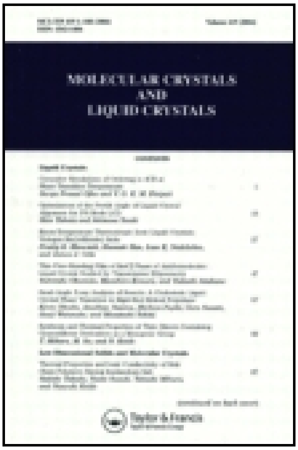

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Electrical Response of Antiferroelectric Liquid Crystal Cells with Asymmetric Response

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Liquid crystal microdisplays are heavily used in applications ranging from static and quasi-static images to video-rate displays. Antiferroelectric liquid crystals with asymmetric response exhibit good properties to be employed in this kind of devices, for example in mobile telephones. Asymmetric response arises from dissimilar surface conditioning onto the cell glass plates. The resulting asymmetric antiferroelectric devices feature multiplexed analogue grey scales with very simple driving schemes. In this work, a comparative study of properties of antiferroelectric liquid crystal cells with symmetric and asymmetric response is carried out. Asymmetric cells give rise dissimilar current peaks depending on the polarity of the applied waveform. This effect may stem from various contributions, such as ionic conductance and free charges accumulated superimposed to the symmetric antiferroelectric response.

Keywords: antiferroelectric liquid crystal; asymmetric response; electric current; frequency dependence; instantaneous polarization; optical transmission

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INTRODUCTION

Liquid crystals are showing an encouraging growth in high-end commercial displays. Devices based on active matrices lead the market of laptop and desktop displays and continuously increase their sharing of home-theatre displays. Nematic liquid crystals are customarily chosen as LC materials for commercial solutions; the long experience gathered on this well-known technology results in cost-effective solutions for most applications.

Antiferroelectric liquid crystals (AFLC), on the other hand, can be driven at video rate on passive matrices, showing optical multistability and intrinsic analogue greyscale. These features allow these materials to compete with nematics in specific medium and high-end market niches where the use of passive matrices may reduce the cost of the device while keeping similar performance to active matrix nematics. This is the case of high resolution microdisplays such as helmet mounted see-through displays, in which the relatively low contrast of AFLC displays is not an issue. Other applications requiring higher contrasts (e.g., cellular phones) can also be accomplished by using orthoconic AFLCs. However, AFLCs also show some drawbacks, mostly derived from the requirement of higher addressing voltages and relatively complex multilevel driving waveforms.

These two disadvantages may be alleviated using antiferroelectric liquid crystals with asymmetric response [1]. The electrooptic response shift in the asymmetric approach reduces the driving voltage levels and consequently the display power consumption. Moreover, asymmetry improves the contrast ratio and allows the use of simple driving schemes [2] based on one single lobe of the AFLC hysteresis curve.

There is a further less mentioned advantage of asymmetric AFLC displays. Ideally, the dark antiferroelectric (AF) state of symmetric AFLC displays is located exactly at 0 V, and the two symmetric ferroelectric states (F+ and F–) are achieved by electrically induced phase transitions exactly at the same voltage level of either sign. In practice, however, the entire double symmetric loop is often slightly shifted and the developed grey levels are not completely balanced. The effect may be due to imperfections in the manufacturing process or derived from the chiral nature of the AFLC materials, contributing to make one of the ferroelectric states slightly more stable than the opposite one. Whatever the reason, this asymmetry jeopardises the use of multiplexed driving schemes based on alternative F+/F– switching that are usually employed in symmetric AFLC displays to achieve DC compensation of the driving waveform.

Nevertheless, this customarily unwanted effect can be deliberately enhanced to take advantage of the shifted response [3], through driving waveforms making use of only one hysteresis lobe to develop the greyscale. Asymmetric surface conditionings result in electric and optical response shifts. The degree of asymmetry depends on a number of manufacturing parameters throughout the fabrication protocol. Unfortunately, actual applications of asymmetric displays are somewhat thwarted by a poor understanding of their electrooptical behaviour.

Asymmetric responses have been previously described in nematic cells, using samples where one face was aligned with a rubbed polymer and the other with tungsten trioxide deposited by cathodic sputtering [4]. In AFLC cells, asymmetry can be originated in the same manner. Specifically [1], AFLC asymmetry has been demonstrated using nylon as polymer, and either tungsten trioxide or silicon monoxide deposited by thermal evaporation.

The origin of this voltage shift is related to charge trapping onto the alignment surfaces [5] and anisotropic electric conductivity. Tentative mechanisms have been proposed elsewhere [6,7]. However, further experimental evidence is required to clarify the underlying processes of ion transport and charge pile-up upon switching. This work contributes to a better understanding of these phenomena by performing simultaneous electric and optical measurements of asymmetric and symmetric AFLC cells.

EXPERIMENTAL

Cell Manufacturing

Throughout the article, cells having received the same surface treatment in both glass plates will be called symmetric AFLC cells, regardless any slight voltage shifts that might show – as mentioned above.

