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30 to 50 ns Liquid-Crystal Optical Switches*

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Abstract: The optical switching time of twisted-nematic liquid-crystal cells using the liquid crystals, 5CB (C_5H_{11}-Ph-Ph-CN), 5OCB(C_5H_{11}-O-Ph-Ph-CN) and PCH5 (C_5H_{11}-Cy-Ph-CN) have been characterized as a function of temperature, prebias voltage and switching voltage, V. The transition time from 90 % to 10 % transmission scales as $V^{-1.9}$ and is limited to 30 to 50 ns by the liquid-crystal breakdown electric field, ~ 100 V μm^{-1}. The time from the initial switching voltage step to 90 % transmission, delay time, decreases with increasing prebias and switching voltage. For 5CB and 5OCB the delay time approaches a constant value at higher electric fields, >10 V μm^{-1}. Both the transition and delay times decrease with increasing temperature. The minimum transition time at temperatures a few degrees below the nematic-isotropic temperature are 32, 32, and 44 ns and delay times are 44, 25 and 8 ns for 5CB, 5OCB, and PCH5 respectively.

OCIS codes: (160.3710) Liquida crystals; (230.3720) Liquid-crystal devices;

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14. ABSTRACT

The optical switching time of twisted-nematic liquid-crystal cells using the liquid crystals, 5CB (C,H,,-Ph-Ph-CN), 50CB(C,Hw O-Ph-Ph-CN) and PCH5 (C,H,,-Cy-Ph-CN) have been characterized as a function of temperature, prebias voltage and switching voltage, V. The transition time from 90 % to 10 % transmission scales as V-1.9 and is limited to 30 to 50 ns by the liquid-crystal breakdown electric field, - 100 V I'm-I The time fi-om the initial switching voltage step to 90 % transmission, delay time, decreases with increasing prebias and switching voltage. For 5CB and 50CS the delay time approaches a constant value at higher electric fields, >10 V ~1Il,-1. Both the transition and delay times decrease with increasing temperature. The minimum transition time at temperatures a few degrees below the nematicisotropic temperature are 32, 32, and 44 ns and delay times are 44, 25 and 8 ns for 5CB, 50CB and PCH5 respectively.

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1. Introduction

Large area, > 0.1 cm^2, fast, < 1 µs, optical shutters have applications in recording images of laser and chemically driven explosions. Mechanical shutters have frame rates of up to 25×10^6 fps for 125 frames [1] and the simpler and more compact electronic shutters using a gated charge-coupled-device, CCD, array have frame rates of 2×10^6 fps for 50 frames [2]. This article reports on a simple twisted-nematic liquid-crystal shutter with demonstrated shutter times of 30 to 50 ns. This fast switching when combined with a CCD array could represent a third approach with superior properties [3].

These liquid-crystal cells when used as optical shutters are characterized by two time constants, the switching time to rotate the liquid-crystal director under the application of an electric field and the recovery time after the electric field is removed. This article is concerned with just the switching time in the presence of an electric field. This time is dependent upon several parameters: the character of the liquid crystal, the temperature, the switching electric field and the pretilt of the liquid crystal director [4]. The pretilt in this report was controlled by the application of a prebias voltage between 0 to 4 V. Using the comparatively small molecular weight liquid crystals 5CB (C_5H_{11}-Ph-Ph-CN), 5OCB(C_5H_{11}-O-Ph-Ph-CN) and PCH5 (C_5H_{11}-Cy-Ph-CN), the above parameters were varied to obtain the shortest practical switching times.

