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The dynamic electro-optic response of liquid crystals (LCs) having positive dielectric anisotropy has been investigated in the fringe-field switching device. Simulation and experimental results show a huge optical bounce near the centre of the pixel electrodes of the device during decaying time of the LC director from an operating voltage. The causality of the said behaviour has been detected as two-step molecular relaxation, first tilt down and then rotating of the LC, which is associated with splay/bend and then twist relaxation, respectively. Reduction of dielectric anisotropy of the used LC material in the device has been suggested as a remedy of reducing optical bounce. The reduction of rotational viscosity also produces optical bounce of lesser duration; however, the intensity of the bounce remains invariant.

**Keywords:** fringe-field switching; liquid crystal display; optical bounce; response time



## 1. Introduction

The improvement of image quality in liquid crystal displays (LCDs) has initiated its wide range of applications and replacement of cathode ray tube (CRT) monitors. The way of development is paved by the adoption of advanced driving modes of LCs, such as in-plane switching (IPS) [1–3], fringe-field switching (FFS) [4–8], multi-domain vertical alignment (MVA) [9–16], etc. However, various important parameters related to overall performance of LCDs, such as response time and viewing angle, still need to be improved in comparison with emissive displays. Present day LCDs uses viscous nematic samples, so that the response time of the LCD is rather slow in the range of milliseconds. In order to improve the response time, low viscous LC materials have been synthesised [17], new driving methods such as overdriving [18] have been developed and also the frame rate has been increased from 60 to 120 or 240 Hz [19]. Increased frame rated LCDs require compatible driving modes with faster response time of LC materials, with significantly lower rotational viscosity. For example, LCDs with 480 Hz frame rate require about 2 ms response time of LCs in all grey levels, which is quite difficult to achieve.

Among various LCD manufacturing technique, FFS driving mode recently became popular with consumers due to its wider viewing angle, higher transmittance and lower operating voltage characteristics compared to other LC modes [20]. The device has not only been applied to manufacture small- and medium-sized portable devices, such as mobile phones and tablet personal computers, but also LC televisions. Several reports have been made in the process of analysing switching principles of the novel device, and superiority in the electro-optic characteristic of the said device has been established. During last 10 years, it has been made known that the light efficiency of the device depends on the rubbing direction [21], electrode structure [22, 23], cell retardation [24, 25], cell gap [26, 27], sign of dielectric anisotropy [22, 28] and magnitude of dielectric anisotropy [29, 30]. Again, the response time depends on the angle between the horizontal component of the applied electric field and the LC director [31]. However, optical bounce occurring in the device during the relaxation process of the LC director from turn-off voltage causing delays in decaying response time has never been reported at all. In the present paper we have examined the origin of optical bounce in the switching-off process in FFS devices by detailed investigation of molecular reorientation and finally proposed the probable solution.

## 2. Switching principle and cell structure of the fringe-field switching mode

Figure 1 shows a cross-sectional view of the schematic cell structure and LC orientation in field-off and on states. The sandwiched cell is formed from

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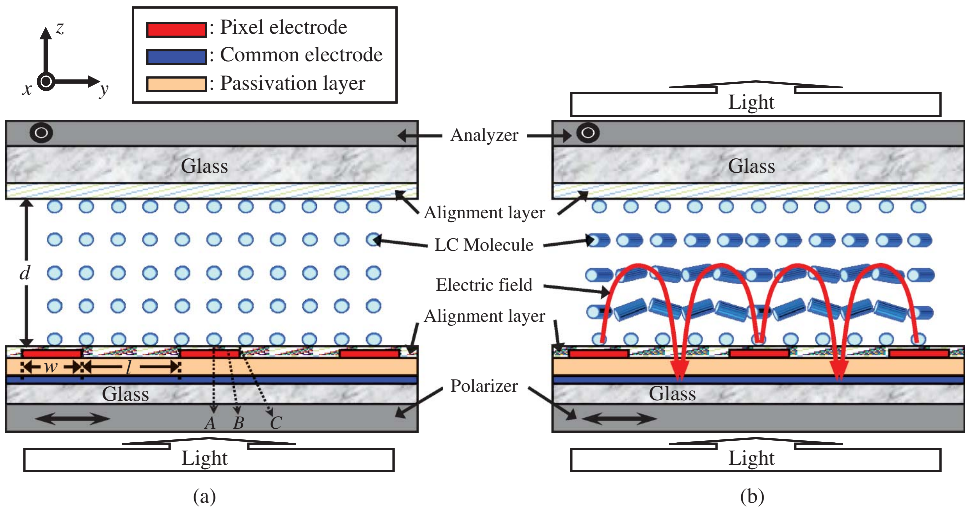


