Optical Response of Structured Vertically Aligned and In-Plane Switching LCDs

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Abstract

The optical response of Structured Vertically Aligned and of In-Plane Switching liquid-crystal displays was measured and compared with simulations. It was found that both switching of liquid crystal molecules from the vertical to the horizontal direction and rotation in the horizontal plane are important. Two- and three-dimensional simulations prove to be very helpful in understanding the response of multi-domain displays.

Introduction

It is well known that liquid crystal displays (LCDs) with wide viewing angles can be obtained by dividing the pixels into domains with different director orientations using slit electrodes and/or protrusions. Examples of such multi-domain displays are structured vertically aligned nematic (SVA)[1,2,3,4,5], twisted nematic[6] and in-plane switching (IPS)[7] LCDs. A drawback of this method is that the domain walls (disclinations) reduce the brightness and that domain-wall motion may decrease the optical response speed.

In this paper we present investigations of SVA and of IPS LCDs. In both cases we measured the optical response and compared it with simulated results obtained using commercial modeling packages[8,9]. Although these studies were performed separately, it turned out that similar mechanisms play a role for the two cases.

Structured Vertically Aligned LCDs

We made a prototype display with a chevron structure (similar to that of Ref. 3) using slits on the active plate and protrusions on the passive plate. Figure 1 shows the (normalized) measured transmission as a function of time when the driving voltage is switched between various initial values and 6 V. At 100 ms the voltage is switched from the indicated voltage to 6 V and at 400 ms the voltage is switched back to the indicated voltage. Several interesting features are noticed.

When switching from 2.4 V or 3 V to 6 V the transmission rises quickly (in about 10 ms) and then decays slowly (in hundreds of ms) towards its end value. This phenomenon is not seen if the switching starts at higher voltages.

If the initial voltage is below the threshold of 2 V, the optical response is different. Figure 2 shows the transmission as a function of time when the voltage is switched from 0 V to various end voltages. It is seen that up to about 5 V the rise time decreases with increasing voltage, but above 5 V the optical response is different and the rise time no longer decreases.

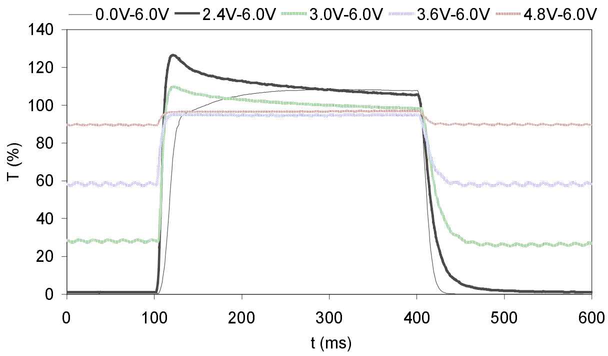

Fig.1. Measured optical response upon switching between the indicated voltages and 6 V.

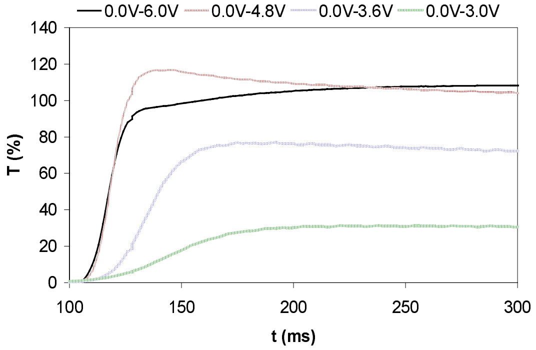

Fig.2. Measured optical response upon switching from 0 V to the indicated voltages.

Both phenomena are connected to the fact that two switching processes play a role in SVA displays. The first process is the fast rotation of the director from vertical to nearly horizontal, based on a splay-bend deformation. The second process is a slow rotation in the horizontal plane, based on a twist deformation.

First we performed two-dimensional (2D) simulations to obtain an idea about these processes. In reality the electric fields are inhomogeneous in three dimensions (3D) due to the chevron-like structure. We mimicked this effect in 2D by taking a pre-tilt that deviates from 90° by 1°. Figure 3 shows the calculated director patterns at 20 ms (i.e. close to the maximum of Fig. 1) and at 300 ms after switching from 2 V to 6 V.

