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Response time characteristics of optical shutter of vertical alignment liquid crystal cell for obliquely incident light

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The temporal transmittance of a liquid crystal (LC) cell shutter was investigated for various incident angles to verify the possibility of a fast switching time. For a mono-domain vertical alignment (VA) cell, the switch OFF time in which the LC restores to its initial alignment state under no driving voltage is found to relate to the angle of the incident light. A decrease of switch OFF time is observed when the azimuth angle of the incident light approaches the azimuth angle of the LC optical axis. For a 4-domain VA cell, switch OFF time is observed not to decrease for any obliquely incident angle.

Keywords: optical shutter; vertical alignment; liquid crystal cell; response time; oblique incidence

1. Introduction

Electro-optical characteristics of liquid crystals (LCs) have been widely used for LC shutter and display applications (*1, 2*). For an optical LC shutter, a fast switch time is important since the processing of a larger amount of data is possible during the same time. However, it is difficult to obtain fast temporal response when LC molecule restores to its initial state under no external driving voltage at switch OFF. To reduce switch OFF time, various approaches have been reported, such as the development of new LC material of lower viscosity and higher birefringence or polymer-stabilised LC cells (*1–4*). The phenomenon of the angular dependence of temporal transmittance of a LC cell has been reported previously (*5, 6*). Its potential as a way of improving LC shutter speed, however, has not been fully exploited.

In this study, the possibility of a faster LC shutter was investigated by considering obliquely incident light. The angular dependence of the temporal transmittance of a LC cell is characterised for a vertical alignment (VA) LC cell and the angular conditions under which switching time decreases investigated.

2. Performance of mono-domain VA cell

An LC cell of the mono-domain VA mode is considered for the application of an optical shutter. Temporal transmittance between switch ON and switch OFF state was investigated to verify the possibility of a faster switching time.

Compensation film and multi-domain structures have been reported to be effective in improving the viewing angle characteristics of LC displays (LCDs) of various types (*2, 7, 8*). Design of the compensation film of VA mode has been reported to reduce angular light leakage at the black state for the display application. In VA mode, LC molecules align homeotropically at the black state and LC configuration of black state is the same, irrespective of the domain structure. So, the retardation condition of the compensation film designed for the LCD of multi-domain VA cell can also be used as an optical LC shutter of mono-domain VA mode.

Dynamic characteristics of an LC shutter were simulated using a commercial simulator (*9*). A vertically aligned LC layer is placed between two layers of transparent electrode, as shown in Figure 1(a). Parameters of the LC materials used for the simulation were a birefringence, Δn, of 0.0836 and dielectric anisotropy, $\Delta\varepsilon$, of –3.7. The cell gap was designed to be 4.1 μm and the initial tilt angle of the LC molecules was selected to be 89°. The azimuth angle of the LC tilt direction was selected as 45° with respect to the optical axis of the polariser, as shown in Figure 1(b). A polariser is attached on one side, whereas compensation films and the analyser are placed on the other side. A positive A-plate of 138 nm and negative C-plate of 275 nm were used as the retardation condition of the compensation films (*8*).

Normalised transmittance values of the VA cell at the static state of each driving voltage were calculated and are shown in Figure 2. When the driving voltage is zero, transmittance is minimised, whereas maximum transmittance occurred approximately at 6 V. Voltage values for switch ON and switch OFF states were selected as $V(\text{on})$ = 6.4 V and $V(\text{off})$ = 0 V,

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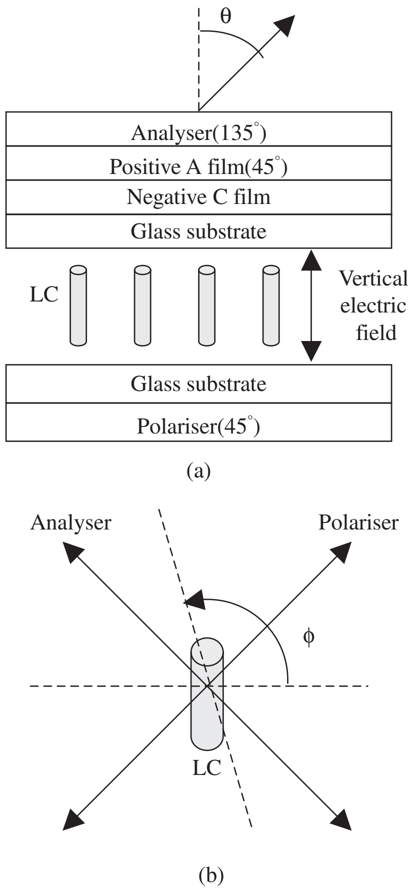


Figure 1. (a) Schematic structure of LC cell of VA mode. (b) Top view of configuration of polarisers and azimuth angle ϕ.