Figure 1. Schematic cell structure with molecular orientation in the fringe-field switching mode: (a) off state and (b) on state.

plane glass plate as the top substrate with transparent pixels and common electrodes both fabricated over the bottom substrate and separated by the passivation layer. The pixel electrode is patterned in slit form with its electrode width ($w$) and inter-electrode distance ($l$). The typical structure in the field-on state generates an electric field in fringe form that has both horizontal ($E_y$) and vertical ($E_z$) components, as indicated in Figure 1.

The normalised transmission of LC devices with the optic axis coincident with one of the crossed polarizer axes is, in general, described by the following equation:

$$T/T_0 = \sin^2 2\Psi(E)\sin^2(\pi d\Delta n_{eff}(E)/\lambda), \qquad (1)$$

where $\Psi(E)$ is an electric field-dependent angle between the transmission axis of the crossed polarizer and the LC director, $\Delta n_{eff}$ is a voltage-dependent effective birefringence, $d$ is cell thickness and $\lambda$ is the wavelength of the incident light. Although the transmission intensity modulation of the FFS device can be completely expressed by the mixed concept of phase retardation and polarization rotation [26], the said transmittance can also be approximately described by Equation (1). The homogeneously aligned LC cell, while placed between the crossed polarizer with one of the polarizer axes coinciding with the LC director, shows dark state in the absence of the field, as $\Psi$ remains zero in this state. With increasing magnitude of applied field, the optic axis of the LC starts to deviate from the polarizer axis and hence the device starts transmitting. The applied fringe field results in both twist and splay/bend deformation of the LC director (see Figure 1(b)) and the tilt generation associated with splay/bend deformation in the field-on state is associated with the optical bounce in the switching-off process, unlike the IPS mode.

The optical bounce has been investigated both by computer simulation and experiment. For calculation purposes, we used the commercially available 'LCD master' (Shintech, Japan) software, where the motion of LC directors is calculated by the Eriksen–Leslie theory and the 2×2 Jones Matrix method is applied for optical transmittance calculation [32]. The simulation is performed with $w$ and $l$ values of 4.0 and 6.0 μm, respectively, with a 0.69 μm thick passivation layer and 4.1 μm cell gap. A LC with physical properties of birefringence ($\Delta n$) = 0.1 at $\lambda$ = 589.3 nm, dielectric anisotropy ($\Delta\varepsilon$) = 8.2, rotation viscosity ($\gamma_1$) = 80 mPa·s, elastic constants splay $K_{11}$ = 9.7 pN, twist $K_{22}$ = 5.2 pN and bend $K_{33}$ = 13.3 pN were used. The simulation process does not include the flexoelectric effect, as it might not be interesting in practical applications for a periodic splay/twist deformed structure in such a small volume of LCs. The surface pretilt angles for both substrates were 2° and the LC was assumed to be aligned at 83° with respect to the $E_y$ of the fringe electric field. The transmittances of single and parallel polarizers were assumed to be 41 % and 35 %, respectively. The centre, between and edge of the pixel electrodes are named $A$, $B$ and $C$, respectively (see Figure 1(a)), in order to describe the reorientation process of the LC molecules in accordance with pixel electrode positions.

