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High-brightness relaxed-bend state in a pi cell stabilized by synchronized polymerization

Bo-Ru Yang,[1,2,a)] Steve J. Elston,[1] Peter Raynes,[1] and Han-Ping D. Shieh[3]
[1]*Department of Engineering Science, University of Oxford, Oxford OX1 3PJ, United Kingdom*
[2]*Department of Photonics and Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu 30010, Taiwan*
[3]*Department of Photonics and Display Institute, National Chiao Tung University, Hsinchu 30010, Taiwan*

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The authors report a synchronized polymer-stabilization technique which can be used to stabilize the nonpermanent states in liquid crystal devices. In this paper, a relaxed-bend state in a pi cell which has a lifetime of only 80 ms is observed and then stabilized by this proposed technique. After stabilizing, the pi cell is immune to undesirable recovery into the splay or twist states, and its optical contrast is much higher than that of the conventional polymer-stabilized pi cell. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2939559]

The liquid crystal (LC) pi cell,[1] also known as the optically compensated bend (OCB) mode,[1–4] is noted for its fast switching speed due to its symmetric LC director profile and parallel backflow. This kind of cell is normally operated in the bend state; however, because of the topological difference between the ground splay state and the bend state, a nucleation transition has to be completed before operation. This transition can be initiated by applying a critical voltage, and then this voltage should be held to sustain the device in the bend state. However, the pi cell still has the tendency of recovering into the splay state.

To prevent this recovery, several techniques have been proposed.[5–12] These can be classified into three categories. The first category is one that uses the splay states instead of the bend states.[6] The second category is to stabilize the twist or bend state.[5,7,8,10–12] However, in the former case, since the bend and twist states need different optical compensations,[13] it is difficult to exploit the full optical dynamic range of both the bend and twist states. Also, the switching time associated with the twist state is much longer than that of the bend state, which is thus undesirable for fast switching devices. In the latter case, the stabilized pi cell has significant phase retardation suppression, which then decreases the contrast ratio of the pi cell. The third category is to use intermittent pulse signals to prevent the recovery from the bend state to the twist state.[9] This method has been reported to maintain a relaxed-bend (RB) state, which has the highest phase retardation, or say the highest brightness, among the range of the bend states. However, there is still considerable tendency of the cell recovering from the bend state into the twist or splay states. Thus, in order to prevent this undesirable recovery, we aim to stabilize the pi cell device in the RB state and therefore perform high optical contrast without the need for impulse driving.

A preliminary observation of the RB state is made. Initially, we pick the empty cells with identical cell gap of 5.5 μm, and fill them with LC material E7 blended with 4% monomer mixture including 90% reactive mesogen (RM257 of Merck) and 10% photoinitiator (Irgacure 907 of Ciba Specialty Chemicals). The alignment layers of the pi cell devices are parallel rubbed polyimide whose rubbing directions are placed parallel to the crossed polarizers. The driving signal is a 10 kHz, 20 V_{pp}, burst sine wave with 50 ms of pulse width. This high voltage impulse ensures the occurrence of the RB state. As shown in Fig. 1, after removing the applied signal, the pi cell remains in the bend state for 80 ms and then transitions into the twist state. From this observation, we deduce that there exists an 80 ms nonpermanent RB state after the removal of the voltage impulse.

To stabilize the nonpermanent RB state, we set up a synchronized polymerization system which enables us to select the specific state to be stabilized. As shown in Fig. 2, an optical chopper is used to block the UV light and only let the UV light impinge on the pi cell during the desired state. That is, we synchronize the driving signal and the UV light impingement on the pi cell. Laser diode LD-1 and photodiode PD-1 are used to monitor the transmission of the pi cell device. Another paired LD-2 and PD-2 are used to trigger the driving signal for the pi cell. A further photodiode (PD-3) is