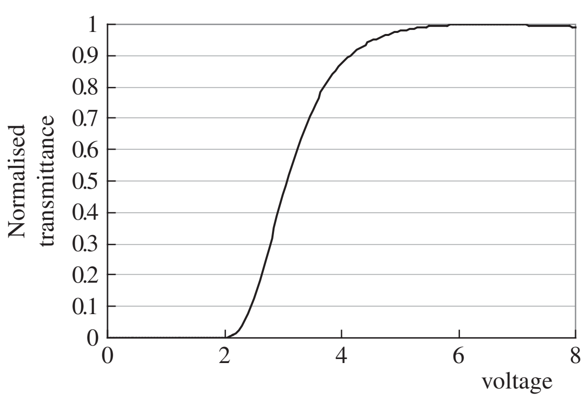


Figure 2. Normalised transmittance of VA Cell under driving voltage.

respectively. The driving voltage condition was selected such that V(off) changes to V(on) at 0 ms and V(on) changes to V(off) at 100 ms. Under this driving voltage profile, temporal transmittance is calculated.

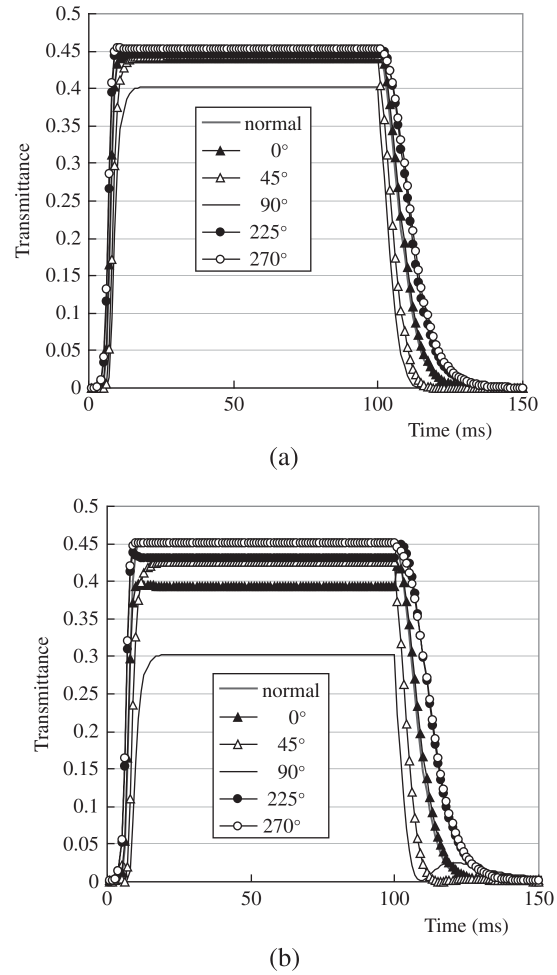
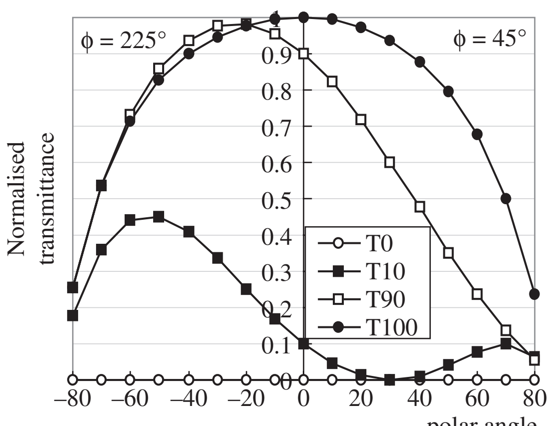


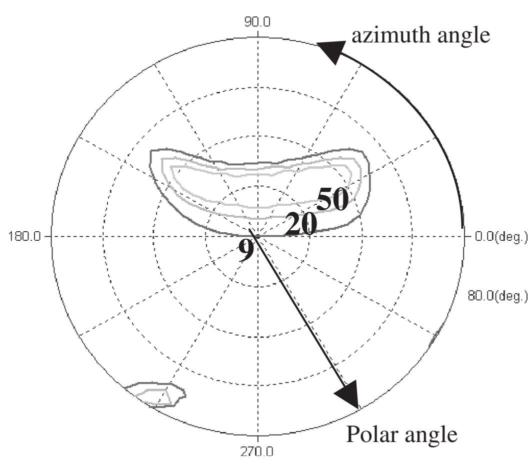
Figure 3. Temporal transmittance of VA LC cell at the polar angle of (a) 20° and (b) 30°. Numbers in the box represent values of azimuth angle. Thick solid line represents temporal luminance for the normally incident light. V(on) value is 6.4 V.

