55.2: Fast Switching Dual-Frequency Liquid Crystal Optical Retarder, Driven by an Amplitude and Frequency Modulated Voltage

Andrii B. Golovin, Sergij V. Shiyanovskii, Oleg D. Lavrentovich
Liquid Crystal Institute, Kent State University, Kent, Ohio, 44242-0001, USA

Abstract

We employed amplitude and frequency modulated voltage in fast switching optical retarder with a high pretilt angle dual-frequency nematic cell. We obtained the response times 150 – 500 µs for an optical retardation shift on 0.3 – 2.2 µm in optical retarder with 12 µm thick nematic cell. The results could be used in beam steering, adaptive optics and display devices.

1.   Introduction

Nematic cells are widely used as optical retarders in various applications [1-5]. We focus on the development of fast-switching liquid crystal optical retarder based on nematic cell.

The optical path of the nematic cell depends on angle between the vector of electric field and the director of nematic. One can increase the length of optical path in a nematic cell for example by Frederiks transition from homeotropic to planar state. But the applications of this type of optical retarder are limited by the relatively slow time response of the liquid crystal cell. The time τ_{on} of the director reorientation caused by the applied voltage U and the time τ_{off} of relaxation to the initial state when the applied voltage is switched off are often estimated as [6]:

$$\tau_{on} = \frac{\gamma_1 d^2}{\varepsilon_0 |\Delta\varepsilon| (U^2 - U_c^2)} \qquad (1)$$

$$\tau_{off} = \frac{\gamma_1 d^2}{\pi^2 K} \qquad (2)$$

where ε_0 is the electric constant, γ_1 is the rotational viscosity of the nematic liquid crystal, $\Delta\varepsilon=\varepsilon_{II}-\varepsilon_\perp$ is the dielectric anisotropy, ε_{II} and $\varepsilon_\perp$ are the principal dielectric permittivities referred to the nematic director, $U_c = \pi\sqrt{\frac{K}{\varepsilon_o |\Delta\varepsilon|}}$ is a certain threshold value of the applied voltage, K is the characteristic elastic constant. According to Eq.(1), one can decrease τ_{on} by increasing the applied voltage. However, the relaxation time τ_{off} depends only on the material parameters and the thickness of the cell and cannot be shortened by a higher electric field, see Eq.(2) $\tau_{off} \sim d^2$. The drawback is that smaller d causes smaller optical retardation (the optical path difference for ordinary and extraordinary waves) ΔL, as $\Delta L \sim d$.

The goal of our work was to resolve contradictory requirements of fast (sub-millisecond) switching and the broad range of switched optical retardations ($\Delta L \geq 1\mu m$).

2.   Fast Switching Dual-Frequency Liquid Crystal Optical Retarder

We use the so-called dual-frequency nematic materials in cells with a high pretilt angle ($\alpha \approx 45$ degrees) driven by a sequence of electric pulses of different frequency and amplitude. We assembled nematic cells with an anti-parallel fashion from plates with a high pretilt angle, which was achieved by oblique deposition of SiO layers (Fig.1). High value of pretilt angle has several advantages. First, the dielectric torque of the applied field is maximized when the angle between the director and the field is about 45 degrees. Second, there is no threshold for director reorientation. Third, high pretilt guaranties strong restoring surface torques that facilitates reorientation from both the homeotropic and the planar states.
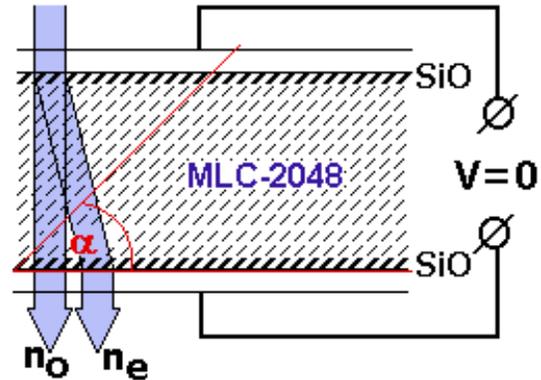

Fig.1 Initial tilted orientation of dual frequency nematic cell.

