# Fast switching dual-frequency liquid crystal optical retarder, driven by an amplitude and frequency modulated voltage

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We demonstrate theoretically and experimentally a fast-switching nematic optical retarder capable to switch a few microns of optical retardation in less than 1 ms. For example, a nematic cell of thickness 14.5 $\mu$m switches 0.3 $\mu$m of retardation within 0.15 ms and 2.5 $\mu$m within 0.5 ms for single passage of beam. The corresponding figure of merit is two orders of magnitude higher than the one known for the best nematic materials synthesized so far. The fit is achieved by employing a dual-frequency nematic liquid crystal in high-pretilt angle cells and a special addressing scheme that features amplitude and frequency modulated voltage. The scheme can be used in spatial light modulators, retarders, beam deflectors, polarization rotator, and displays.  [DOI: 10.1063/1.1625114]

Electrically controlled liquid crystal (LC) cells are at the heart of many modern optical applications, such as LC displays, optical retarders, beam deflectors, polarization rotators, and such.[1] In many cases (for example, in LC optical phased arrays[2] and adaptive optics),[3] a desirable mode of operation is to switch a large phase retardation, say, one wavelength, within a short period of time, say, 1 ms. The maximum retardation shift $\Delta L_{\max}=(n_e-n_o)d$ is a linear function of the cell thickness $d$, while the switching time varies as $d^2$; $n_o$ and $n_e$ are the ordinary and extraordinary refractive indices, respectively. When the field is switched off, a typical LC cell with $n_e-n_o\approx 0.2$ and $d=5\ \mu$m switches $\Delta L_{\max}\approx 1\ \mu$m within $\tau_{\text{off}}=\gamma_1 d^2/\pi^2 K\sim 25$ ms, where $\gamma_1\sim 0.1\ \text{kg m}^{-1}\ \text{s}^{-1}$ and $K\sim 10^{-11} N$ are the characteristic rotation viscosity and elastic constant of the LC, respectively.[1] The figure of merit $\text{FoM}=\Delta L_{\max}^2/\pi^2\tau_{\text{off}}$, expressed in terms of the material parameters $\text{FoM}_m=K(n_e-n_o)^2/\gamma_1$ is typically (1–10) $\mu\text{m}^2$/s.[4] To resolve the contradictory requirements of a short response time and a large amplitude of switched optical retardations, several approaches have been explored. (a) Recent synthesis advances produced nematic materials with $\text{FoM}\sim 10^2\ \mu\text{m}^2$/s, but only at elevated temperatures 80–100 °C.[5] (b) Passing the beam through the cell many times increases FoM, as $\Delta L$ increases while $\tau_{\text{off}}=\text{const}$;[6,7] multiple passes, however, increase light losses. (c) Employing dual-frequency nematic (DFN) cells, in which the director relaxation towards its stable planar state parallel to the bounding plates is assisted by high-frequency voltage pulses;[3] the scheme switches $L=0.13\ \mu$m within 0.8 ms, i.e., $\text{FoM}=\Delta L_{\max}^2/\pi^2\tau_{\text{off}}\approx 2\ \mu\text{m}^2$/s.

In this work, we demonstrate an extraordinary high (for the single passage of beam) $\text{FoM}=\Delta L_{\max}^2/\pi^2\tau_{\text{off}}\sim 10^3\ \mu\text{m}^2$/s produced by DFN cells with special boundary conditions and driving scheme.

The studied DFN MLC-2048 (EM Industries, NY) has a positive dielectric anisotropy below some critical frequency $f_c$ and a negative dielectric anisotropy at $f>f_c$; for 20 °C, $\Delta\varepsilon=3.2$ at $f=1$ kHz and $\Delta\varepsilon=-3.1$ at 50 kHz. The nematic cells were assembled in an antiparallel fashion from glass plates coated with a conducting indium tin oxide and obliquely deposited thin SiO layers. The latter yield a high pretilt angle $\alpha_b$ the director $\mathbf{n}$ makes with the substrate. In what follows, we describe cells with $\alpha_b\approx 45°$, although the results were similar for a much broader range of angles $10°\leqslant\alpha_b\leqslant 80°$. Electric voltage aligns $\mathbf{n}$ perpendicularly to the plates (the so-called homeotropic state) when $f<f_c$, and parallel to the plates when $f>f_c$. The nontrivial pretilt $\alpha_b\neq 0,90°$ increases the dielectric torque acting on the nematic director (with a maximum at $\alpha_b=45°$), eliminates the threshold of reorientation, and yields a strong restoring torques that facilitate reorientation from both the homeotropic and the planar states.