Figure 3 shows temporal transmittance curves for incident light of polar angles of 20° and 30° and the azimuth angles of 45° intervals. For the same dynamic motion of LC molecules, the amount of phase change and transmittance is affected by the direction of the incident light, as shown in Figure 3. The time interval in which the temporal transmittance reaches 10% and 90% difference level from the initial to the final transmittance is accordingly affected. Compared with light of normal incidence, temporal transmittance values show steeper temporal change at the condition of azimuth angle 45° and 90° and slower change at other azimuth conditions when the driving voltage changes from V(on) to V(off) in a time of 100 ms. The VA LC cell configuration has left–right mirror symmetry. As temporal transmittance values for azimuth angles of 45° and 135° are the same, only an azimuth angle of 45° is shown in Figure 3. Similarly, conditions for azimuth angles of 180° and 315° are omitted from Figure 3.

Transmittance values of LC at the various angles were calculated from the static LC state condition. These transmittance values, which are normalised with respect to the maximum transmittance at normal incident angle, are shown in Figure 4(a). The T_0 curve represents the angular transmittance of LC state, the transmittance of which is 0% at normal incidence. The other curves represent 10, 90 and 100% transmittance of the LC state at normal incidence, respectively. For the VA mode, the static LC state of one transmittance value can be uniquely connected to dynamic LC state of the same transmittance, since there are no special dynamic phenomena such as backflow. Therefore, the response time of any incident angle can be derived



(a)



(b)

Figure 4. (a) Transmittance versus polar angle at azimuth angle of 45° (right) and 225° (left) derived from the static LC state. (b) Contour of transmittance ratio of mono-domain VA between LC states, the transmittance of which are 90% and 10% at the normal incidence. Polar angle is represented as the distance from the center of the circle.

from the temporal response along the normal direction if the angular transmittance of the static LC state is known. Values of T_{10} and T_{90} in Figure 4(a) are 0.1 and 0.9 at normal incidence but decrease for an azimuth angle of 45° and increase for an azimuth angle of 225° as the polar angle increases. These profiles are connected with the steep decrease of temporal transmittance of Figure 3. Figure 4(b) shows the contour of transmittance ratio between the T_{90} and T_{10} curves. In the normal direction, this ratio is 9. This contour shows a steep increase in the azimuth angle range 45–135°, whereas it shows a gradual decrease for the range of other azimuth angles. The angular region in which the ratio is much higher than 9 implies the possibility that temporal response is much faster than that of the normal incidence. Though the angular dependence of T_0 and T_{100} also affect the switch ON/OFF time, transmittance changes relatively little for small polar angle range, as shown in Figure 4(a).

In Figure 3, the mono-domain VA cell exhibits shortening of switch OFF time for an incident light of azimuth angle range 45–135°. On the other hand, temporal transmittance profile of Figure 3 shows slower increase from V(off) to V(on) transition and this will result in slower switch ON time compared with that of the normal incidence. However, switch ON time can be shortened by the increase of driving voltage, as higher driving voltage is known to cause faster response of LC molecules (*10*). So, temporal transmittance for V(on) = 10 V was calculated and compared with that for V(on) = 6.4 V. These results are shown in Figure 5(a). The temporal profile for 10 V and polar angle of 20° is almost equivalent to that of normal incidence.

Temporal transmittance from V(on) = 10 V to V(off) was calculated and is shown in Figure 5(b). From this result, switch OFF time is calculated as the time interval between 10% and 90% transmittance, and is shown in Table 1. As the polar angle increases, OFF time becomes shorter, but bouncing profile becomes more noticeable where transmittance reaches the local minimum, increases and then decrease again. The Bounce in Table 1 is defined as the ratio of maximum transmittance and transmittance of local peak that appears after the local minimum in Figure 5(b). At the same polar angle, OFF time is shorter, bouncing is stronger and maximum transmittance is smaller for an azimuth condition of 90° than for 45°.

The extinction ratio at switch OFF time is defined as ratio of transmittance values when voltage changes from V(on) to V(off). When the bouncing profile is considered, extinction ratio will be at least smaller that the inverse value of the bounce. In this respect, conditions of incident angles of (20, 45) (20, 90) and (30, 45) provide improvement of switch OFF time as well as a good extinction ratio.