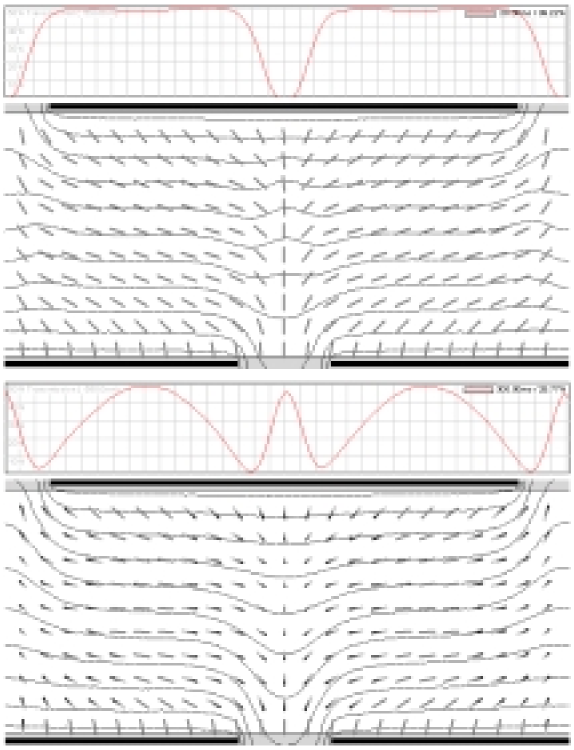

Fig. 3. Calculated director patterns and transmission (vs. lateral co-ordinate) at 20 ms (top) and 300 ms (bottom) after switching from 2 to 6 V.

The observed effect of a fast rise followed by a slow decay of the transmission is also present in the simulation. We found that the details depend strongly on the values used for the pre-tilt. From the calculated director patterns it can be seen that during the fast rise the directors rotate from vertical to nearly horizontal in the plane of drawing (Fig. 3, top), whereas at a longer time scale a twist out of the plane of drawing takes place (Fig. 3, bottom).

Next we performed 3D simulations using a chevron structure. Although the actual pixel structure cannot be simulated in the present software, an idea of the physical processes can be obtained. Figure 4 gives mid-cell cross sections for a simple chevron structure showing the director pattern and transmission at several times. Figure 5 shows the corresponding optical response, yielding the same qualitative behavior as the measurements (and the 2D calculation). Also here the directors rotate in a plane perpendicular to the slits in the first tens of ms. Next, starting from the chevron edges, the directors rotate towards the slit direction. At a longer time scale the twist propagates through the whole cell and disclinations are formed which have the director parallel to one of the polarizers. Depending on the details of the chevron structure, these disclinations may rotate for a long time before equilibrium is reached. Microscopic measurements on test cells with various chevron structures confirm this picture.

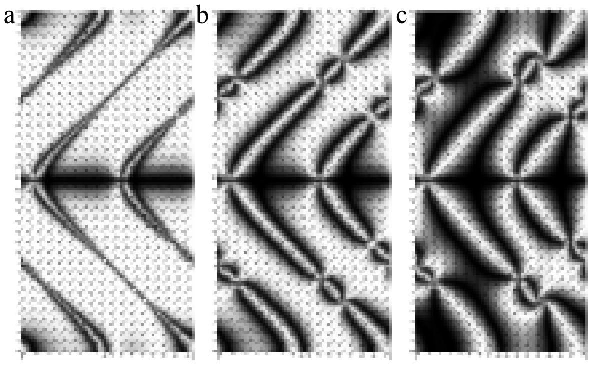

Fig. 4. Calculated mid-cell director pattern and transmission at (a) 30 ms, (b) 100 ms and (c) 300 ms after switching from 2 to 6 V.

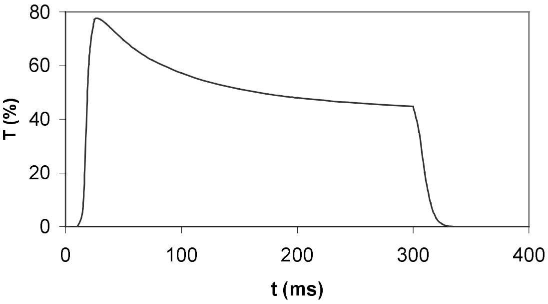

Fig. 5. Calculated optical response upon switching from 2 to 6 V at 0 ms and from 6 to 2 V at 300 ms.

