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Temporal characteristics of the optical shutter of a vertical alignment liquid crystal cell designed for obliquely incident light

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The simple configuration of a liquid crystal (LC) cell shutter has been investigated for the purpose of rapid switching time. The LC cell is designed to cater for oblique incident light with vertical alignment. A decrease in switch-off time is observed when the azimuth angle of the incident light is either parallel or perpendicular to the optical axis of the polariser and about 45° to the optical axis of the LC tilt. A LC cell having a larger extinction ratio has been devised in which retardation films are no longer required.

Keywords: liquid crystal display; vertical alignment; optical shutter; oblique incident light

1. Introduction

Electro-optical switching of liquid crystal (LC) cells has been widely used for optical shutter applications since the LC shutter has the merit of low power and low cost [1, 2]. The rapid temporal response of LC is possible when a strong driving voltage is applied at switch-on. However, it is difficult to obtain a rapid temporal response when the LC molecule returns to its initial state at switch-off, when there is no external driving voltage.

At switch-off the temporal response is determined by the material parameters of the LC such as viscosity and the elastic constants. The modification of the material parameters such as viscosity, or a change in the LC cell characteristics by polymer stabilisation, has therefore been studied as a means of producing a more rapid temporal response [1–4]. On the other hand, a LC shutter has been reported recently in which a faster response at switch-off is observed when the oblique incident light is in a specific direction to the normal [5]. This angular temporal characteristic is reported to be related to the angular dependence of the transmittance of the LC cell [6, 7].

However, in the previous description of the angular dependence of the temporal response of the LC cell, the cell structure consisted of an LC layer and multiple layers of anisotropic material known as compensation films. The main purpose of the compensation films is to reduce the leakage of light at minimum transmittance at all directions of incidence [2, 8]. In the case of an LC shutter the direction of the incident light may be limited to one specific direction and it is therefore not necessary to design a LC cell structure for a range of angles of incidence.

In the present paper it will therefore be initially assumed that only one specified oblique direction is to be employed as the incidence direction for the LC shutter. Other possible directions of incidence are then selected for which a compensation film is unnecessary and more rapid temporal change may take place. Temporal transmittances are analysed for these directions of incidence, and in addition the possibility of further modification of the LC cell structure will be considered.

2. Selection of incidence direction and cell design

A LC cell in vertical alignment mode (VA) has been considered, in which at zero driving voltage the LC molecules initially align homeotropically between two crossed polarisers. Since the LC cell parameters, such as optical axis and retardations, are a function of incident direction (θ, ϕ), these parameters are noted as effective axis, effective retardation, etc. to differentiate them from those which apply at normal incidence.

To make an efficient LC shutter for an oblique direction of incidence, with little light leakage at a state of minimum transmittance, the direction of linear polarisation of the incident light after passing through the first polariser and the LC layer should be perpendicular to the transmissive axis of the analyser.

Figure 1(a) shows the situation in which the azimuth angle of the incident direction is selected to be either parallel or perpendicular to that of the

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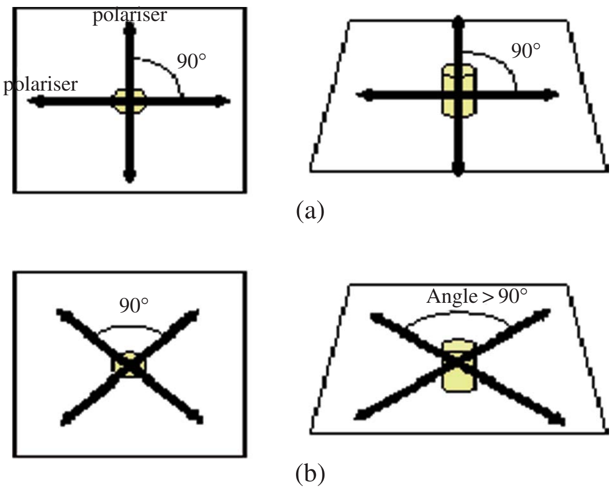