## 3. Results and discussion

The electro-optic performance of the device has been investigated by computer simulation as well as experiment. Both investigations show maximum

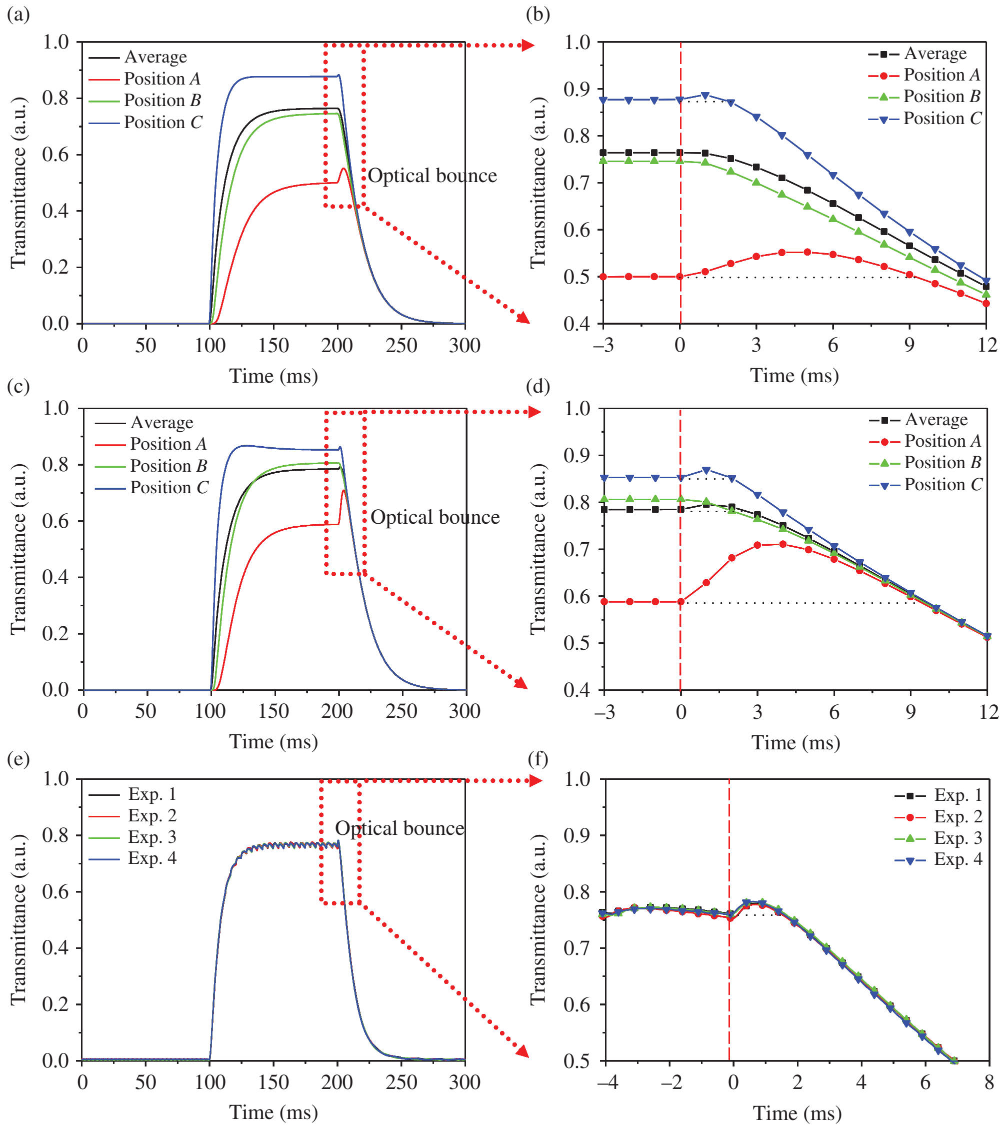


Figure 2. (a) Calculated time-dependent transmittance with respect to pixel electrode positions without considering flow effect. (b) Magnified time-dependent LC relaxation process after voltage-off in Figure 2(a). (c) Calculated time-dependent transmittance with respect to pixel electrode positions in the flow effect added simulation. (d) Magnified time-dependent LC relaxation process after voltage-off in Figure 2(c). (e) Experimentally obtained time-dependent transmittance with repeated measurements of four times. (f) Magnified experimental result in response time during the relaxation process.