2. Experiment

The twisted-nematic liquid-crystal cells used with these experiments have an active area of 0.1 cm^2 and gap thickness of either 5 or 10 µm. Details of lithography, etching and metallization are given elsewhere [3]. The cell was designed to minimize its internal resistance and capacitance, having an RC time constant between 1.0 and 2.5 ns Figure 1 shows the details of the cell assembly. Cells were often reused to characterize several liquid crystals under the same conditions. Each time the cell was reused it was disassembled, cleaned in acetone and in an oxygen plasma, rerubbed and filled with another liquid crystal in a vacuum of < 10 Pa and a few degrees above the nematic-isotropic temperature, T_{N-I}. The cells eventually failed due to arcing during high voltage operation and were replaced with new cells. To the accuracy of our experiments results were consistent between cells.
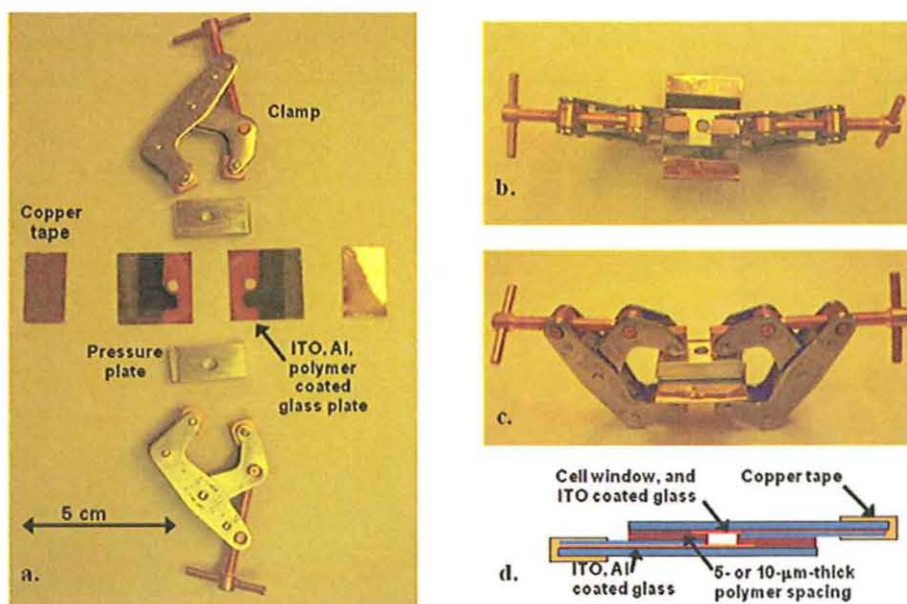

Fig. 1 Assembly of a reusable liquid-crystal cell. (a) Cell parts. (b) Cell assembled top view. (c) Cell assembled side view. (d) Schematic cross section of liquid-crystal cell. The pressure plates and clamps are not shown.

The measurement system consisted of a HeNe laser producing ~ 10 mW of 632 nm polarized light. The light passes through a liquid-crystal cell and into a polarizing-cube beam-splitter, which generates two light beams of opposite polarization. The intensity of each beam was monitored by a fast Si photodiode and recorded by a digital oscilloscope with a 2 ns rise time. Figure 2 shows the experimental step up.