Figure 1. Change in effective optical axis for different viewing directions at voltage-off with LC cell in VA mode. Difference between the azimuth angle of the viewing direction and the transmissive axis of the polariser is (a) 0 or 90° and (b) 45° to the normal.

transmissive axis of the crossed polarisers. The azimuth angle, ϕ, of the incident light is selected to be zero degrees. Voltage-off (V(off)), in which the driving voltage is zero, corresponds to the minimum transmittance. The optical axis of the LC is perpendicular to the direction of polarisation of the first polariser. The state of polarisation is therefore not changed by the LC at V(off). Moreover, the effective angle between the axes of the two polarisers remains 90° for any oblique incidence direction for this azimuth condition. Little light leakage is therefore expected at the LC state of V(off). On the other hand, when the azimuth condition of ϕ is other than zero degrees, the effective angle between the axes of the two polarisers is no longer 90°. An example of $\phi = 45°$ is shown in Figure 1(b), where the light leakage would be larger for oblique incidence at the state of the minimum transmittance compared with that for normal incidence. Since light leakage is much smaller with the configuration in Figure 1(a), this configuration was chosen for a more extensive analysis.

Switch-off may be defined as the transition from voltage-on (V(on)) to V(off), and similarly switch-on is the change from V(off) to V(on). A decrease in switch-off time has been reported in LC cells using compensation films, where the angle between the azimuth of the incidence direction and the optical axis of the LC molecules lies between –45° and 45° [5]. Since the condition of the compensation films affects the angular luminance, and the angular luminance is related to the characteristics of the temporal luminance, the angular temporal luminance needs to be analysed for the LC cell structure in which no compensation films are used. In the section following we will attempt to estimate the temporal behaviour of the LC cell without the presence of a compensation film. Since a change of direction in the optical axis of an LC affects the final polarisation state, the effect of the initial azimuth angle of the LC optical axis must also be considered.

3. Results and discussion

The temporal electro-optical characteristics of a LC cell with vertical alignment were calculated for the configuration shown in Figure 2. A commercial simulator, LCD Master^{TM}, was used for the calculation [9]. A layer of vertically aligned LC molecules was placed between two layers of transparent electrodes. The polariser was attached on one side of the LC layer and the transparent electrodes, and the analyser was placed on the opposing side. A wavelength of 550 nm was selected for the incident light. The parameters of the LC materials used for the simulation were: birefringence, Δn, 0.0836 at 550 nm; dielectric anisotropy, $\Delta\varepsilon$, –3.7; elastic constants, $k_1 = 14.9$ pN, $k_2 = 8.2$ pN and $k_3 = 15.1$ pN; and rotational viscosity, γ_1, 0.126 Pa s. A cell gap of 4.1 μm was chosen, and the retardation, $d\Delta n$, of the LC layer was 343 nm. The condition of strong anchoring energy was used for the calculation. A tilt angle of 89° was selected. The azimuth angle of the LC tilt direction under driving voltage was A_0 with respect to the optical axis of the polariser, as shown in Figure 2.

For the case $A_0 = 45°$, transmittance values of the VA cell were calculated for a driving voltage step of 0.05 V for an incident direction of $(\theta, \phi) = (0, 0)$ and (20, 0), respectively. The results calculated for transmittance vs driving voltage are illustrated in Figure 3. When the driving voltage was zero, transmittance was a minimum; maximum transmittance occurred above

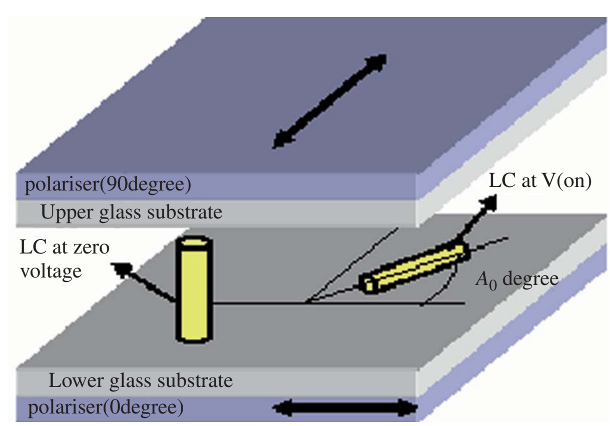

Figure 2. Side view of schematic configuration of the LC cell in VA mode. Polariser angles in parenthesis represent the azimuth angles of the optical axis of each anisotropic layer.