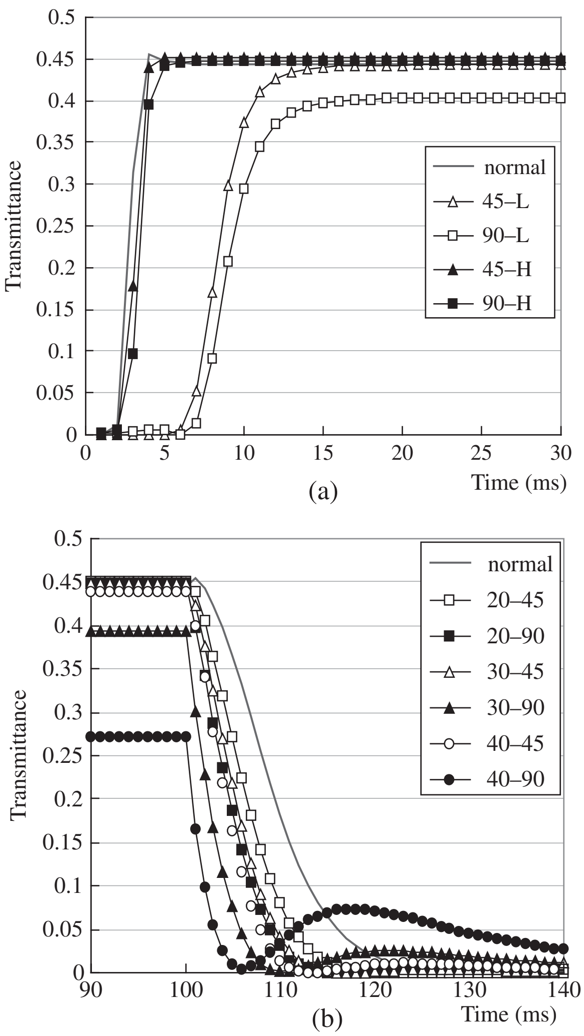


Figure 5. (a) Temporal transmittance of VA LC cell at the polar angle of 20°. Numbers on the right side represent the azimuth angles. L and H represent V(on) of 6.4 V and 10 V, respectively. (b) Temporal transmittance of VA LC cell at V(on) = 10 V at the various incident angles. Pairs of numbers on the upper right side represent the polar and azimuth angles.

Table 1. Switch OFF time versus incident angle.

(0, ϕ)	OFF time/ ms	OFF time ratio/ %	Tranmittance max.	Bounce	Extinction ratio
(0, 0)	12.5	100	0.444	No	–
(20,45)	9.75	78	0.451	0.2%	500
(20,90)	8.25	66	0.448	1.2%	83
(30,45)	8.3	66	0.449	0.8%	125
(30,90)	5.85	47	0.393	6.4%	15.6
(40,45)	7.2	58	0.438	2.5%	40
(40,90)	3.08	25	0.272	27%	3.7

Switch OFF time at normal incidence is known to decrease for LC materials of lower viscosity and higher birefringence (*1–3*). Switch OFF time ratio is related to angular dependence of transmittance. Major factors that affect angular dependence of transmittance are the retardation of LC cell and compensation films. So the switch OFF time ratio in Table 1 is little changed by the parameters of the LC material. When collimated light is incident on the LC cell along the oblique direction, faster switch OFF time can be obtained for the same LC shutter. For example, in case of incident angles of 40° polar angle and 45° azimuth angle switch OFF time is only 58% of that of normal incident light.

3. Performance of 4-domain VA

In display applications of VA mode, a 4-domain structure has been proposed to obtain the wide viewing angle characteristics and widely used for the display application (*11*). To check the possibility of an LC optical shutter that has the merit of fast switching for wide angular range, the temporal angular dependence of a 4-domain VA cell was investigated. The LC cell configuration of 4-domain VA is shown in Figure 6(a). This configuration has 4-fold rotation symmetry. As the viewing angle characteristic of this LC cell also has 4-fold symmetry, only incident angle conditions of azimuth angle of 0° and 45° were investigated. The same LC cell condition as mono-domain LC is used and 4-domain transmittance is obtained by rotating the angle of each mono-domain LC cell 90, 180 and 270°, respectively, and summing the result. Figure 6(b) shows the contour of transmittance ratios between LC states transmittance of which are 90% and 10% of that at normal incidence. Temporal transmittance is shown in Figure 7. Unlike the result for mono-domain VA, no azimuth condition is observed that switch OFF time shortens. In Figure 6(b), transmittance ratio is smaller than 9 for any angles in contrast to mono-domain contour of Figure 5, where an angular range of transmittance ratios higher than 9 exist. In the case of mono-domain VA, switch OFF time increases or decreases depending on the angular condition. In case of temporal transmittance of 4-domain structure, one domain of faster switch OFF is compensated by three domains of slower switch OFF and the faster switch OFF condition can no longer exist for 4-domain VA.