Prior to optical switching the liquid-crystal cell is prebiased with the application of an AC or in some cases a DC voltage between 0 to 4 V, which is adjusted to reduce the optical transmission to ~ 90% of its maximum value. This prebias causes a pretilt of the liquid-crystal director from being parallel to the surface of the cell electrodes and significantly reduces the switching time during the application of the switching voltage pulse. A switching voltage step of 10 to 900 V is applied to the liquid-crystal cell, which rotates the average director from approximately parallel to perpendicular with respect to the cell surface. This changes the polarization of the light exiting the cell and diverts it from photodiode A to photodiode B, as shown in Fig. 2. The switching time of light from photodiode A to photodiode B is characterized by two time periods, the delay time, τ_D, and the transition time, τ_T. τ_D is defined as the period between the time when the switching voltage step reaches half of its ultimate value, Time = 0 in the graphed figures, and the time when the light signal in photodiode A is 90 % of its previous unswitch value. τ_T is defined as the period between the times when the light signal from photodiode A changes from 90 % to 10 % of its original value. The definition of τ_D and τ_T is graphically shown in Fig. 2. Once the liquid-crystal cell has optically switched the switching voltage is removed. More than a few microseconds at electric fields approaching 100 V μm^{-1} will cause the cell to failure by arcing.
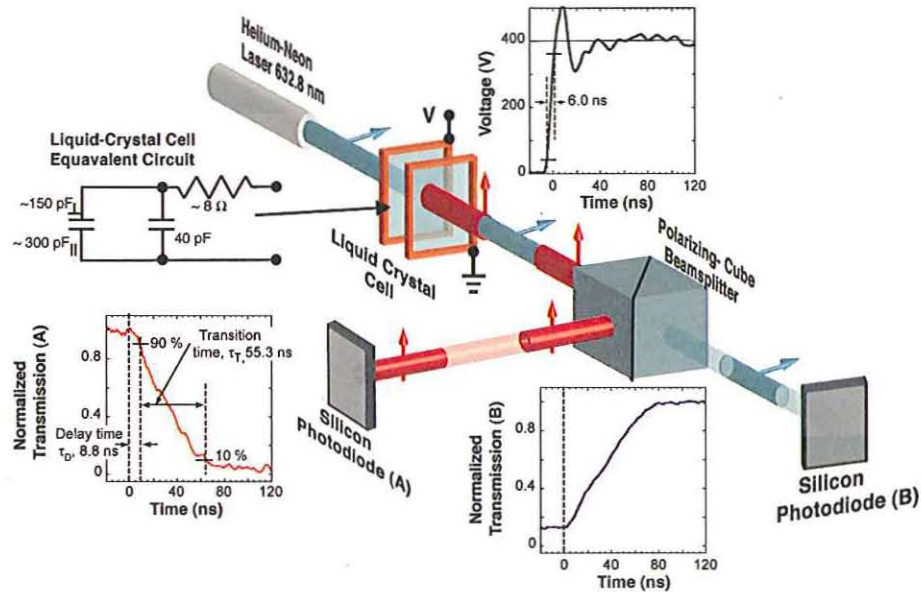

Fig. 2. Experimental setup, HeNe laser, liquid-crystal cell, polarizing beam splitter, and two silicon photodiodes. On the left is the equivalent circuit for a 5-μm-gap cell. Below that, is the graph of the normalized output as a function of time from Si photodiode (A). The graph defines the delay, τ_D, and the transition, τ_T, times. The graph on the right shows waveform of the voltage step applied to the liquid-crystal cell. Below that graph is the normalized signal from Si photodiode (B) as a function of time.

2.1 Prebias

If the director is parallel to the electrode surface, perpendicular to the applied switching electric field, then the initial torque on the director by the electric field is very small, resulting in a large τ_D before the cell switches. A variety of techniques have been used to generate a pretilted director including treatment of the liquid-crystal cell electrodes with specific polymers [5], angled evaporation of SiO_2 [6], or applying a prebias voltage to the cell prior to the switching voltage [7]. This is consistent with the data in Figs. 3 and 4 where τ_D decreases by an order of magnitude with an increase in prebias voltage from 0 to 1 V. The same voltage increase only decreases the transition time, τ_T, by a factor of ~2. To obtain the shortest practical switching times the prebias voltage was adjusted to reduce the transmission to ~ 90% of the maximum value for the data shown in Figs. 6 through 12. Initially a DC prebias voltage was used and this worked well for 5CB, but other liquid crystals proved to be more conductive and an AC bias had to be used. The increase in conductivity is a result of ion contamination in the liquid crystal. Under DC prebias conditions these ions move in the liquid crystal and reduce the electric field of the prebias voltage. The prebias voltage can be increased to compensate the field reduction, but the required voltage becomes time dependent as more ions are generated and the experimental results are compromised when

the DC prebias voltage is more than a few volts. The ions cannot respond to an AC prebias voltage at frequencies > 20 Hz. It was not feasible to repeat all the experiments with the same bias conditions so a DC prebias was used for most of the 5CB data while an AC prebias was used for most of the PCH5 data.
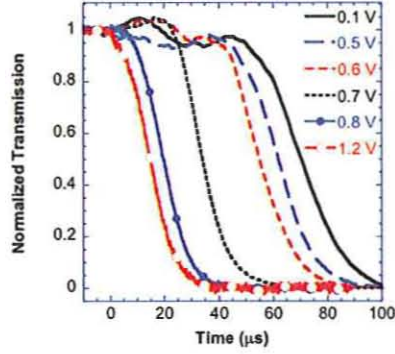