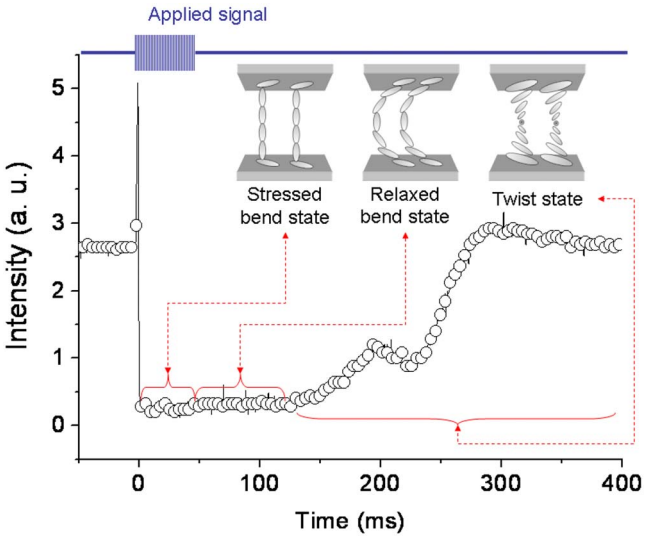

FIG. 1. (Color online) Oscilloscopic trace of the RB state formation and its collapsing into twist state. The rubbing direction of the pi cell is parallel to the crossed polarizers. The driving signal is set to 20 V_{pp} for 50 ms. After removing the voltage signal, the pi cell remains in the RB state for 80 ms.

a)Electronic mail: ybr.eo93g@nctu.edu.tw.

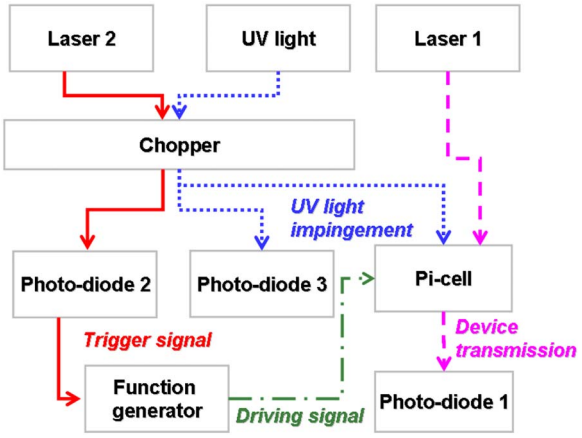

FIG. 2. (Color online) Experimental setup of the synchronized polymerization. LD-1 and PD-1 are used to monitor the transmission of the pi cell device. LD-2 and PD-2 are used to trigger the driving signal for pi cell. PD-3 is placed near the pi cell to detect the impingement of UV light on the pi cell. The chopper is used to synchronize the driving signal and the UV light impingement.

placed near the pi cell to detect the impingement of the UV light (365 nm, 30 mW/cm^2) on the pi cell.

The operational principle of this synchronized polymerization system can be explained by considering the various signals involved. As shown in Fig. 3, to ensure the signals are synchronized, the light signal passing from LD-2 to PD-2 is used to trigger the function generator. Thus, even if the rotational period of the chopper is slightly varied, all of the applied signals remain phase locked. The driving signal is a burst sine wave of 10 kHz, 20 V_{pp} for 50 ms and then 0 V_{pp} for a period until the next trigger signal occurs. To ensure adequate dosage of UV light, the optical chopper's rotational period is set to 300 ms which thus determines the period of this driving waveform. Moreover, by changing the delay time between the trigger signal and the driving signal, we can shift the UV light exposure corresponding to the device transmission, which thus selects the desired state to be stabilized.

To compare the effect of the synchronized polymerization with that of the conventional polymerization, we further make 4% and 2.5% reactive mesogen mixed pi cells and stabilize them with conventional polymerization. Experimentally, it has to be noted that during exposure, the applied voltage should be as low as possible to maximize the phase

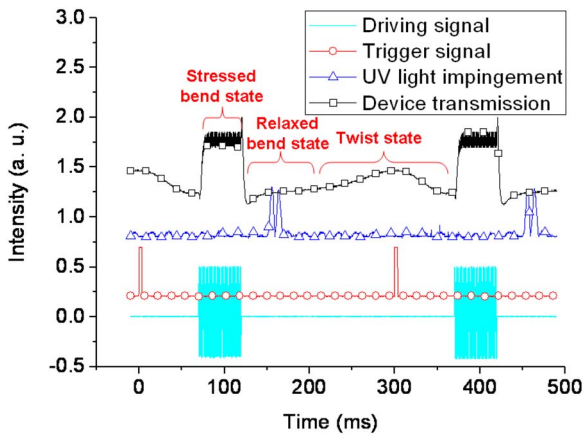

FIG. 3. (Color online) Oscilloscopic traces of synchronized polymerization. The pi cell is positioned 45° between crossed polarizers.