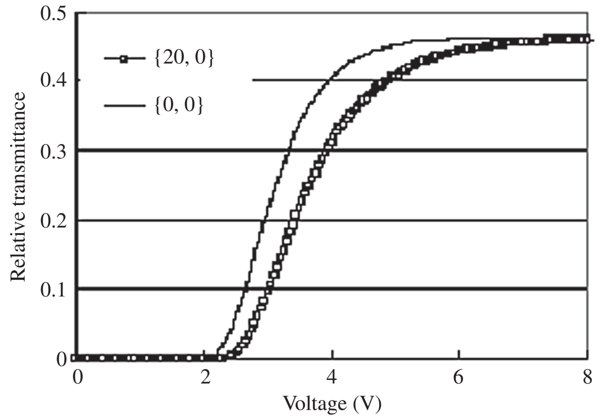

Figure 3. Calculated relationship between driving voltage and transmittance at the viewing direction (θ, ϕ) = (20, 0) and (0, 0).

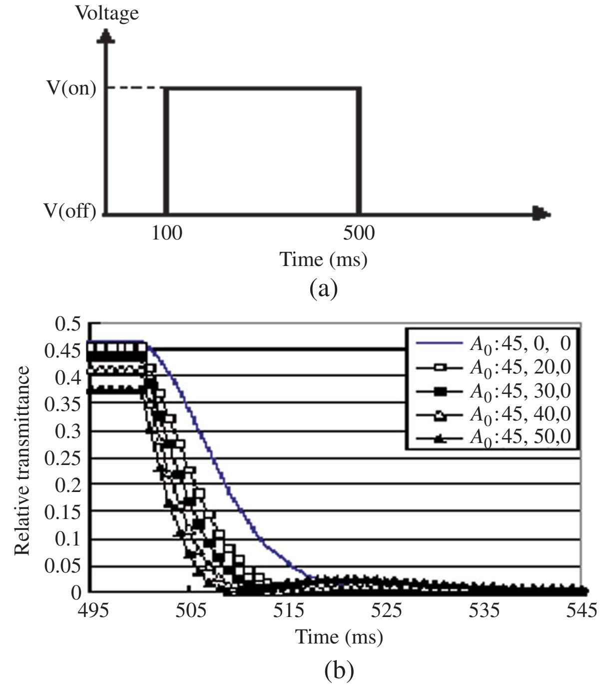

Figure 4. (a) Driving voltage profile using two voltage levels for switch-on and switch-off, (b) calculated temporal transmittance for different incidence angles where the voltage changes from V(on) = 6.4 V to V(off) = 0 V. In the box at the upper right, A_0 is 45° and is defined in Figure 2. The second and the third numbers in the box represent polar and azimuth angles, respectively. The horizontal axis represents time.

6 V. Within the voltage range 2–3 V, transmittance for the incident direction of (20, 0) was less than that for (0, 0) at a similar driving voltage. Moreover, this angular dependence of transmittance was related to the faster decrease at switch-off occurring at a non-zero value of θ [5]. From the data in Figure 3, the voltage values of a LC shutter at switch-on and switch-off are selected as V(on) = 6.4 V and V(off) = zero.