4. Conclusion

Temporal transmittance of a VA LC cell changes, depending on the incident light direction. For a mono-domain VA LC cell, when the azimuth angle of incident light approaches the azimuth angle of the LC optical axis and polar angle is more than 20°, switch OFF times are calculated to decrease more than 30% compared with that for normal incident

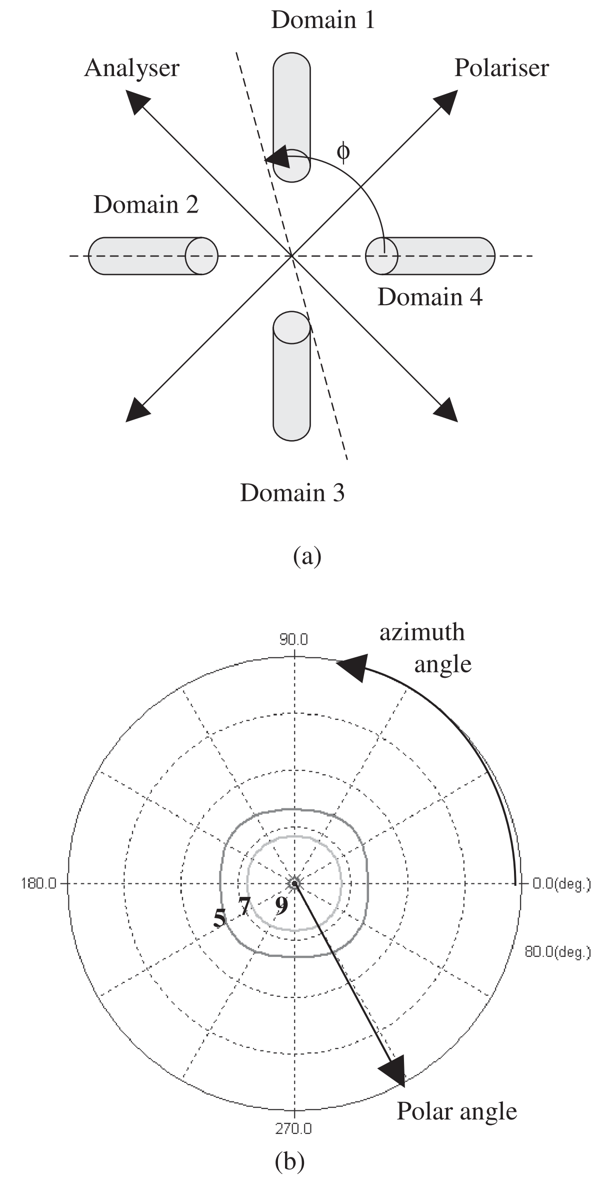


Figure 6. (a) Top view of configuration of domains, crossed polariser, azimuth angle in 4-domain VA. (b) Contour of transmittance ratio of 4-domain VA between LC states, the transmittance of which are 90% and 10% at the normal incidence.

light. For 4-domain VA LC cell, switch OFF is observed to increase for any obliquely incident angles.

Various methods have been reported to reduce switch OFF time of LC cells (*1–4*). When LC cells

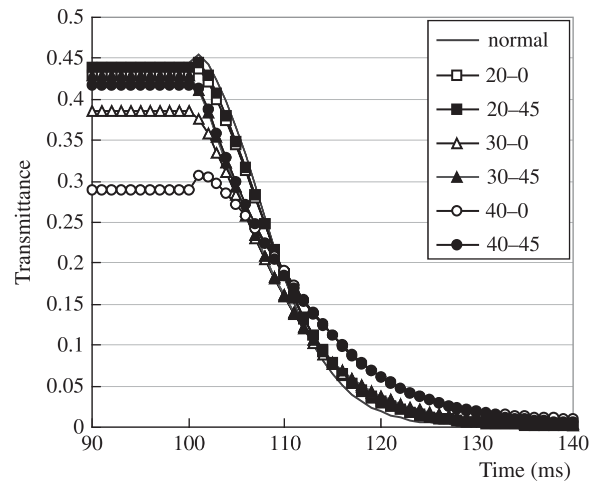


Figure 7. Temporal transmittance for 4-domain LC cell at the various incident angles. Pairs of numbers on the upper right side represent the polar and azimuth angles. Thick solid line represents temporal luminance for the normally incident light.

used for these reported methods have the appropriate characteristics of angular dependence, switch OFF may be further reduced using obliquely incident light compared with that of normally incident light.

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