transmittance of the device at 4.2 V applied voltage and hence this has been chosen as the voltage to be applied for simulating the response time characteristics. Figure 2 shows time-dependent transmittance curves of the FFS device using simulation in general, which includes the flow effect of LCs and the experiment. In the FFS device, the field-induced LC orientation is periodically changing along the horizontal direction, because the in-plane field intensity depends on electrode positions and thus the dielectric torque and elastic torque to rotate the LC director are different, depending on electrode positions. It is worth mentioning here that, while including flow effect in the simulation, we allow LC directors to deform in accordance with electric field-induced normal deformation of LCs in the high field regime, in order to convey the deformation to the neighbouring LC director in either direction, which is not very prominent in a normal simulation. Hence, the simulation including flow effect is more realistic and the results are closer to the experimental investigation. The results of normal simulation are depicted in Figure 2(a) and the magnified form of the same is included in Figure 2(b) at important electrode positions (*A*, *B* and *C*) for investigating the optical bounce of the FFS device. The simulation results show the strongest optical bounce at position *A*, causing the response time to hold up for 9.2 ms, followed by position *C*, showing an optical bounce of 1.7 ms. However, position *B* and simulation on average hardly show any optical bounce. The results of simulation including flow effect are depicted in Figure 2(c) and the magnified form of the same is included in Figure 2(d) at important electrode positions (*A*, *B* and *C*) for a more realistic investigation of the optical bounce in the FFS device. Interestingly, the optical bounce is found in similar positions as for the normal simulation. The simulation results show the strongest optical bounce at position *A*, causing the response time to hold up for 9.2 ms, followed by position *C*, with the average area showing optical bounce of 2.0 and 2.4 ms, respectively. Nevertheless, the magnitude of bounce is found to be increased and also becomes noticeable in an average from simulation results. The optical bounce observed in simulations has also been confirmed by experimental investigation. The test FFS cells have been fabricated for the experiment with conditions similar to computer simulations and henceforth time-dependent transmittance has been monitored, as shown in Figure 2(e), with the magnified form of the same shown in Figure 2(f). All repeated experimental results show optical bounce, causing the response time to hold up for from 1.5 to 2.3 ms.

In order to understand the origin of such optical bounces, the time-resolved LC director profile has been investigated. Figure 3 shows the pixel electrode position-dependent tilt and twist angles after removal of the operating voltage as obtained from simulation



