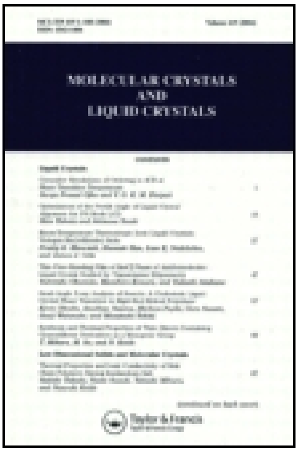

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White Light Liquid Crystal Shutter with Sub-Millisecond Response

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WHITE LIGHT LIQUID CRYSTAL SHUTTER WITH SUB-MILLISECOND RESPONSE

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Abstract A white light liquid crystal (LC) shutter is constructed and performance evaluated. A film-compensated parallel-aligned LC cell is used in reflective mode for achieving fast response time. This shutter shows a 400 μs response time, 110:1 contrast ratio and low operation voltage at room temperature.

1. INTRODUCTION

Parallel-aligned liquid crystal (LC) cell is known to exhibit a fast response time when the bias voltage is several times higher than the threshold voltage.[1] A nematic modulator with 100 μs response time has been demonstrated using the undershoot voltage effect and a low viscosity mixture.[2] However, the contrast ratio of a single parallel-aligned LC cell decreases drastically as the bandwidth of the incident light increases.

Double-parallel-cell[3] approach has been developed for improving the contrast ratio of display devices employing a broadband white light source. In this approach, the compensation cell provides a perfect phase match to the master cell at all wavelengths. As a result, high speed modulation of white light becomes possible. Although the tunable compensator provides flexibility in selecting the operation voltage, the use of two LC cells doubles the weight and cost. It is highly desirable to replace the compensation cell by a light-weight phase retardation film. A highly desirable property of such a film is that its birefringence dispersion should be similar to the LC mixture used, so that good phase compensation can be achieved at every wavelength.[4] This phase-matched retardation film greatly enhances the black-to-white contrast ratio.

In this paper, we demonstrate a white light nematic LC shutter with a fast response time, high contrast ratio and low operation voltage.

2. EXPERIMENT

The experimental configuration of the high speed LC modulator is shown in Fig.1.

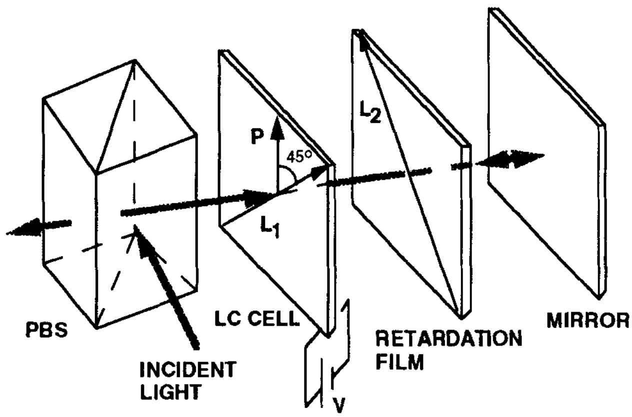

FIGURE 1 Experimental set up for demonstrating high speed white light modulator. PBS = Polarizing beam splitter.

The incoming light (white light or a laser beam) is separated by the polarizing beam splitter (PBS) into s- and p-waves. The s-wave transmits through (not shown) and p-wave is reflected by the PBS. The reflected beam is impinging normally to the LC cell and phase compensation film. The LC cell used is a 4-μm-thick, parallel-aligned E-63 (Merck) mixture operated in the reflective mode. The phase retardation plate used here is a uniformly stretched polymeric film with its optical axis (L_2) orthogonal to the LC director (L_1). Two polymeric films are considered: polycarbonate (PC) and polyvinylalcohol (PVA), they all have a positive birefringence (Δn). The molecular structure of PC film is similar to many commonly used LC mixtures. Thus, its Δn dispersion is nearly identical to that of the LC mixture in the whole visible region. A good phase compensation is then obtained for every wavelength which results in a high contrast ratio for white light application. On the other hand, the Δn of PVA stays at 0.0037 in the visible region and is very insensitive to wavelength. Thus, PC is a better phase retardation film for practical application than PVA. For E63 mixture, its major component is cyano-biphenyl; its conjugation is longer than that of PC film. Thus, some phase mismatch is expected.