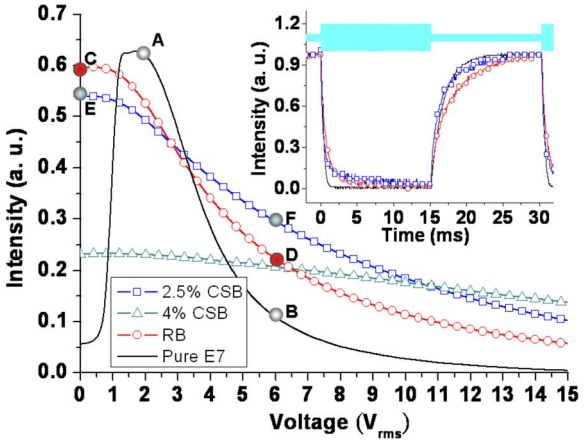

FIG. 4. (Color online) Transmission/voltage behavior of the pi cells. The pi cells are positioned 45° between crossed polarizers. The device conditions are: pi cell with pure E7, 4% mesogen mixed pi cell stabilized in the RB state, 2.5% and 4% pi cells stabilized with conventional polymerization in the stressed bend state. The light source for the measurement is a 5 mW He–Ne laser on 632.8 nm. Inset: response times of the pi cells. The voltage signal is a burst square wave with 15 V_{pp} for 15 ms and then 4 V_{pp} for 15 ms.

retardation in the field-off state. However, with a voltage of less than 3 V_{rms}, the bend state has a high risk of recovery into the twist state.[7] Thus we apply a 3 V_{rms} square wave while simultaneously polymerizing the pi cell with a constant irradiation of UV light. Subsequently, the transmission/voltage behavior of the stabilized pi cells is measured by placing their rubbing direction at 45° to the crossed polarizers. The driving signal is a 10 kHz square wave and gradually increases from 0 to 15 V_{rms}. As shown in Fig. 4, considering the conventional driving range of OCB mode TFT-LCD (2–6 V_{rms}, square wave),[4] the intensity operational range (the difference between the highest to the smallest intensity) of the original pi cell is 0.525 ($\overline{AB}$). However, the reason that the OCB mode is conventionally operated with voltages larger than 2 V_{rms} is to prevent its transition from the bend state to the twist state. Since the polymerized pi cells have been stabilized in the bend state (this has been verified by placing the rubbing directions of the pi cells parallel to the crossed polarizers, which shows no transmission), the optical compensation can still work even at 0 V_{rms}. Therefore, the driving range of the polymerized pi cells can be further extended from 2 to 0 V_{rms}. In this case, the intensity operational range of the RB state stabilized pi cell is 0.375 ($\overline{CD}$) while that of the best case of the conventional polymerization stabilized pi cell is 0.25 ($\overline{EF}$).

The response times of the stabilized pi cells are then measured with the same experimental arrangement with a driving signal of a 10 kHz, burst square wave (with 15 ms of 15 V_{pp} and 15 ms of 4 V_{pp}). As shown in the inset of Fig. 4, the switch-on times (90% to 10%) of the pi cells with pure E7, when stabilized in the RB state, and when stabilized with conventional polymerization (the case of 2.5% mesogen) are 0.73, 2.44, and 2.42 ms, and the switch-off times (10% to 90%) are 4.4, 8.4, and 6.3 ms. The RB stabilized pi cell has slower response, which results from its less rigid (or say less well-constructed) polymer fibril, since the polymerization is executed with dynamic flow.

Although a commercial pi cell is capable of performing with an overall response time of around 3 ms, the LC mate-

rial we use here is simply E7, so the response time can be further optimized by using low viscosity LC materials. Moreover, we can increase the switching speed of this proposed pi cell by a dual frequency driving method.[10,14,15]

The difference of the intensity operational range results from the various profiles of LC director after polymerizations. In the case of the pi cell stabilized in the RB state, the LC director throughout the device is stabilized in a more relaxed (i.e., lower tilt) state, which thus has higher freedom of switching compared to the pi cell stabilized using the conventional polymerization. To further increase the intensity operational range, we have tried to lower the concentration of the reactive mesogen for synchronized polymerization (it was reported in Ref. 7 that using lower concentrations results in higher intensity operational range), however, using concentrations lower than 4% produces only partial stabilization of the bend state.

We have demonstrated a synchronized polymer-stabilization technique, which can be used to stabilize the nonpermanent states in LC devices. In this paper, the nonpermanent RB state which was reported to have high brightness[9] is observed and stabilized by our proposed technique. This pi cell stabilized in the RB state has the attributes of high intensity operational range (an enhancement is obtained by a factor of 1.5 compared with the best case of the conventionally polymerized pi cell) and feasibility for full dynamic range optical compensation (no twist state occurs during the device operation). This proposed pi cell device could be used with a switching backlight technique to achieve a complete dark state and lower the power consumption.[16]

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