Simulation conditions for the driving voltage profile are such that the driving voltage changes from V(off) to V(on) at 100 ms and changes from V(on) to V(off) at 500 ms, as shown in Figure 4(a). Under these conditions of the driving voltage profile, temporal transmittance has been calculated for the various incidence angles of (θ, 0). Since switch-on time is determined by the driving voltage, and can be made shorter by applying a higher voltage, its optimisation is not described in the present paper [10], and it is only the behaviour of the switch-off time which will be considered in detail. Figure 4(b) shows the calculated temporal transmittance when the driving voltage changed from V(on) to V(off). Figure 4(b) shows the trend in profiles of temporal luminance, which become steeper as the angle, θ, increases for a fixed azimuth angle. In addition, the profiles also show a "bounce" phenomenon, where transmittance reaches a minimum, increases slightly at the bounce peak, and then decreases steadily to a minimum value. A maximum transmittance of 90% and a minimum of 10% can be determined. Switch-off time may thus be defined as the time interval between 10% and 90% transmittance.

The characteristics of the temporal transmittance for different incidence directions, θ, are summarised in Table 1. The extinction ratio is defined as ratio of maximum transmittance to the bounce peak. As the polar angle, θ, of the incidence direction increases, switch-off time decreases and a LC shutter of faster switching time becomes possible. However, the extinction ratio decreases with larger values of θ, and a smaller extinction ratio impedes the usefulness of the LC shutter. A method for increasing the extinction ratio was therefore needed.

Table 1. Calculated characteristics of temporal transmittance at $A_0 = 45°$ and V(on) = 6.4 V.

A_0	θ	Switch-off time (ms)	Ratio of Off Time at θ and 0° (%)	Maximum transmittance	Bounce peak	Extinction ratio
45	0	13.18	100	0.463	–	–
45	20	9.67	73	0.452	0.0009	508
45	30	8.06	61	0.437	0.004	106
45	40	6.71	51	0.412	0.012	35
45	50	5.57	42	0.377	0.025	15

When a driving voltage is applied to an LC cell in VA mode, the angle between the azimuth of the polariser and the optical axis of the tilted LC molecules has typically been chosen to be $A_0 = 45°$ to maximise the value of the maximum transmittance. However, the effective angle of oblique incidence deviates from that of the normal incidence. In the case of the configuration shown in Figure 2, the effective angle between the azimuth of the polariser and the optical axis of the tilted LC has been calculated for the various incidence angles and the results are shown in Figure 5. When A_0 is initially 45°, the effective angle for the larger value of θ is greater than 45°. A_0 should therefore initially be selected to be less than 45°, so that the effective angle becomes 45° for a specific value of θ.

From the results in Figure 5, for an incident angle, θ, of 20, 30, 40 or 50°, the angle A_0 is selected to be 43.2, 40.9, 37.5 or 32.7°, respectively, to obtain an effective angle of 45° for each value of θ. For these values of A_0, temporal transmittances have been calculated using the driving voltage profile in Figure 4(a). The results are shown in Figure 6 and summarised in Table 2.

Compared with the results in Figure 5(b) and Table 1, where A_0 was fixed at 45°, the maximum transmittance is almost the same, switch-off time is slightly greater, but the extinction ratio is larger for a similar value of θ. The results show that the selection of a value of A_0 below 45° is effective for giving a larger extinction ratio, although the value of the ratio is still less than that for normal incidence.

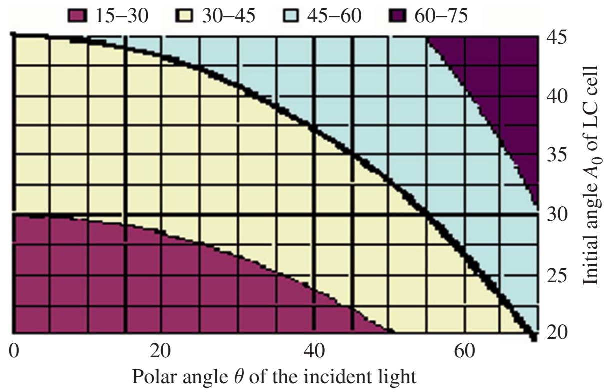

Figure 5. Calculated contour map of the effective angle between optical axes of LC and polariser for different A_0 and polar angles (θ) of incidence light. The thick solid line represents the conditions where the effective angle is 45° (colour version online).