2.1 Laser Experiment

We first performed experiments using three laser wavelengths, λ=632.8, 514.5 and 488 nm to simulate red, green and blue as used for color display. Fig.2 shows the voltage-dependent transmission of the LC cell alone (without compensation film) at reflective mode for these three laser wavelengths. As seen from Fig.3, it is unlikely to find a common dark state for all three wavelengths unless an extremely high voltage (> 50 V_{rms}) is applied. In this regime, nearly all the LC directors are aligned to be perpendicular to the substrates except for the boundary layers. These boundary layers are quite difficult to be reoriented by the electric field.

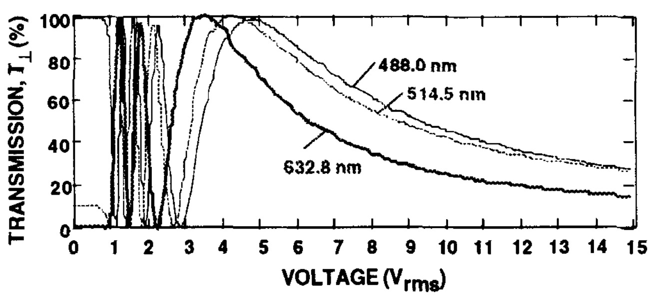

FIGURE 2 Voltage-dependent transmission of the 4-μm E63 cell alone at three laser wavelengths. No common state is observed.

It is unpractical to operate a LC modulator at such high voltage because the electrical breakdown may occur at the indium-tin-oxide electrodes. To reduce the dark state voltage, an uniaxial PVA film with a small dΔn (=39 nm) is used as a phase compensation plate. Results are shown in Fig.3.

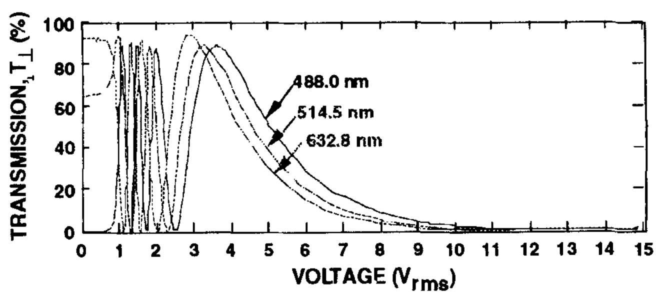

FIGURE 3 Voltage-dependent transmission of E63 cell with a PVA phase compensation film. A common state appears at 12 V_{rms}.

From Fig.3, a common dark state is observed at 12 V_{rms} for all three laser wavelengths employed. The residual phase retardation contributed from boundary layers of the LC cell is cancelled externally by the PVA film. If the dark state is optimized for one wavelength (e.g., λ=514.5 nm),a contrast ratio as high as 900:1 was obtained. However, a lower contrast ratio was observed for other laser wavelengths at the same voltage. This is owing to the dramatic $\Delta n(\lambda)$ mismatch between PVA film and LC. A thin PC film would provide a better phase match for all three visible wavelengths employed. However, such a thin (~25 μm) PC film is not available. To stretch a thin PC film while preserving good uniformity is a challenging task.

Response time of the LC modulator was measured from 3.2 to 12.0 V_{rms} at T=23°C and λ=514.5 nm. Result is shown in Fig.4.