Fig. 3 Normalized transmission as a function of time for several prebias RMS AC voltages. The cell gap is 5 μm and is filled with 5CB at 30 °C. The switching voltage was 40 V.
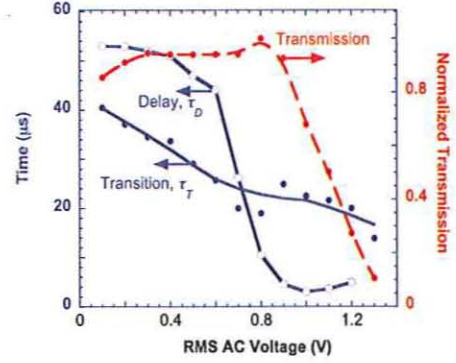
Fig. 4 τ_D, τ_T and normalized optical transmission as a function of prebias voltage for the same cell used in Fig. 3.

2.2 Quasi-static and high voltage DC pulse

Figures 5 and 6 compare the liquid-crystal cell properties when switched by quasi-static DC voltage and a high voltage DC pulse. For the quasi-static measurement the voltage was ramped from 0 to 40 V and back at 0.32 V s^{-1} for a total time of 250 s. With a 40 V bias the transmitted beam is attenuated by 1000 with ~0.1 V hysteresis at 50 % transmission between the voltage ramp increasing and decreasing in time.

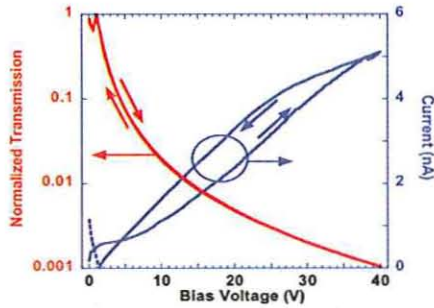Fig. 5 Normalized transmission and bias current as function of voltage for a 10-μm-thick 3-mm-diameter 5CB cell at 32.9 °C. The dotted line indicates negative current.
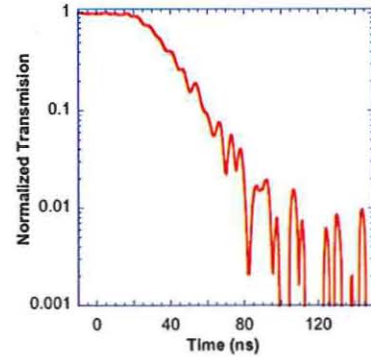
Fig. 6 Normalized light transmission with the application of a 800 V step on a cell similar to that used for Fig. 5

The low leakage current, < 6 nA at 40 V, is characteristic of 5CB, but if the liquid crystal was exposed to laboratory air over a period of several months it became more conductive requiring an AC bias voltage. The low hysteresis, ~ 0.1 V, is a result of the low ion content in the liquid crystal. Hysteresis over a volt and leakage currents of several micro amps are common with more conductive liquid crystals, which require an AC prebias voltage. Note the same reduction in transmission by ~ 1000 occurs for both the quasi-static and the DC pulse switching. The high voltage switching pulse results, as shown in Fig. 6, were independent of the liquid-crystal conductivity.

3. Simple model

τ_T of a twisted-nematic liquid-crystal cell for electric fields, >10 V μm^{-1}, is approximated by eq. 1 [8]

$$\tau_T = \frac{\gamma}{\varepsilon_0 \Delta \varepsilon E^2}$$

Eq. 1

Where the switching electric field, $E = V/d$, is the switching voltage, V, across the cell divided by the cell gap, d, γ is the rotational viscosity, $\Delta\varepsilon$ is the change of the dielectric constant between the director perpendicular and parallel to the electric field, and ε_0 is the vacuum permittivity, 8.85×10^{-8} F μm^{-1}.