The calculated results for switching from 0 to 6 V was found to be qualitatively the same as for switching from 2 to 6 V. However, the measured effect (Fig. 1) is different. As was pointed out by Konovalov et al.[4], this effect is due to the fact that the director is rotated over 45° degrees at high voltage. Obviously this effect is not taken into account properly in the simulations. The reason is probably that after rotation from vertical to nearly horizontal the twist has a random direction if the begin voltage is 0 V. Next a slow in-plane reorientation takes place to a preferential direction defined by the slits and /or protrusions.

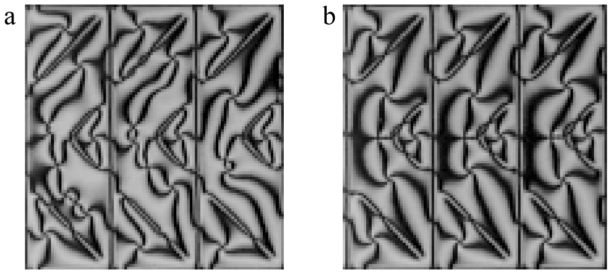

Fig. 6. Microscopic pictures of an SVA test cell with chevrons, 1 s after switching (a) from 0 to 6 V and (b) from 2 to 6 V.

Figure 6 shows microscopic pictures of a test cell between crossed polarizers (at ±45° with the slit directions) after switching from 0 to 6 V and from 2 to 6 V. It is seen that indeed the domains are randomly oriented in the first case. In the second case, qualitative agreement with the calculated patterns of Fig. 4c is obtained.

In-Plane Switching

In this section we will discuss new results for IPS cells. In a recent paper[10] we compared the measured optical response of these cells with 2D simulations. The model used at that time made use of one effective elastic constant for the liquid crystal. Furthermore, it was not possible to give the surrounding medium a dielectric constant different from one. Here we present results using a 2D model[11] that allows use of three elastic constants, as well as the appropriate dielectric constant for the glass plates. We compared the results and performed microscopic test-cell measurements to obtain more insight in the switching behavior.

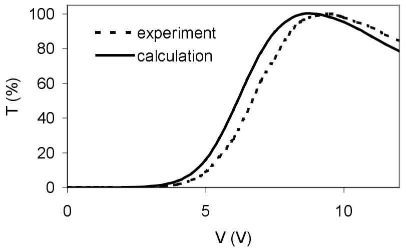

Fig. 7. Normalized average transmittance versus applied voltage.

The used LCD parameters are: K_1 = 13.2 pN, K_2 = 6.5 pN and K_3 = 18.3 pN, $\varepsilon_\perp = 3.1$, $\varepsilon_\parallel = 8.3$, $\gamma = 0.1$ Pa·s, n_o =1.479, n_e = 1.576, $\varepsilon_{glass} = 3.5$, electrode width 4 µm, electrode distance 13 µm, cell thickness 4 µm, pre-tilt 1°, pre-twist 80°. (For more details we refer to Ref. 10.) We found that the overall agreement with the experiments is at least as good as for the calculations presented in Ref. 10. The calculated transmission-voltage curve (Fig. 7) is shifted nearly 0.5 V to lower voltages with respect to the measurement.

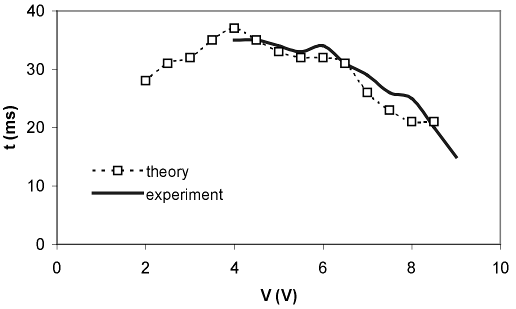

Fig. 8. LC switching time versus applied voltage for switching from *V*–0.5 V to *V*.

Figure 8 shows the LC switching time for switching from *V*–0.5 V to *V*. The agreement between theory and experiment is remarkably good. The same applies for the T-t curves for off-on and on-off switching.

Figure 9 shows the calculated transmittance versus transverse distance. It is interesting to note that the transmittance in the center of the gap between two electrodes is lower than at the borders. The reason seems to be that the in-plane twisting process is slower than the rotation in the vertical direction.