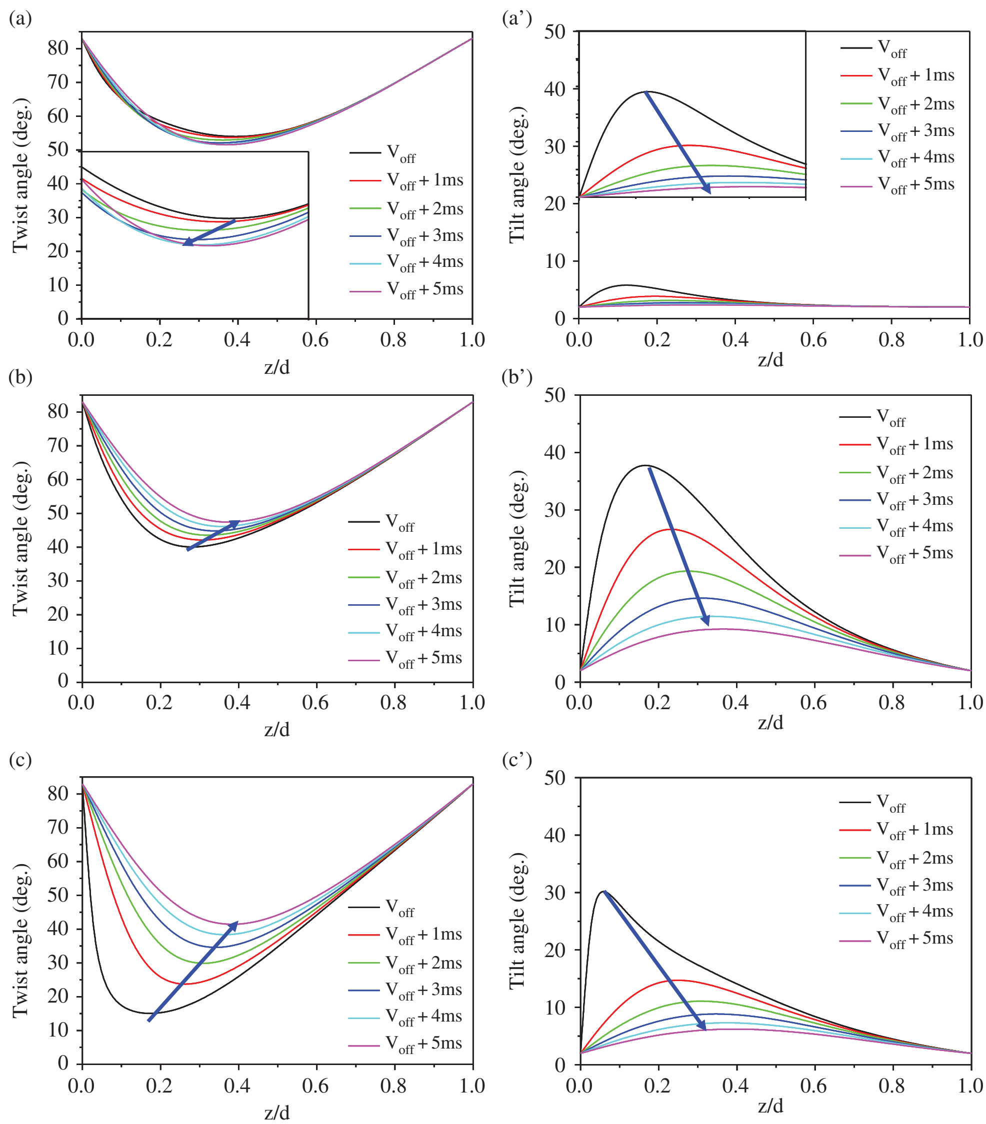


Figure 3. Time-dependent twist and tilt angles with respect to pixel electrode positions: (a, a') position *A*; (b, b') position *B*; (c, c') position *C*.

results. The twist angle of LC directors is found to decrease over pixel electrode positions *B* and *C*, as shown in Figure 3(b) and (c). However, at position *A*, the LC director twists in the reverse direction for 3 ms after removal of the electric field. Simultaneously, the calculated tilt angle shows an abrupt drop of its magnitude at position *B*. The LC materials in general possesses a higher bend elastic constant ($K_{33}$) in comparison with the twist elastic constant ($K_{22}$). Therefore, relaxation of the bend deformation is faster than that of twist deformation, causing the LCs at *A* to be twisted more than those of the original twist angle by strong elastic torque given by neighbouring molecules of the LCs at *A*. Moreover, tiny optical bounces are observed at positions *B* and *C*, as shown in Figure 3(c), because of the rapidly decreasing tilt angle of the LCs.

Based on computer simulation results and careful analysis, we have proposed the molecular reorientation model during switch-on and switch-off process. This is to analyse the cause of the reverse twist, which generates a huge optical bounce at position *A*. Figure 4(a) indicates twist behaviours of LC directors in accordance with pixel electrode positions by application of the electric field. The dielectric torque drives the LC director to twist at position *C* and the same is subsequently followed at position *B*. The deformation of the LC directors at position *B* induces elastic deformation over LCs, around the middle of the pixel electrodes (position *A*) and hence the device exhibits bright state.

On the contrary, after removing the electric fields, the LC directors start to align back to their initial state. The restoration process starts at position *C*, followed by *B* and finally occurs at position *A*. In the process of removal of the electric field, the flow of twist deformation from the pixel edge to between and finally to the centre induced backflow over the LC directors at position *A*. The reverse-twist-caused backflow originates a large optical bounce around the middle of the pixel electrode and hence delays the electro-optic response during field removal.

Analysing the behaviour of LC directors, it has been confirmed that the reverse twist at position *A* is caused by the twist and rapid tilt relaxation of LCs at position *B*. In particular, the orientation of LCs at position *A* is mostly affected by tilt deformation at position *B*, as exhibited in previous researches [24]. Therefore, if we use a LC with lower magnitude of $\Delta\varepsilon$, then the tilt angle at position *B* would be suppressed due to smaller dielectric torque and, thus, the level of such optical bounce at position *A* might be reduced. The variation of response time with respect to the magnitude of $\Delta\varepsilon$ is shown in Figure 5. Considering the whole area of the FFS cell, the optical bounce decreases with decreasing $\Delta\varepsilon$ and disappears when $\Delta\varepsilon$ becomes equal to 3.2. However, a tiny optical bounce is still observed at position *A*, although it negligibly delays response time.

