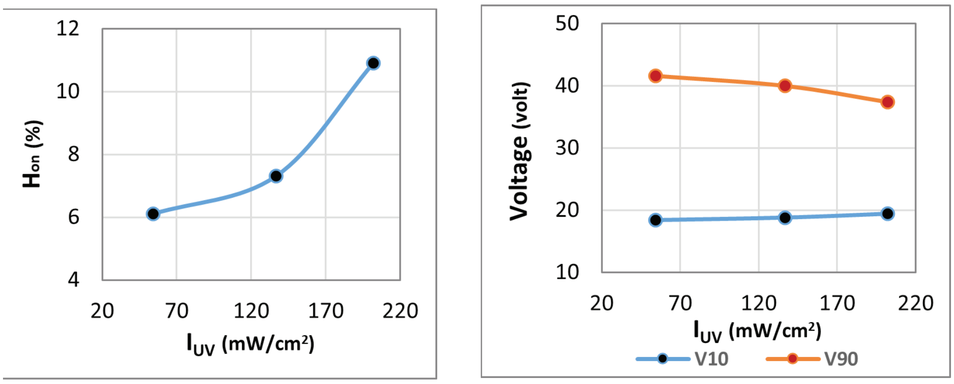

Figure-4: The effect of post-curing on haze and switching voltages of PDLC film cured at 162.8 mW/cm^2

In general, the accelerated post-curing of PDLC provide the phase separation and network formation to continue or relax, therefore the droplet size/shape and polymer stiffness change after the initial cure. That in turn, affects the optical transmissions, switching voltages, contrast ratio and response times.

According to Figures 2-4, the effect of post-curing on PDLC film clearly indicates that Hon increases at all three UV curing intensities. Such increasing trend of Hon by increasing the post-curing intensity seems be due to refractive index miss-matching caused by change in the morphology, in accordance with other studies [37-40] that post-curing decreases the liquid crystal droplet sizes and scattering efficiencies. On the other hand, the effect of accelerated post-curing on the switching voltages provides various trends. Although these trends are not as large as in Hon, but requires some detail explanation. For example, according to Figures 2-4, the threshold voltage V_{10} exhibits a small decreasing trend at 43.2mW/cm^2, but is invariant at 106.5mW/cm^2 and 162.8mW/cm^2 curing intensities. Whereas the saturation voltage V_{90} exhibits a small increasing trend at 43.2mW/cm^2, but shows small decreasing trends at 106.5mW/cm^2 and 162.8mW/cm^2 curing intensities. In general, the switching voltage evolution under accelerated post-curing is governed by a coupled interaction between droplet radius reduction, anchoring enhancement, polymer modulus increases and possible changes in effective elastic constant. The modest experimental voltage shifts observed in this study are consistent with partial compensation among these parameters. In short, upon post-curing, the experimentally observed minor voltage variations indicate near-compensation between morphology, anchoring energy and elastic contributions. In contrast, the haze increase is dominated by refractive index mismatch amplification and droplet size redistribution.

4. Conclusion

In this report at first only pre curing was tested and it was found out that working in very high energies can improve EO/haze properties and can lead to better homogeneity in morphology (V_{90}-V_{10} is lower). Adding post curing to the system has bad effect on morphology and thus also on haze. This should be because of temperature in the UV box, or inhomogeneity in the UV flux/temperature on the way of the film. The accelerated UV post-curing increases haze and provides no significant advantage in switching voltage reduction. A brief conclusion of the accelerated post-curing on utilized PDLC formulation under the tested conditions are as follows:

- Increasing primary UV curing intensity improves electro-optical performance by reducing haze and switching voltages.
- Accelerated UV post-curing increases haze at all tested intensities, indicating morphology changes and refractive index mismatch. Switching voltages exhibit only minor variations under post-curing, suggesting partial compensation between droplet modification and anchoring energy effects.
- Post-curing under the tested industrial conditions is not beneficial for this PDLC formulation.

The findings of this study demonstrate that, accelerated UV post-curing of utilized PDLC formulation is not beneficial for large-scale industrial production and may induce morphological over-stabilization that degrades optical homogeneity. Further recommended studies could include, utilizing accelerated post-curing on other PDLC formulations, comparative natural aging, morphological characterization via SEM and light scattering, FTIR residual conversion analysis and controlled thermal annealing experiments.

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