Depending on the frequency of the applied voltage, the director reorients towards homeotropic state or towards the planar state (Fig.1), because the dielectric anisotropy $\Delta\varepsilon$ of the dual-frequency nematic changes the sign at crossover frequency. For example, the nematic material MLC-2048 has $\Delta\varepsilon$=3.22 at frequency 1 kHz and $\Delta\varepsilon$=-3.08 at 50 kHz at the room temperature.

We used the optical setup with the cell placed between two crossed polarizer prisms to measure the time evolution of the optical response of the cell, Fig.2. Incident light from He-Ne laser (λ=633nm) is a normal to the cell plates. The projection of the director onto the cell substrates makes an angle 45° with the axes of polarizer and the analyzer prisms.
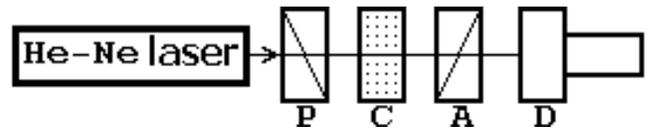

Fig.2. He-Ne laser (633nm), P is the polarizer, C is liquid crystal cell, A is the analyzer, D is the photodetector.

For this optical setup the intensity I of the transmitted light depends on the phase retardation $\Delta\varphi = 2\pi\dfrac{\Delta L}{\lambda}$ as:

$$I(\Delta\varphi) = I_0 \sin^2 \frac{\Delta\varphi}{2}, \qquad (3)$$

where I_o is the intensity of incident light (we neglect small corrections due to the reflection of light at interfaces, scattering at director fluctuations, etc.). Figure 3 shows the signal of photo-detector D (top trace) as the function of amplitude and frequency of the applied voltage (bottom trace). The variation of the photodetector signal between two minima (for example, between points A and B in Fig.3) corresponds to the phase shift $\Delta\varphi = 2\pi$. The total optical retardation is $\Delta L \approx 2.5\mu m$ when the applied voltage is changed between 25V at 50 kHz, 0V and 25V at 1 kHz.
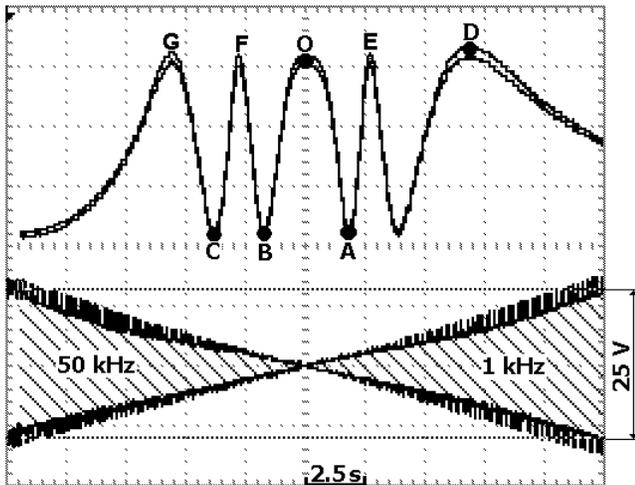
Fig.3. Optical transmission of 12μm thick nematic cell (top trace) registered by the photodetector D as the function of applied voltage (bottom trace) at 50 kHz (left part) and 1 kHz (right part).

The dual-frequency nematic allows us to control the switching dynamics in **both** directions by the applied voltage. We started with the special short pulse (SSP) of large amplitude to speed up the switching. The low-and high-frequency SSPs were used for switching toward the homeotropic and planar states, respectively. Amplitude and duration of the SSP were adjusted to minimize the transition time to the final state, which is controlled by the following "holding" voltage of appropriate frequency and amplitude. As we show below, SSP allows to achieve 2 μm optical retardation shift during 0.5 ms.