For the purpose of comparing the measured τ_T with that calculated from eq. 1, $\Delta\varepsilon$ [9,10] and γ [11] as a function of temperature were obtained from published data. Fig. 7 shows the transmission of a typical 5CB cell as a function of time for several temperatures, keeping all other parameters constant. From the data shown in Fig. 7, and other measurements, a comparison of the measured τ_T to that calculated from eq. 1 is shown in Fig. 8. At temperatures below 15 °C cells filled with 5CB exhibit an anomalous transmission tail. Because of this tail, data below 16 °C were not used in Fig. 8. We were not able to super cool the other liquid crystals to the same extent and they did not exhibit this anomalous transmission tail.
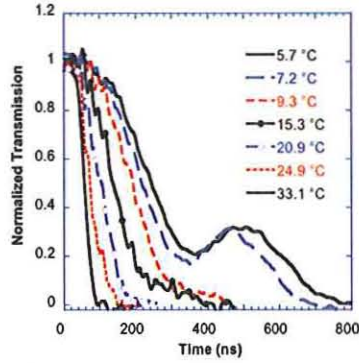
Fig. 7 Normalized transmission through a 10-μm-thick 5CB cell as a function of time for several temperatures. A 900 V step was applied to the cell at Time=0. 5CB was super cooled to 5 °C, 19 ° C below its crystallizing temperature, 24 °C.
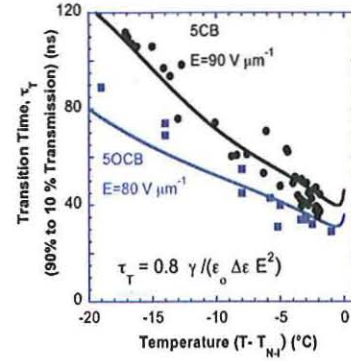
Fig. 8 Comparison of the measured τ_T for 5CB and 5OCB with eq. 1 times a scalar constant of 0.8 as a function of temperature. T_{N-I} is 35.3 °C for 5CB and 68 °C for 5OCB. The parameters used in eq. 1 were obtained from references 9 to 11. ε_o=8.85x10^8 F μm^{-1}.

4. Results

A reasonable correlation between the calculated and measured switching times as a function of temperature for 5CB and 5OCB is shown Fig. 8. PCH5 exhibits a similar agreement. τ_D and τ_T were also characterized as a function of the switching electric field, E, from 4 to 90 V μm^{-1} by varying the switching voltage from 20 to 900 V, and the results are depicted in Figs. 2, 9 through 12. τ_T monotonically decreases with increasing E, but τ_D approaches a constant value at high electric fields for 5CB and 5OCB. For 5CB the total switching time, the sum of τ_D and τ_T, is dominated by τ_D for $E > 30$ V μm^{-1}. However, the τ_D for PCH5 continues to decrease with increasing E and its switching time is dominated by the τ_T for E approaching 100 V μm^{-1}.

Figure 11 shows the best times obtained for the three liquid crystals tested. The very small τ_D for PCH5 is comparable to the rise time of the voltage pulse, 6 ns. The small delay time for PCH5 required a cell and switching circuit redesign. The cells, which were normally 10 μm thick, were changed to 5 μm allowing for a higher electric field with a smaller switching voltage. The lowered switching voltage allowed for a reduction in the switching circuit's output resistance and an overall reduction in the rise time of the voltage step.

