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Vertically-Aligned Polymer Stabilized Liquid Crystals (VA-PSLC) with a Curing Voltage for Fast-Response Wavelength-Tuning Applications

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We present experimental results obtained for a Vertically-Aligned Polymer Stabilized Liquid Crystal (VA-PSLC) with a curing voltage. The curing voltage was found to help reduce the otherwise strong scattering effect of the VA-PSLC. This liquid crystal mode was placed inside a Fabry-Perot cavity to achieve a wavelength tunable filter. Wavelength tuning range was found to decrease as curing voltage increased, which is consistent with what we expected since molecules had a larger pretilt angle when the curing voltage was higher. Shortening of response time (>10X) was found as polymer concentration increased since the polymer effect helped improve the response speed. These filters can have potential applications in wavelength tuning applications (e.g. WDM) in telecommunication systems where high speed is desirable. This new liquid crystal mode of VA-PSLC with a curing voltage can also find applications where both fast response time and pure phase modulation are desirable.

Keywords Fast response; wavelength tuning filter; Vertically-Aligned Polymer Stabilized Liquid Crystal; VA-PSLC; curing voltage; Fabry-Perot; Pure Phase modulation

1. Introduction

Nematic liquid crystal Fabry-Perot filters [1–2] can be used for wavelength tuning applications (e.g. WDM Wavelength Division Multiplexing) in telecommunication systems. Compared to other types of nematic liquid crystal modes such as Parallel Alignment (PA) and Twisted Nematic (TN), Vertical Alignment (VA) liquid crystal mode tends to have faster response time (relaxation time) than other nematic liquid crystal modes due to the higher K33 elastic constant. In order to reduce the response time further, it is well-known that by adding a small amount of polymer to the liquid crystals bulk one can help improve the speed of the restoration process. However, this can often lead to strong scattering. For example, in Vertically Aligned Polymer Stabilized Liquid Crystal (VA-PSLC), which is also known as VA anisotropic gel [3], the scattering is strong under an applied voltage since LC molecules rotate randomly to different directions under an applied electric field. This strong scattering effect was proposed and developed for potential applications where

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high light efficiency was required since no polarizers were needed in these devices [4–5]. However, it has also recently been shown that [6], by adding a pretilt angle to this VA-PSLC mode, e.g. using rubbing method, it is possible to reduce the scattering significantly while fast response time and good contrast ratio can still be obtained. In this paper, we propose to induce this pretilt angle, not only by rubbing, but also by a "curing voltage" during the UV-curing process of the polymerization. Our experimental results suggest that this method can indeed provide much less scattering compared to the cells without curing voltage. We applied this VA-PSLC with curing-voltage to a Fabry-Perot filter to achieve a wavelength tunable filter with fast response time. Apart from wavelength tunable filters, this new liquid crystal mode of VA-PSLC with a curing voltage can also be applied to applications where fast response pure phase modulation is desirable such as those proposed for Liquid crystal on Silicon devices (LCoS) [7].

2. Operation Principle of VA-PSLC

Figure 1 shows the operation principle of the VA-PSLC with a pretilt angle. This pretilt anlge can help fix the direction of the LC molecules to rotate so that the molecules can rotate more uniformly in one direction, i.e. instead of tilting in different direction and causes strong scattering as in a VA anisotropic gel (with no rubbing and no pretilt angle). In ref. [5], this pretilt angle was provided by rubbing alone. We attempted to reproduce their experimental results using rubbing method. However, we were not able to produce satisfactory results since quite strong scattering still remained. Therefore, apart from rubbing, we also added a curing-voltage to the VA-PSLC cell such that the molecules were already tilted at an angle during the polymerization process (the tilt direction was along the rubbing direction). After polymerization and the removal of the curing voltage, we expect the molecules to remain more or less in the same tilted direction since the polymers were formed along this tilted direction. We found that, by using this approach, we were able to obtain VA-PSLC cells with much less scattering compared to the those without a curing voltage since the molecules can now rotate more uniformly in a preferred (pretilt) direction provided by the curing voltage and the rubbing process.

3. Fabrication of VA-PSLC Test Cell with a Curing Voltage

Two cleaned ITO glass substrates with dimension of about 2 cm × 2 cm were first coated with a thin layer of homeotropic alignment agent (DMOAP). The substrates were then rubbed in a uniform direction to provide the pretilt direction for the liquid crystal molecules.