An example of the applied voltage profile with two SSPs is presented in Fig.4. The first SSP (duration 100μs) produces fast reorientation to the state A, which is closer to the homeotropic configuration than the initial state O. A square-wave holding voltage at 7 *kHz* follows to maintain the state A. The A state is switched into the initial state O by the second SSP (duration 120μs, frequency 50 *kHz*); the amplitude of the holding voltage in this particular example for the state O is zero. At each step of phase switching we observed approximately *30 μs* time delay between applied voltage and response signal registered by the photodetector.
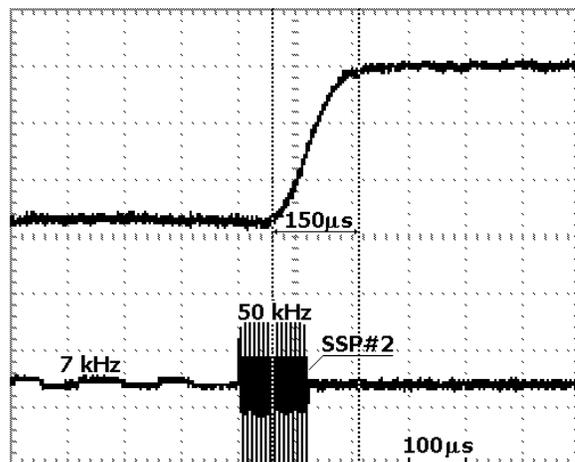
Similar fast switching can be achieved between states A and B (see Fig.3) or any other. The state B is closer to the planar state than the state A, and it is maintained by 50 *kHz* holding voltage.

a) 25 ms/sqr;

b) 100 μs/sqr;
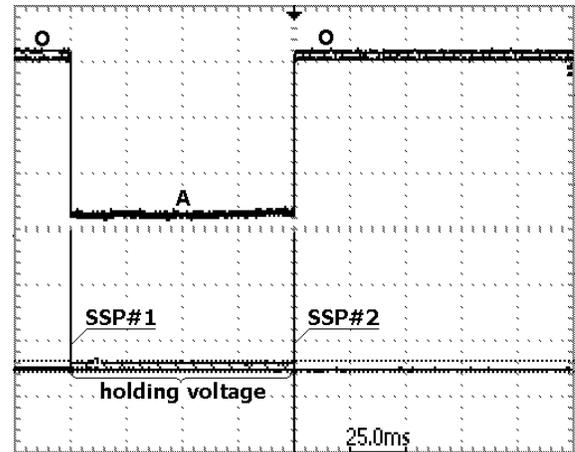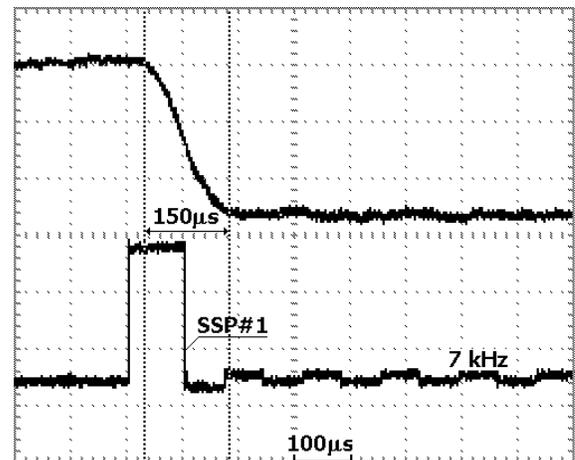
c) 100 μs/sqr

Fig.4. Fast $O \rightarrow A$ and $A \rightarrow O$ transitions (see Fig.3) triggered by two SSPs (top trace) (a), the transition signal and waveform diagram of the applied voltage (bottom trace): (b) SSP and holding voltage on 7 kHz, (c) SSP on 50kHz.

3. Optical Retardation Switching with Large Amplitude of the Swing

Various devices in beam steering, optical communication and adaptive optics require large swing of optical retardation $\Delta L \geq 1 \mu m$ with fast switching times (less than 1 ms).

The dual-frequency liquid crystal optical retarder, driven by SSPs demonstrated 0.5 ms of the switching time for the optical retardation shift by $\Delta L \approx 2.2 \mu m$. Figure 5 shows the signal of photodetector D for this value of the optical retardation shift, corresponding to the transition C $\rightarrow$ D in Fig.3. The state C was held by applied voltage on 50 kHz. To obtain the fast phase switching to the state D we applied pulse with amplitude 100 V during 0.5 ms, after that we hold the state D by voltage on 1 kHz.
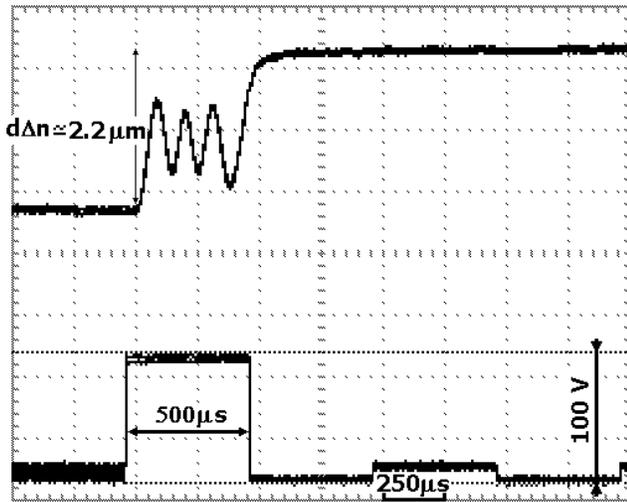

Fig.5. Fast optical retardation shift on $\Delta L \approx 2.2 \mu m$ by one SSP.