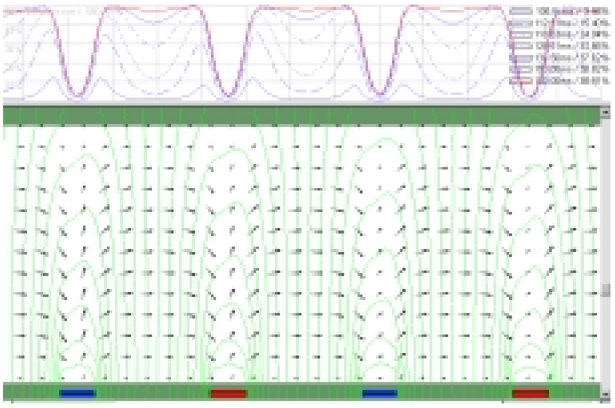

Fig. 9. Upper part: transmittance versus transverse co-ordinate during the off-on switching process (from 1.2 to 9.5 V; the switching starts at 100 ms.) The lower part of the figure shows the calculated director pattern at 50 ms after the start of switching.

We checked experimentally whether the transmission at intermediate gray levels shows a dip in between two electrodes. Figure 10 shows the transmission of the cell at high magnification. The black stripes are the 4 µm-wide aluminum electrodes, which are driven as described in Ref. 10 with a positive voltage of 6 V. The 13 µm-wide regions between the electrodes are much brighter close to the electrodes than in the center. This is in good agreement with what is found using the simulation program. The line scan (Fig. 11) agrees very well with a calculation using a 6 V voltage.

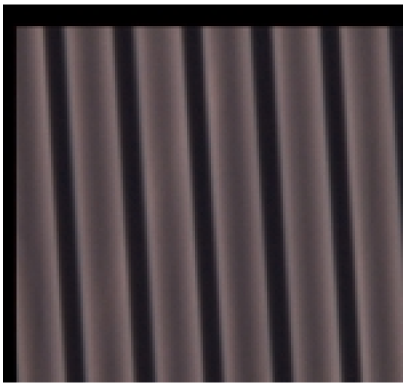

Fig.10. Microscopic picture of IPS cell at driving voltage 6 V.

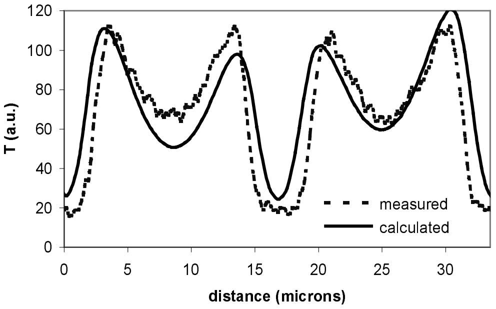

Fig. 11. Horizontal line scan in Fig. 10 (dotted) and calculated transmission (solid line).

We investigated the influence of the two effects, viz. the use of three elastic constants instead of one and the use of a realistic dielectric constant of the surrounding glass. The main effect is that a larger dielectric constant of the surrounding medium results in a faster vertical rotation, a slower in-plane twisting and more pronounced dips.

Conclusion

For IPS we found good agreement between simulations and experiments for both static and dynamic results, as well as for the spatially resolved transmittance. In the case of SVA we obtained qualitative agreement and better insight in the mechanisms responsible for the response, whereas the exact behavior seems to depend on the details of the chevron structure and the display history. It is interesting to note that, although for SVA a rotation from the vertical to the horizontal direction and for IPS a rotation in the vertical plane is intended, the two mechanisms play a role in both cases.

Some of the observed phenomena may give rise to annoying effects. For instance in the described SVA display, the transmission is reduced because of the presence of disclinations. We succeeded to minimize this effect by choosing a proper electrode structure and switching scheme[12].

To understand and solve this kind of problems, model calculations are very helpful. For a complete understanding, good 3D simulation tools are needed. This implies that the presently available software should be extended in several ways. In the first place it is not yet possible to use realistic structures with a fine mesh because of memory limitations. More fundamentally, the optical calculations do not take into account the lateral variation of the refractive index. Recently it was shown that the finite-difference time-domain method[13] can account for this effect in 2D. We expect improved methods to become available for 3D as well.

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