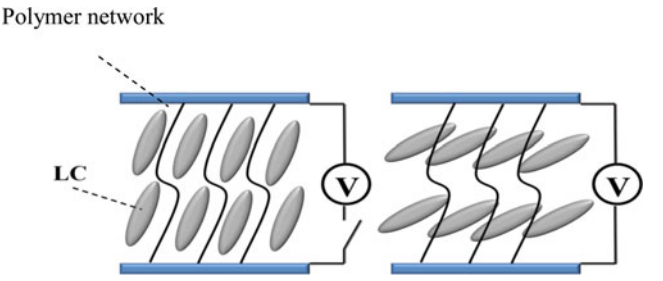

Figure 1. Schematic diagram showing the operation principle of a VA-PSLC with pretilt angle.

After that, ball spacers of 5μm were sprayed on one of the substrates. The two substrates were then assembled and glued together using UV epoxy. The empty cell was later filled with a mixture of nematic liquid crystal HNG60600-200 (from Fusol Material Co. with $\Delta\varepsilon = -0.15$ and $\Delta n = 0.09$) and UV-curable M1-diacrylate monomer (bisphenol-A-dimethacrylate) through the capillary action. The concentration of monomer that we added varied from 3 wt% to 11%, and correspondingly the concentration of liquid crystal was varied from ~97 wt% to 89 wt%. A little amount of photoinitators was also added. After that, the filling hole was sealed with UV epoxy. The cell was then irradiated by UV light with intensity of about 0.1mW/cm to photo-polymerize the monomers. During this UV curing process, an applied voltage (e.g. 1.5 V, 2 V etc) was applied to the cell through the ITO electrodes at the same time. After the polymerization process and the removal of curing-voltage, fabrication of a VA-PSLC with curing-voltage was then completed.

4. Experimental Results and Discussions

Figure 2 shows the Transmission vs. Voltage (T-V) curves of a VA-PSLC that we measured and obtained for test cells with and without a curing voltage. No polarizers were required. In this illustration, we chose an example of VA-PSLC with polymer concentration of 7 wt% and liquid crystal concentration of ~93 wt%. As seen clearly from figure 2, without a curing voltage (i.e. curing voltage = 0 V), the T-V curve is similar to a VA-PSLC (or VA anisotropic gel) and with a strong scattering at high voltage (~12 V in this example). However, after applying a curing voltage of 1.5 V or 2 V during the fabrication process, we found that the scattering was much reduced and the transmission remained very high even at high voltage since molecules were now rotating in a more uniform direction instead of tilting randomly in different directions.

Next, we demonstrate that the response time of VA-PSLC devices can indeed be shortened by the polymer effect. Relaxation time (100% to 10% transmission) of VA-PSLC with different polymer concentrations were measured and are shown in Fig. 3. We measured the relaxation time before and after the UV-curing process. The measurements were performed using test cells placed between crossed polarizers. Figure 3 shows that, by adding polymer inside the VA-PSLC, the response time was indeed shortened by the polymer effect from ~37 ms to ~2 ms by increasing the polymer concentration from 0 wt% to ~11 wt%. Higher polymer concentration would lead to a higher operation voltage. An

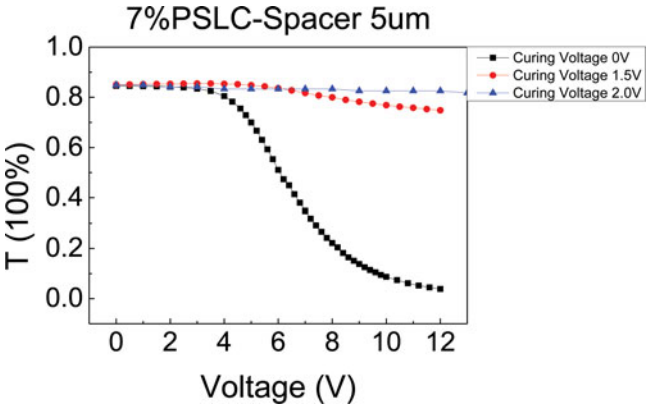

Figure 2. T-V curves of a VA-PSLC with (1.5 V & 2 V) and without (0 V) a curing voltage.