Device operation often requires the cyclic switching between two values of the optical retardation. Figure 6 shows the example of such operation with cyclic shift of the optical retardation $\Delta L \approx 1.266 \mu m$. The cyclic operation was performed by the transition between states E and F in Fig.3. Initially we applied the holding voltage with rms amplitude U=3V on 7 kHz to adjust the state E. We used SSP pulse on 50 kHz with rms amplitude U=80 V to perform transition E→F and than we held state F by holding voltage on 50 kHz with rms amplitude 3V. We held the state F during 2.5 ms to show the switching process backward to state E on same oscilloscope picture. Further we performed transition F→E applying the SSP pulse on 7 kHz of carrier frequency with rms amplitude U=92 V. Duration of both switching times -ON and –OFF (corresponding to transitions E→F and F→E) was about 500 µs.

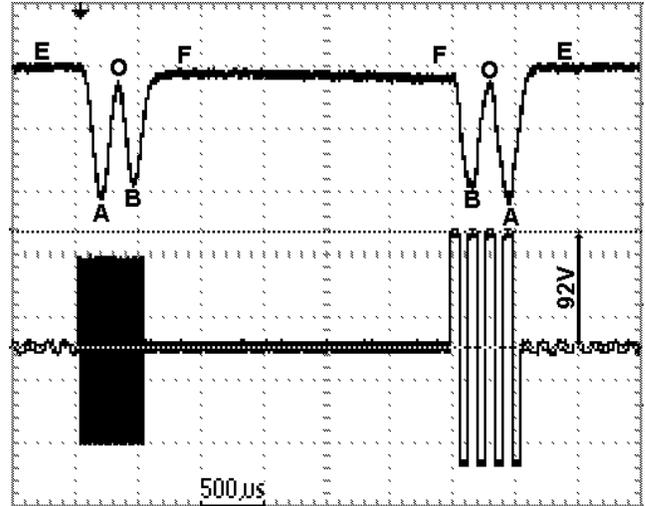Fig.6. One cycle of fast switching between states E and F in Fig.3, switching amplitude of the optical retardation is $\Delta L \approx 1.266 \mu m$.

Dual frequency liquid crystal retarder is capable of more complicated scenario of the optical retardation with the multi-step switching. Figure 7 shows oscilloscope picture of dynamics of switching between state A and state B in Fig.8. Total swing of this transition composed $\Delta L \approx 1.6 \mu m$ of optical retardation during the $\tau_{A \rightarrow B} \approx 1.2 \ ms$. Initial transition from state O to state A was performed by first five SSPs of low frequency with rms amplitude 70V. Than 10 steps of transition between states A and D by SSPs with high frequency and rms amplitude 100V were performed. To obtain the fast relaxation to initial state O we performed another 5 steps of shifting. In this experiment each SSP produced optical retardation by $\Delta L_{STEP} \approx 0.16 \mu m$ during $\tau_{STEP} \approx 120 \ \mu s$.

All SSPs of applied voltage had time duration $\Delta t_{SSP} \approx 70\text{-}80 \mu s$ and these pulses were separated by intervals of $\Delta t_{U=0} \approx 30 \mu s$ with zero applied voltage.