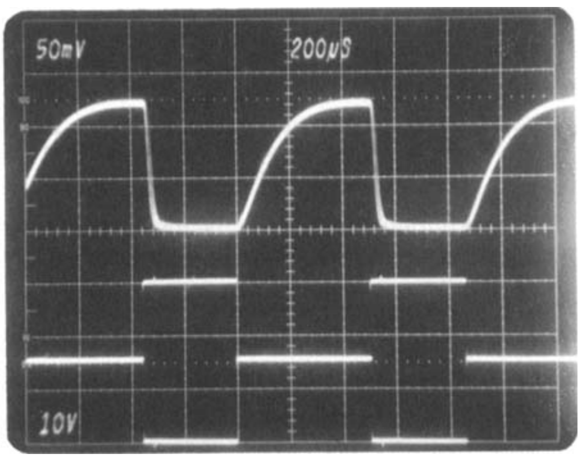

FIGURE 4 Response time of the E63 LC modulator at reflective mode. T=23°C, λ=514.5 nm. Voltage is switched from 3.2 to 12 V_{rms}. f=10kHz square waves. Lower traces are waveforms of the applied voltage; upper traces are the corresponding optical signals.

From Fig.4, the rise time for the optical signals (with voltage switched off) is about 400 μs and the decay time (with voltage turned on) is about 30 μs. To further improve the response time, two simple methods can be considered: 1. choosing a low viscosity LC mixture, and 2. operating the LC cell at an elevated temperature. Increasing the temperature to 40°C, the response time is decreased to ~200μs.

2.2 White Light Experiment

We also compare the white light transmission characteristic of the E63 cell with and without a phase compensation film. A xenon lamp was used as the white light source. Results are shown in Fig.5.

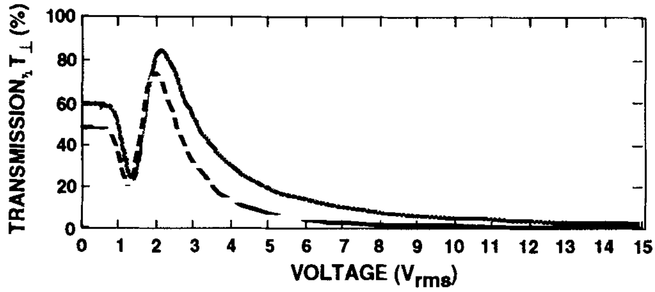

FIGURE 5 Voltage-dependent white light transmission of E63 cell with (dashed lines) and without (solid lines) PVA compensation film. In this experiment, a transmissive mode is used.

From Fig.5, the cell without a compensation film exhibits no acceptable dark state at $V<15\ V_{rms}$. Note that the result shown in Fig.5 is for the transmissive mode operation. For reflective mode, the residual phase from the boundary layers will be doubled. That implies in order to keep the same dark state the applied voltage needs to be doubled. Adding a PVA film greatly reduces the dark state voltage and enhances the contrast ratio. The black-to-white contrast ratio was measured to be 110:1. The dark state voltage for the film-compensated LC cell is the same for both transmissive and reflective mode operations. Once a perfect phase compensation is achieved in one propagation direction, it remains unchanged for double passes.

3. DISCUSSION

The contrast ratio of the parallel-aligned LC modulator is very sensitive to the incident angle of the incoming beam. A small divergence angle could degrade the contrast ratio of a parallel-aligned cell greatly. For a laser beam, the measured contrast ratio is usually in the 1000:1 regime. However, for white light the contrast ratio drops by about ten times to 100:1. This is because the laser beam is much easier to collimate than the incoherent white light. Normally the divergence angle of white light is about ±3°. Although this angle seems small, it is enough to cause light leakage in the dark state. As a result, the contrast ratio of the LC cell is reduced significantly.

Another problem in the proposed LC modulator (shown in Fig.1) is in its optical loss. As shown in Fig.1, we have only used the beam reflected by the polarizing beam splitter; the transmitted 50% light is therefore wasted. One method to recover the lost 50% of light is to implement another identical LC modulator in that channel.[5] By carefully aligning these two modulators and adjusting the operation voltage, a white light modulator with sub-millisecond response time, low operation voltage, high contrast ratio and high optical efficiency can be achieved.

4. CONCLUSION

A film-compensated parallel-aligned LC cell is used in reflective mode for demonstrating a high speed white light modulator. In addition to fast response time, the operation voltage is below 15 V_{rms} and black-to-white contrast exceeds 100:1.

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