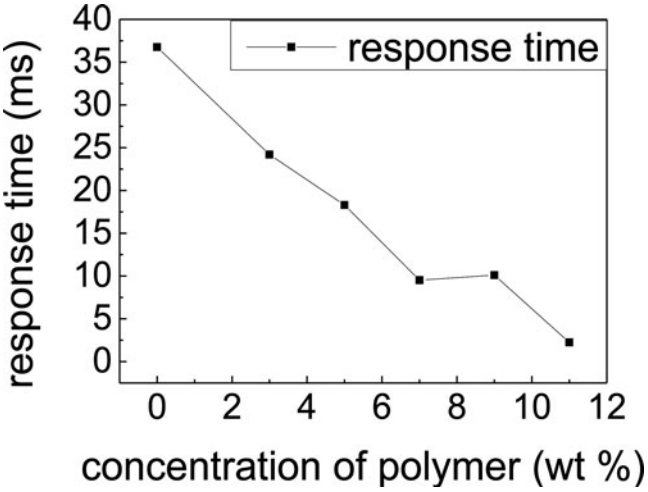

Figure 3. Shortening of response time (relaxation time 100% to 10%) of VA-PSLC with different polymer concentration.

even faster response time can also be achieved by using faster liquid crystal materials, e.g. ones with lower viscosity. The mechanism for the improved response speed of VA-PSLC is that, after UV curing process, the polymers formed from the monomers can provide strong restoration force to help restore the LC molecules back to the original position and thus lead to a shortened response time.

In the following, we report results obtained by placing the VA-PSLC with a curing-voltage inside a Fabry-Perot (FP) cavity. A schematic diagram of the structure of this FP device is shown in Fig. 4. The fabrication of this device is similar to the fabrication process of a VA-PSLC normal test cell with curing-voltage described above, except that we first coated extra layers of multi-layer reflective dielectric mirrors onto both ITO glass substrates before coating the homeotropic alignment layers. In this particular experiment, we chose reflectivity to be about 80% to 90% (centre around 633 nm) in order to increase the light transmission. If we want to improve the performance of the filter such as Finesse, we can

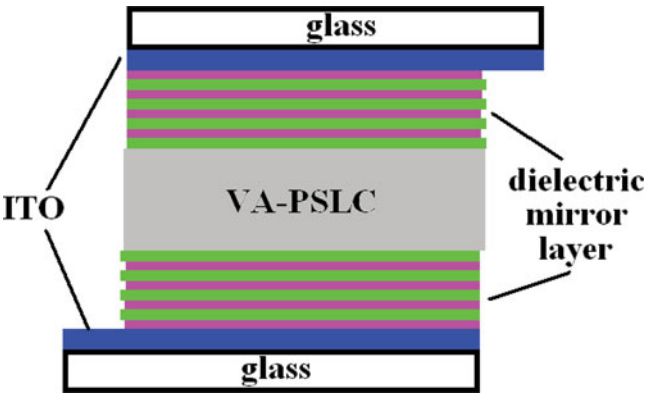

Figure 4. Structure of a VA-PSLC Fabry Perot filter.

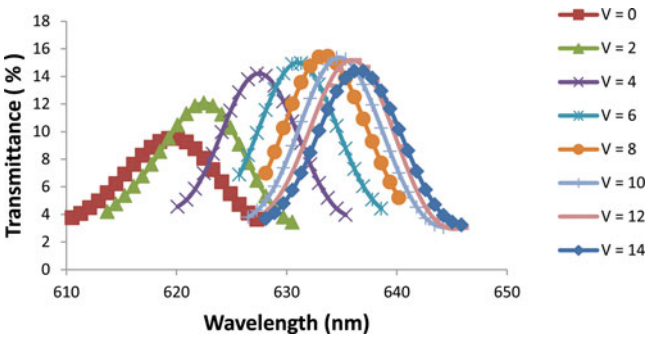

Figure 5. Wavelength tuning of a Fabry-Perot filter filled with VA-PSLC having a curing voltage of 3 V (cell gap = 5 μm, polymer concentration = 3%).

use higher reflectivity of >90%. Dielectric mirrors were preferred over metallic mirrors due to smaller adsorption and better adhesion to the surface of ITO glass.