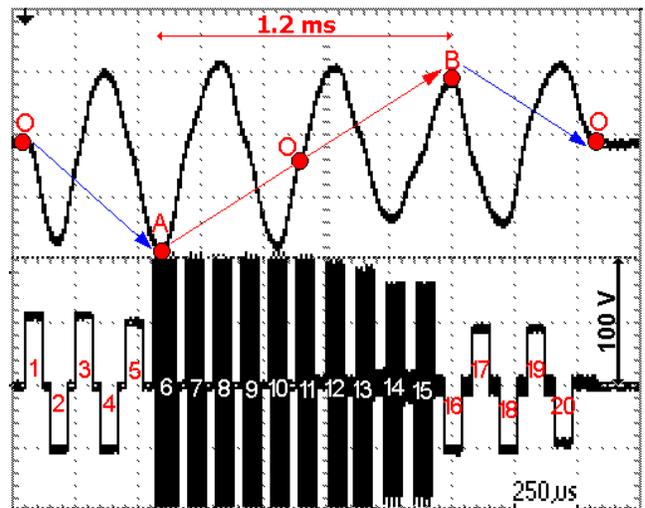
Fig.7. Fast optical retardation switching with $\Delta L = 10 \Delta L \approx 1.6 \mu m$ in $\tau_{A \rightarrow B} \approx 1.2 \ ms$, where A and B are states of the dual frequency liquid crystal in Fig.8.
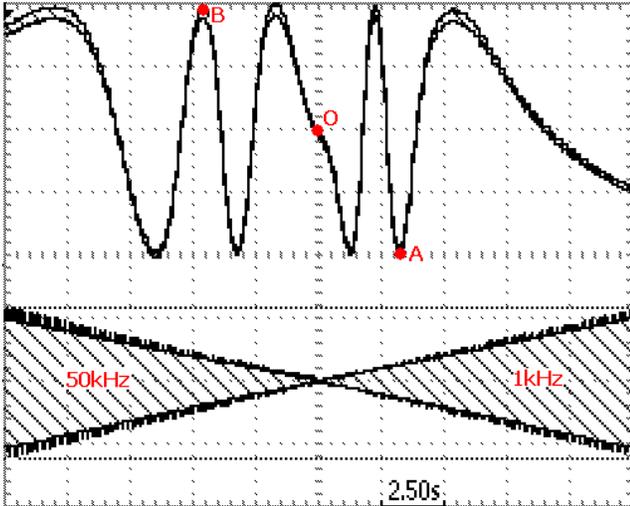
Fig.8. The photodiode signal shows dynamics of phase shift caused by transition between quasi-planar states B and quasi-homeotropic state A. In state O applied voltage is 0V.
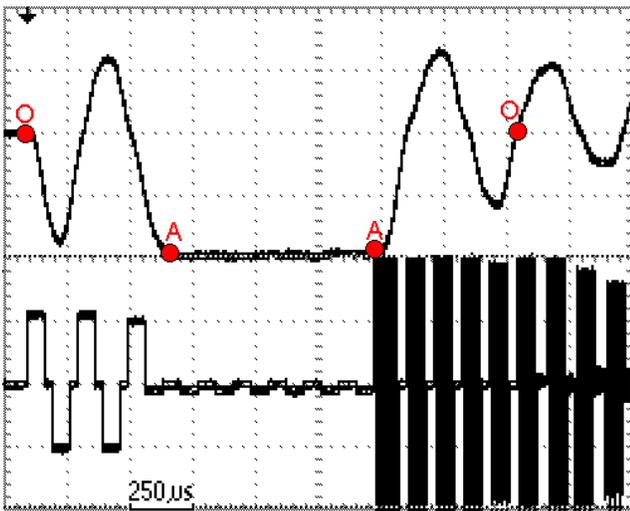

Fig.9. In optical retardation similar to scenario on Fig. 7 "the pause" of the switching process was performed in state A.

We tested the controllability of fast switching with different scenarios of the driving voltage in different experiments including scenarios with "the pause" in the optical retardation shifting. We used the holding voltage at appropriate carrier frequency and amplitude to obtain such a pause in the optical retardation

shifting. For example, Fig.9 shows the oscilloscope picture of switching with the pause at the moment when the configuration of nematic cell corresponds to state A in Fig.8. For this aim, we used the holding applied voltage at frequency of 7 kHz with rms amplitude U=3.5V between fifth and sixth SSPs.

4.   Conclusion

We obtained response times of $150 - 500$ μs for an optical retardation shift on $0.3 - 2.2$ μm in fast switching optical retarder with 12 μm thick dual frequency nematic cell.

The retarders with such parameters are suitable for broad applications in optical communications, laser location, display technique and etc.

Our report is based on materials of U.S Provisional Patent Application Serial No. 60/350,747 [7].

5.   Acknowledgements

6.   References

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