Figure 6 shows the variation of response time as a function of $\gamma_1$ for fixed $\Delta\varepsilon$ (Figure 6(a) and (c) = 3.2, and Figure 6(b) and (d) = 8.2). The results of optical bounce characterised in all areas of the simulated test cell are depicted in Figure 6(a) and (b) and the magnified form of the same is included in Figure 6(c) and (d) at important pixel electrode position *A*. The observed changes are inevitable, as we know the response times of LC devices are linearly proportional with rotational viscosity. In particular, Figure 6(c) and (d) shows the proportionate reduction of bounce time in accordance with $\gamma_1$. However, all the curves are of similar intensity at position *A*. In conclusion, the variation of optical bounce is directly proportional to the magnitude

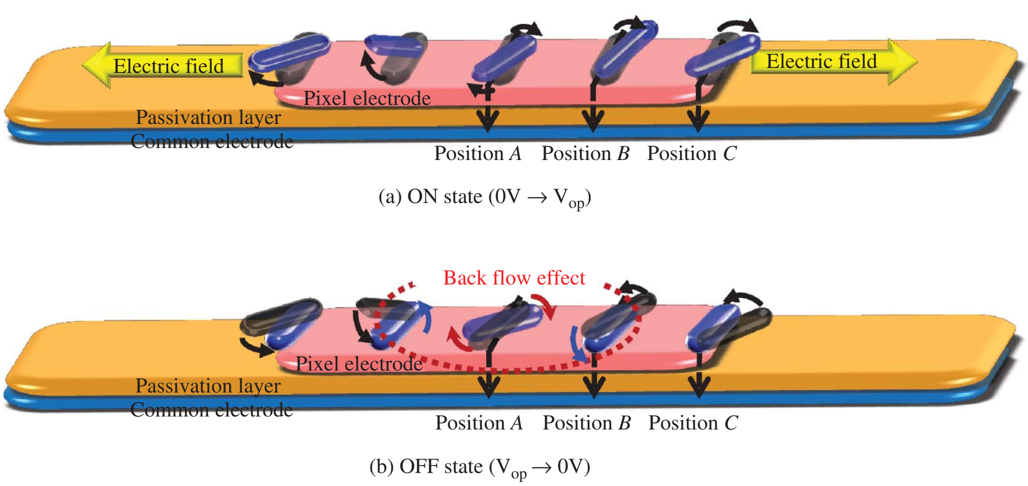


Figure 4. Schematic illustration of LC molecular orientations according the pixel electrode positions. (a)Voltage-on state. (b) Voltage-off state.

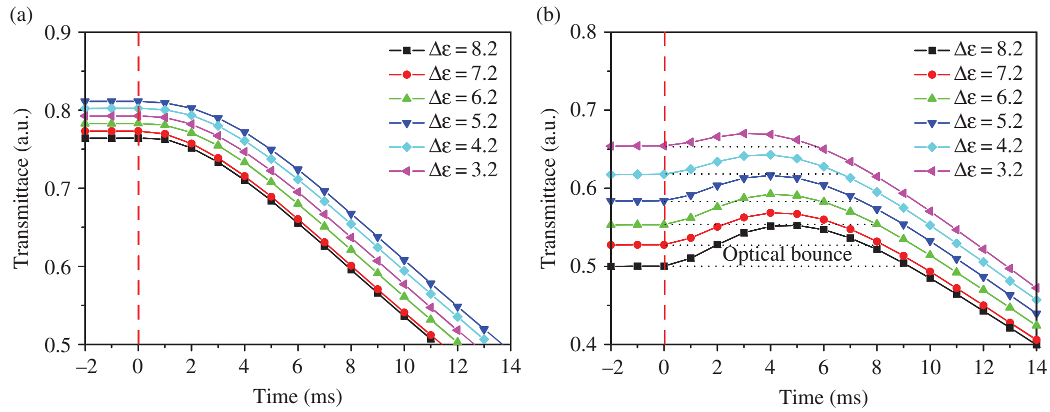


Figure 5. Time-dependent transmittance according to the magnitude of $\Delta\varepsilon$: (a) average transmittance considering all electrode positions; (b) position $A$.