Figure 5 shows an example of the experimental results that we obtained for the wavelength tuning using these FP devices with filled VA-PSLC. In this example, we demonstrate the results using a VA-PSLC with polymer concentration of 3 wt% and liquid crystal concentration of 97 wt%. The curing voltage used in this was ∼3 V. The measurement was taken using a spectrometer with a white light source. The incident light was polarized along the rubbing direction. The applied voltage to the Fabry-Perot cavity was varied from 0 to 14 V. The wavelength tuning range was found to be about 17.5 nm for wavelength around 630nm. Note that in this particular sample (with 3 wt% polymer concentration), we used a curing voltage of 3 V instead of 2 V or 1.5 V. Compared to curing voltages of 2 V or 1.5 V, we found that a curing voltage of 3 V (or above) could help lead to an increase in transmission (i.e. even less scattering) as the applied voltage increased as shown by the wavelength tuning results in Fig. 5. We believe that this may be caused by some initial drop in transmission at 0 V caused by scattering due to competition between the tilted LC molecules and the tilted polymers, since the LC molecules were trying to rotate back to original vertical alignment after the removal of the curing voltage. We will investigate this interesting effect and observation further in the future.

We also performed a similar wavelength tuning experiment for devices with different curing voltages. The results are shown in Table 1. The wavelength tuning range decreased from ∼30 nm to ∼10 nm as curing voltage increased from 2 V to 4 V or 5 V and didn't increase much further as applied voltage further increase. These results can be explained by the fact that, as we increased the curing voltage, the LC molecules would have a larger pretilt angle at the off-state, so that the LC molecules would rotate by a smaller angle under

Table 1. Wavelength tuning range of the VA-PSLC Fabry-Perot filter with different curing voltages

Curing Voltage	Wavelength tuning range
2 V	30 nm
3 V	17.5 nm
4 V	10.5 nm
5 V	9 nm

an applied voltage and hence change of refractive index "experienced" by incident light became smaller. Therefore, the wavelength tuning range also became smaller and smaller as the curing voltage became higher and higher. Once the curing voltage was beyond ∼4 V, the molecules were almost all rotated to the horizontal level (i.e. in the saturation state), and hence no further increase in wavelength tuning was observed. The results obtained are therefore quite consistent with what we expected. Some residual wavelength tuning remained even at 5 V and is believed to be due to some non-uniform tilting of liquid crystal molecules at high voltage (e.g. due to the alignment competition between vertical alignment of liquid crystal molecules and the polymer structure). We will investigate the effect further in the future.

5. Conclusion

We have demonstrated experimental results obtained for a VA-PSLC with a curing-voltage. The curing voltage was found to be able to help reduce the otherwise strong scattering of VA-PSLC significantly. The response time of this VA-PSLC was shortened from ∼37 ms to ∼2 ms as we varied the polymer concentration from 3 wt% to 11 wt%. By placing this VA-PSLC with curing voltage inside a Fabry-Perot filter, we observed wavelength tuning. The wavelength tuning range was about 30 nm for wavelength around 630 nm region was reduced to about 10 nm as the curing voltage increased since the molecules had a larger pretilt angle for device with a higher curing-voltage. The results are therefore consistent with what we expected. These FP devices can have potential e.g. in applications such as wavelength tuning in WDM systems in telecommunication. Furthermore, this new mode of VA-PSLC with a curing voltage can also be applied to applications where both fast response time and pure phase modulation are desirable such as those required for LCoS devices. Reduction of scattering and shortening of response time are key advantages of these devices.

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References

[1] Patel, J. S. *et al.* (1990). *Applied Physics Letters*, *57*(17).
[2] Hirabayashi, K. *et al.* (1993). *Journal of Lightwave Technology*, *11*(12).
[3] Hikmet, R. A. M. (1992). *Mol. Crystal Liq. Crystal*, *213*(117)
[4] Lin, Y. H. *et al.* (Dec 2005). *Journal of Display Technology*, *1*(2).
[5] Lin, Y. H. *et al.* (2008). *Opt. Express*, *16*(3).
[6] Hicks, S. E. *et al.* (Nov. 2011). *Journal of Display Technology*, *7*(11).
[7] Bleha, W. P., & Lei, L. J. A. (2013). *Proc. of SPIE* Vol. *8736*, 87360A–1.