We carried out the experiments at 32 °C, where $f_c=31$ kHz. The low-frequency driving voltage was applied at 7 kHz and the high-frequency at 50 kHz. The voltage dependence of phase retardation was measured in a standard fashion, with the LC cell of thickness $d=14.5\ \mu$m placed between two crossed polarizers, Fig. 1. The projection of $\mathbf{n}$ onto the cell plates makes an angle 45° with the axes of polarizer and the analyzer, so that the intensity $I$ of transmitted light of wavelength $\lambda$ is:[1] $I(\Delta L)=I_0\sin^2\pi\Delta L/\lambda$, where $I_0$ is the intensity of incident light (we neglect small corrections caused by reflection at interfaces, scattering at director fluctuations, etc.). Figure 1 shows $I$ (top trace) versus applied voltage $U_{\text{rms}}$ at two frequencies (bottom trace). A variation of $I$ between two neighboring minima (e.g., A and B in Fig. 1) corresponds to the retardation shift $\Delta L=\lambda=633$ nm. A larger shift $\Delta L=4\lambda\approx 2.5\ \mu$m is achieved between states C and D, when $U_{\text{rms}}$ changes from 6.3 V to 0 at 50 kHz and then from 0 to 8 V at 7 kHz.

Let us now demonstrate theoretically that substantial amounts of phase retardation (few wavelengths) can be switched in a submillisecond regime. To describe a DFN cell with a high $\alpha_b$, we neglect backflow effect, electric field non-homogeneity, and use a one elastic constant approximation. The polar angle $\beta$ between $\mathbf{n}$ and the normal to the cell is governed by the dynamic equation[1]

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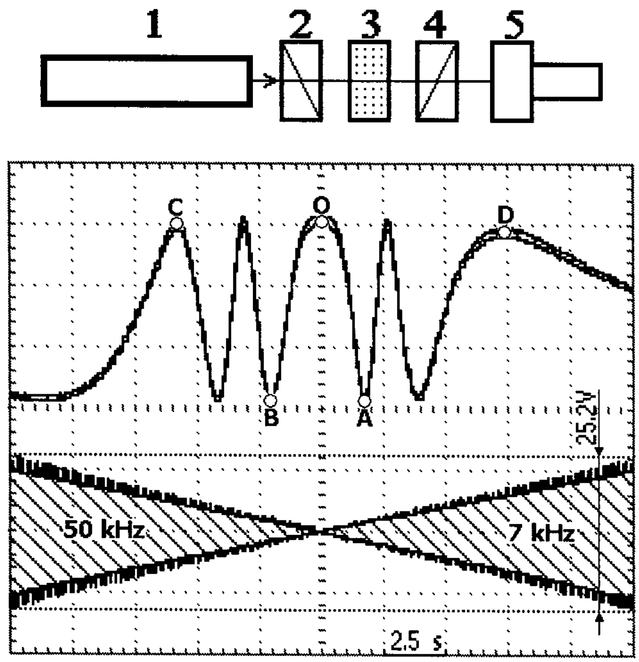


FIG. 1. Optical setup: (1) He–Ne laser (633 nm), (2) polarizer prism, (3) LC cell, (4) analyzer prism, and (5) photodiode (top) and optical retardation vs amplitude and frequency of the applied voltage (bottom).

$$\gamma_1 \beta_t = K\beta_{zz} - \Delta\varepsilon\varepsilon_0 \frac{U^2}{d^2} \sin\beta\cos\beta, \tag{1}$$

where $\varepsilon_0$ is the electric constant, $\gamma_1$ is the rotational viscosity, $\Delta\varepsilon=\varepsilon_\parallel-\varepsilon_\perp$ is the dielectric anisotropy, $\varepsilon_\parallel$ and $\varepsilon_\perp$ are the dielectric permittivities referred to $\mathbf{n}$; subscripts denote corresponding derivatives. The surface orientation of $\mathbf{n}$ is fixed, $\beta(\pm d/2)=\beta_b=90°-\alpha_b$. This approximation of infinitely strong anchoring is justified by the fact that even at $U_{\rm rms}=25$ V (low-frequency addressing) we do not observe a perfect homeotropic reorientation.

For a dc (low-frequency) field, $\beta(z)$ remains in the range $0\leqslant\beta(z)\leqslant\beta_b$. Assuming small birefringence $(n_e-n_o\ll n_o)$, phase retardation of the cell reads

$$\Delta L \approx \frac{(n_e^2-n_o^2)}{2n_e^2}\int_{-d/2}^{d/2}\sin^2\beta dz = \frac{\overline{\Delta L}}{d\sin^2\beta_b}\int_{-d/2}^{d/2}\sin^2\beta dz, \tag{2}$$

where $\overline{\Delta L}$ is the retardation of the homogeneous structure $\beta(z)=\beta_b=\text{const}$ at $U=0$.