The bounce phenomenon occurs when two different LC states result in a similar value for the transmittance at the oblique incidence direction. For example,

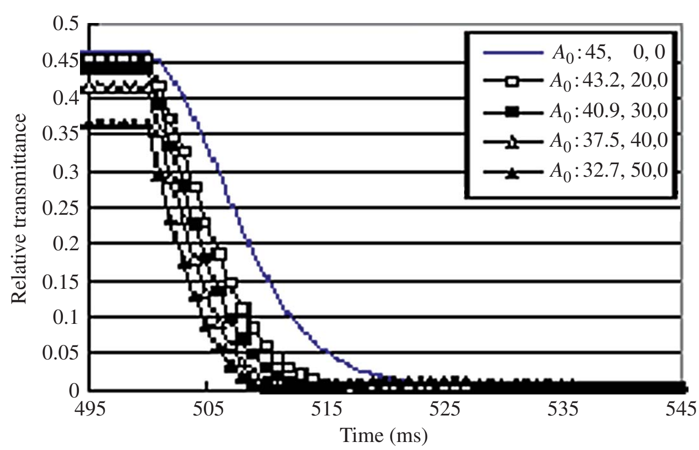

Figure 6. Calculated temporal transmittance for different incidence angles when the voltage changes from V(on) = 6.4 V to V(off) = 0 V. In the box at the upper right, the numbers following A_0 represent the values of A_0 for the transmittance curve of each incidence angle. The second and the third numbers in the box represent the polar and azimuth angles, respectively. The horizontal axis represents time.

Table 2. Calculated characteristics of temporal transmittance at $A_0 < 45°$ and V(on) = 6.4 V.

A_0	θ	Switch-off time (ms)	Ratio of Off Time at θ and 0° (%)	Maximum transmittance	Bounce peak	Extinction ratio
45	0	13.18	100	0.463	–	–
43.2	20	9.75	74	0.454	0.0008	575
40.9	30	8.34	63	0.441	0.003	140
37.5	40	7.20	55	0.415	0.007	57
32.7	50	6.33	48	0.364	0.011	32