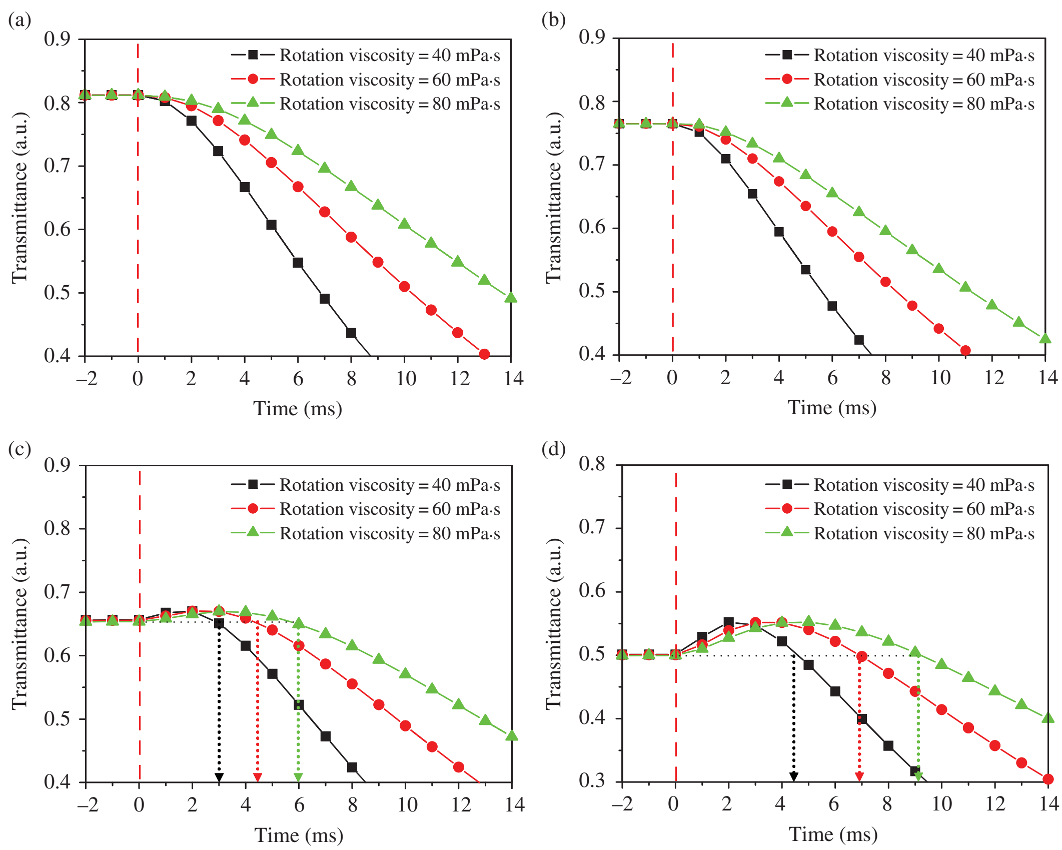


Figure 6. Time-dependent transmittance according to the magnitude of $\Delta\varepsilon = 3.2$ (a), (c), $\Delta\varepsilon = 8.2$ (b), (d), and the magnitude of rotation viscosity; average transmittance considering all electrode positions (a), (b) and position $A$ (c), (d).

of $\gamma_1$; however, it does not control the intensity of the causes. Nevertheless, the magnitude of $\Delta\varepsilon$ proportionately decreases with $\gamma_1$ for typical LC materials, hence the variation of $\gamma_1$ with fixed $\Delta\varepsilon$ values are interesting for academic purposes, but such experiments might not be possible in reality.

Hence, we propose the probable solution for removing optical-bounce-induced delay in electro-optic response time characteristics in the commercialised novel FFS device.

## 4. Summary

The time-dependent transmittance and pixel electrode position-dependent LC director configuration has been investigated for FFS devices using both computer simulation and experiments. Our investigation revealed the occurrence of a huge optical bounce at the middle of the pixel electrodes due to LC backflow induced reverse twist in the said regime. The optical bounce can be reduced by using LC materials with lesser dielectric anisotropy, as we have finally proposed as a remedy to the problem. The reduction of rotational viscosity also leads to a lesser duration of optical bounce with invariant intensity. The present investigation paves the improvement of response time with minimum optical bounce and optimisation of LC properties for homogeneously aligned FFS devices.

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