Linearizing Eq. (1) with respect to $\sin\beta$ and combining Eqs. (1) and (2), one obtains the dynamic equation for $\Delta L$:

$$\gamma_1 d^2 \Delta L_t = 4K\Delta L\left(\frac{\overline{\Delta L}^2}{\Delta L^2}-1\right)-2\Delta\varepsilon\varepsilon_0 U^2\Delta L \tag{3}$$

with the stationary solution

$$\Delta L = \overline{\Delta L}\sqrt{\frac{K}{K+\Delta\varepsilon\varepsilon_0 U^2/2}} \tag{4}$$

that describes experimental data in Fig. 1 well, see Fig. 2.

The dynamics caused by an instantaneous voltage increase from 0 to $U$ follows the law

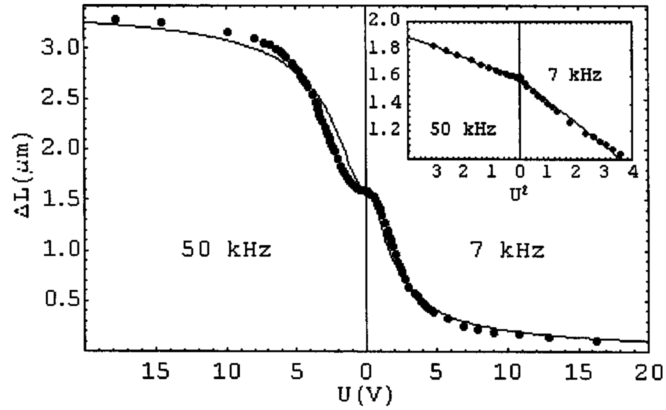


FIG. 2. Optical retardation vs applied voltage: dots correspond to experiment with MLC-2048 at 32 °C; dashed curve corresponds to calculations with Eq. (4) and $\overline{\Delta L}=1.58$ $\mu$m, $\Delta L_{\max}=3.43$ $\mu$m, $K=19$ pN; for small U, $\Delta L-\overline{\Delta L}\propto U^2$ and the linear fit allows one to determine the dielectric anisotropy: $\Delta\varepsilon(7\text{ kHz})=2.44$, $\Delta\varepsilon(50\text{ kHz})=-1.17$.

$$\Delta L = \sqrt{\frac{\overline{\Delta L}^2 K(1-e^{-t/\tau_{2f}})}{K+\Delta\varepsilon\varepsilon_0 U^2/2}+\Delta L(t=0)^2 e^{-t/\tau_{2f}}}, \tag{5}$$

where

$$\tau_{2f}=\frac{\gamma_1 d^2}{8K+4\Delta\varepsilon\varepsilon_0 U^2}\approx 1.2\tau_{\rm off}\frac{U_0^2}{U_0^2+U^2} \tag{6}$$

is the characteristic response time for a DFN cell with a large pre-tilt angle and $U_0=\sqrt{2K/(\Delta\varepsilon\varepsilon_0)}$. With $\gamma_1\approx 0.2\text{ kg m}^{-1}\text{ s}^{-1}$ (measured for MLC-2048 in the lab), one can clearly see that the typical response time is submillisecond when the applied voltage is in the range of 10–100 V. However, Fig. 1 and Eq. (4) demonstrate that the most significant changes in $\Delta L$ are achieved when $U_{\rm rms}<10$ V. Therefore, the optimum driving scheme for DFN cells should include a special short pulse (SSP) of high amplitude to initiate fast director orientation, followed by a relatively low voltage to keep the retardation at the desired level. The model predicts that FoM can be dramatically increased by SSP pulses:

$$\text{FoM}\approx\frac{K(n_e-n_o)^2}{1.2\gamma_1}\left(1+\frac{U^2}{U_0^2}\right). \tag{7}$$

For the high-frequency regime, when the applied voltage is $U(t)=\sqrt{2}U_{\rm rms}e^{-i\omega t}$, one can still use Eq. (3) if the characteristic response time $\tau_h\gg\omega^{-1}$. For $\Delta\varepsilon(\omega)<0$, the tilt angle $\alpha(z)=90°-\beta(z)$ remains in the range $0\leqslant\alpha(z)\leqslant\alpha_b$ and satisfies the same equation as Eq. (3). Thus, the high-frequency case follows the same Eqs. (3)–(5) with the replacements $U\rightarrow U_{\rm rms}$, $\Delta\varepsilon\rightarrow|\Delta\varepsilon(\omega)|$, $\Delta L\rightarrow\Delta L_{\max}-\Delta L$ and $\overline{\Delta L}\rightarrow\Delta L_{\max}-\overline{\Delta L}$; the model suggests the same driving scheme with high-amplitude SSPs followed by low-amplitude holding voltages.