5. Discussion

The application of very large electric fields on liquid-crystal cells demonstrates that the liquid-crystal τ_T is dependent upon ratio of the rotational viscosity to the change in the dielectric constant, $\gamma/\Delta\varepsilon$, vary as $\sim E^{-1.9}$, and is limited by the electric field break down ~ 100 V μm^{-1}. Several groups have shown that the response times of liquid crystals are limited by several parameters including their dielectric relaxation time [14]. Dielectric relaxation times of the liquid crystals a few degrees below T_{N-I} are 15, 2.5, and 7-10 ns for 5CB, 5OCB and PCH5 respectively [12,13].
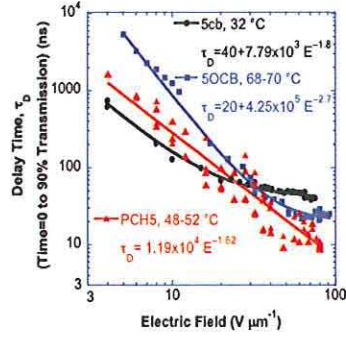
Fig. 9 Measured τ_D as a function of switching voltage. The liquid crystals were few degrees below their T_{N-I}. The curves are a visual fit to the data using a power law and a constant. E is in V μm^{-1} and τ_D in ns for the equations in the figure .
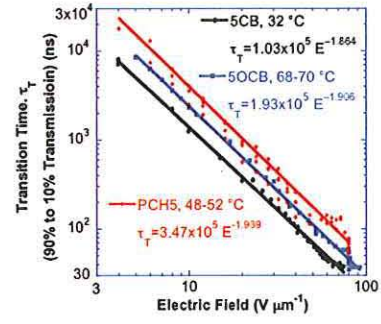

Fig. 10 Measured τ_T as a function of switching voltage. The liquid crystals were few degrees below their T_{N-I}. The curves are a least square fit power law. E is in V μm^{-1} and τ_D in ns for the equations in the figure .
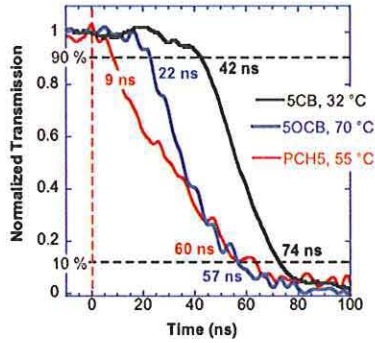

Fig. 11 The best switching times for the liquid crystals tested. The electric fields were between 80 and 90 V μm^{-1}. The delay times and transition times are noted on the graph. The cell gap was 10 μm for 5CB and 5OCB and 5 μm for PCH5.
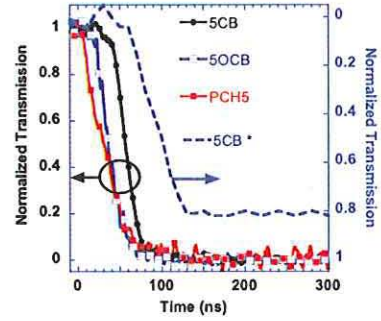

Fig. 12. The same data as shown in Fig. 11 with the addition of the fastest switching time known to us in the literature [4]. The incomplete switching, from 0% to 80% for 5CB*, shown in ref 4, is not understood [15].

To the accuracy of these measurements τ_T is limited by the electric field breakdown of the liquid crystal cell and not by the dielectric relaxation time. τ_D for 5CB and 5OCB asymptotically approaches 40 and 20 ns respectively. However, the τ_D for PCH5 approaches no time limit even for fields of 80 V μm^{-1}

To the best of our knowledge Gu et.al. [14] and Takanashi et. al [3] are the only published reports of nematic liquid-crystal cells with switching times < 100 ns. It is difficult to compare Gu's experimental results with ours. However, we can make a direct comparison with Takanashi's results as shown in Fig. 12. He uses a larger switching electric field, 120 V μm^{-1}. The largest electric field that would give consistent results for our setup was 80-90 V μm^{-1}. In spite of this, t_D and t_T reported here were smaller than Takanashi's. This may be the result of Takanashi's more elegant approach to obtain pretilt with a rubbed polymer. The polymer reduces the electric field applied to the liquid crystal and might not have resulted in the optimum pretilt.

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