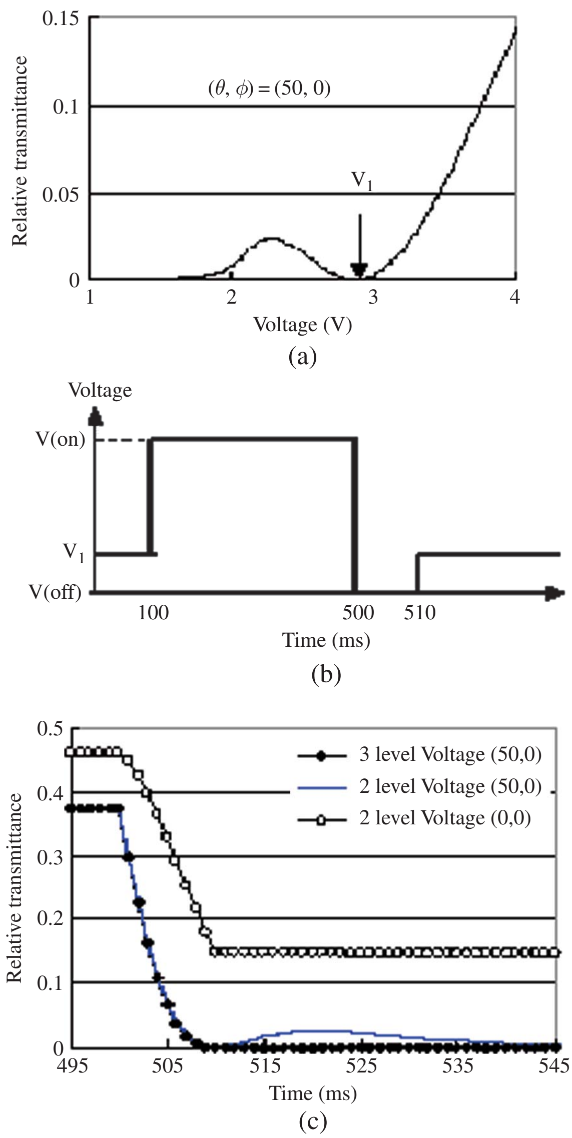

Figure 7. (a) Calculated voltage–transmittance curve of LC cell for $A_0 = 45°$ and incidence angle $(\theta, \phi) = (50, 0)$. (b) Driving scheme using three levels of voltage to reduce the bounce phenomenon. (c) Calculated curves of temporal transmittance when driving voltage schemes using two and three levels are applied respectively. The two numbers in parenthesis are the polar and azimuth angle of the incident direction. The horizontal axis represents time.

in the transmittance–voltage curve for a LC cell at $A_0 = 45°$ and $(\theta, \phi) = (50, 0)$, minimum transmittance occurs when the driving voltage is zero or close to 2.8 V, as shown by the transmittance–voltage curve in Figure 7(a). It takes about 10 ms to reach the first minimum value in the temporal transmittance curve in Figure 4(b). A new driving voltage profile at three voltage levels were therefore considered in order to reduce the bounce phenomenon. Its voltage profile is shown in Figure 7(b), and a time interval of V(off) was selected in consideration of the profile of temporal transmittance. In this driving scheme of switch-off, zero voltage was initially applied, and the LC state changed in a similar manner to that in Figure 4(b) for the 10 ms following application of V(off). As the LC recovers its initial vertical alignment, the LC reaches a state similar to that where the driving voltage, $V_1 = 2.8$ V. By changing the driving voltage from zero to V_1 at this point, the LC state becomes stable and the transmittance accordingly remains at a minimum. The concept of using more than two levels of voltage has been used in LCD applications to obtain faster response times [1, 11]. Figure 7(c) shows the results when driving schemes using three and two voltage levels were applied. Temporal transmittance does not exhibit the bounce phenomenon at an incidence direction of $(\theta, \phi) = (50, 0)$ when a driving scheme of three voltage levels, rather than two, is applied. Accordingly, a high extinction ratio can be obtained at large incidence directions by suitable selection of driving voltage profile. Since the driving voltage profile in Figure 7(b) is optimised for an incidence direction $(\theta, \phi) = (50, 0)$, it cannot be applied to other incidence directions. An example of the voltage profile of three levels applied to the incidence direction of $(\theta, \phi) = (0, 0)$ is shown in Figure 7(c). In this case, the value of minimum transmittance becomes as high as 30% of maximum transmittance, and this is not suitable for the shutter application.

4. Conclusions

The usefulness of a LC shutter of VA mode has been considered specifically for oblique incidence. By limiting the incidence angle to just one direction, additional compensation films are no longer needed in the LC cell to compensate for the unwanted phase change. Compared to the temporal response at normal incidence, a quicker response time is possible when the azimuth angle of the incident light is either parallel or perpendicular to the azimuth angle of the axis of the polariser, and about 45° from that of the optical axis of LC tilt. A reduction of more than 40% is observed in switch-off time. These results are similar to those reported earlier for LC cells employing multiple layers of compensation films.

Bounce phenomena are observed for a given oblique direction, and would decrease the extinction ratio and limit the usefulness of the LC shutter. The bounce phenomenon can be reduced by reducing the angle between the azimuth of axis of the LC and polariser from 45° to a smaller value. Alternatively, the driving voltage can also be modified in consideration of the temporal transmittance. The effectiveness of these two approaches in reducing the bounce phenomenon is confirmed by the calculated temporal transmittances.

In terms of practical application, the performance of the proposed configuration will be affected by working conditions such as the wavelength or working temperature, compared with those for normal incidence. Hence, fine tuning of the working conditions is necessary to obtain the best results for the proposed configuration.

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