Fast switching of relatively small ($\Delta L\approx0.3$ $\mu$m) and large ($\Delta L\approx2.5$ $\mu$m) optical retardation is experimentally demonstrated in Figs. 3 and 4, respectively. In Fig. 3, the first SSP (duration 100 $\mu$s, $U_{\rm rms}=50$ V) triggers fast reorientation towards the homeotropic state. A square-wave holding voltage $U_{\rm rms}=2$ V at 7 kHz follows to hold the cell in the state A (the states are labeled as in Fig. 1). The A state is

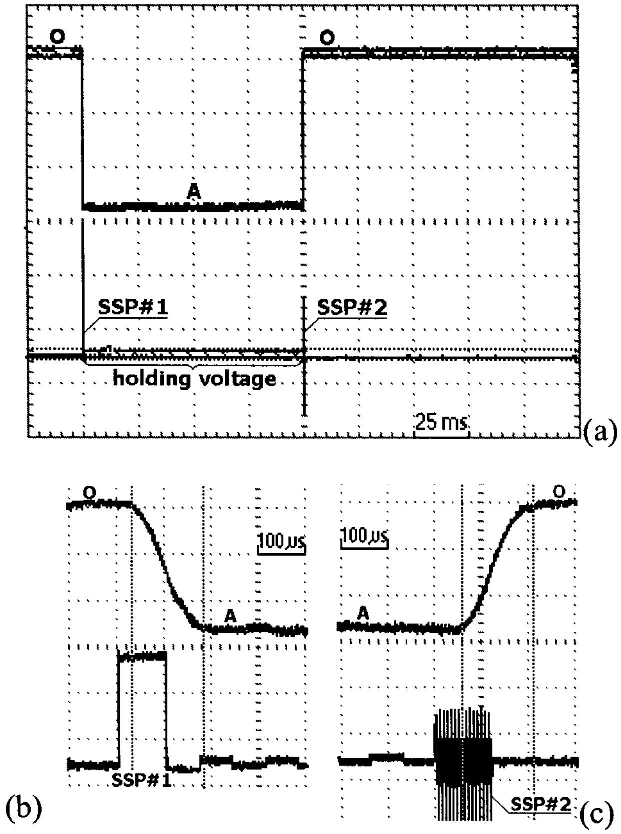


FIG. 3. Fast phase shift on $\Delta L = 0.3$ $\mu$m by driven holding voltage 7 kHz and two SSPs; (a) 25 ms/sqr; (b), (c) 100 $\mu$s/sqr.

switched back into the initial O state by a second SSP (duration 120 $\mu$s, $U_{\mathrm{rms}} = 25$ V at 50 kHz); the holding voltage is zero for the state O.

Figure 4 shows C↔D transition, switched with SSPs of 100 V amplitude. The switching times are ~0.5 ms.

There are some general features of fast switching worth mentioning. First, there is a small time delay (30–50 $\mu$s) between the initial front of a SSP and the corresponding front of the photodiode signal, Figs. 3 and 4. The delay in DFN switching might be related to the broad frequency spectrum and phase matching of the sharp edges of the applied voltages. Second, the transient maxima and minima seen in Fig. 4 are relatively small (meaning that the modulation of light

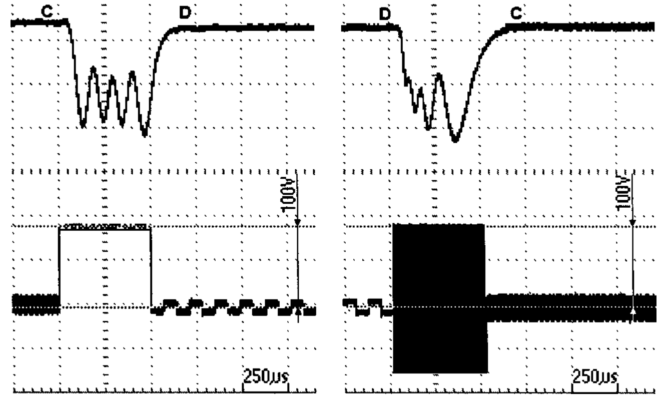


FIG. 4. Fast switching on $\Delta L = 2.5$ $\mu$m during $\tau \approx 0.5$ ms.

intensity is not complete). There are few possible reasons of this effect: (a) in-plane nonhomogeneity of pretilt angle, anchoring energy, surface viscosity, etc.; and (b) the structural transition can be accompanied by an in-plane flow, which in turn may cause director dynamics.

To conclude, we have demonstrated fast switching (hundreds microseconds) of large amplitudes of optical retardation (few microns). The technique allows one to switch relatively thick (for example, 10–15 $\mu$m) dual frequency nematic cells using electric pulses with frequency and amplitude modulations. Typical performance of a 14.5 $\mu$m thick cell filled with a MLC-2048 is such that a phase swing by 2.5 $\mu$m is achieved within 500 $\mu$s, while a swing by 0.3 $\mu$m is achieved within 150 $\mu$s.

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