Symmetric AFLC cells are manufactured as regular nematic cells, using two ITO-coated glass plates covered with a buffed polymer – e.g., polyimide or nylon – acting as alignment layer. Thickness is significantly lower (1.5–2 μm) and either parallel or antiparallel homogeneous orientation can be chosen. In this work, the cell thickness was 1.5 μm. Cells were parallely assembled with similar rubbed nylon surfaces on both plates, and filled with the antiferroelectric mixture CS-4001 (Chisso Petrochemical Corp.). Monopixel cells, with an effective area of 0.7 cm × 1 cm between electrodes, were used. The electrooptical response at low frequency of the cells was obtained afterwards. The temperature was held at a constant value 40°C through a temperature controller. Cells were placed in a hot stage (Linkham LTS-E-350). As symmetric cells had to be used for comparison of asymmetric cells, only those symmetric cells having negligible voltage shifts were included in the experimental pool.

Asymmetric antiferroelectric cells were fabricated using the same manufacturing protocol as symmetric cells. A 75 Å silicon monoxide layer was deposited by thermal evaporation onto one of the glass plates, the opposite one being processed with buffed nylon as in the symmetric case.

Electrooptic Characterisation

The characterisation system consisted of two blocks (Fig. 1). The optical response of samples was checked using a polarized microscope (Eclipse 600) and a large area photodiode. Simultaneously, the electric response was evaluated through the switching current measurement.

The resulting electrooptical response – between crossed polarizers aligned as the rubbing direction – at low frequency is a characteristic symmetric double hysteresis loop, developing grey levels as the amplitude of the external signal is increased.

In ideal symmetric devices, hysteresis is centred with regard to the zero voltage of the driving signal (Fig. 2). Usually, triangular AC signals of low frequency (1 Hz or lower) are chosen in quasi-static regime [8]. Electric current follows reorientations of the molecular indicatrix. The current sign changes when the sign of the triangular slope changes (lower curve of Fig. 2). Field induced optical transmission is customarily associated with changes on the switching current profile [9]. Current profile may be also related to instantaneous polarization, derived from the integrated area below the electric current.

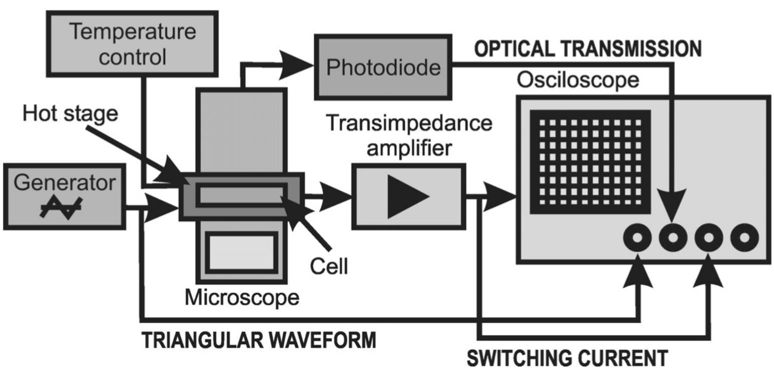

FIGURE 1 Experimental set-up.

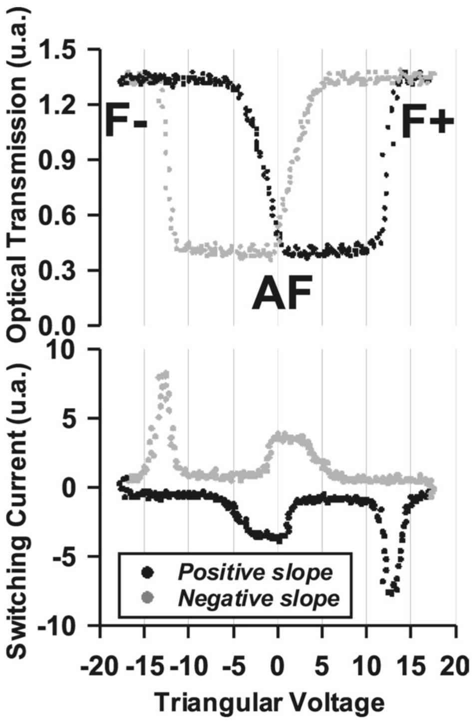

FIGURE 2 Optical hysteresis and electric current in a symmetric antiferroelectric cell.

Electric Measurements

Electric current measurements have been simultaneously recorded along with optical transmission under AC triangular waveforms of constant amplitude (17.5 V) and different frequencies: 30 mHz, 100 mHz, 300 mHz, 1 Hz, 3 Hz, 10 Hz, 30 Hz and 100 Hz. The circuit for electric measurements was based on an operational amplifier with a very low bias current (fA) in a configuration of transimpedance. The chosen peak voltage leads to the optical saturation of the liquid crystal for all applied triangular frequencies.

RESULTS AND DISCUSSION

Symmetric Antiferroelectric Liquid Crystal Cells

Results of simultaneous measurements of optical transmission and electric current have been represented in Figure 3. Every graph

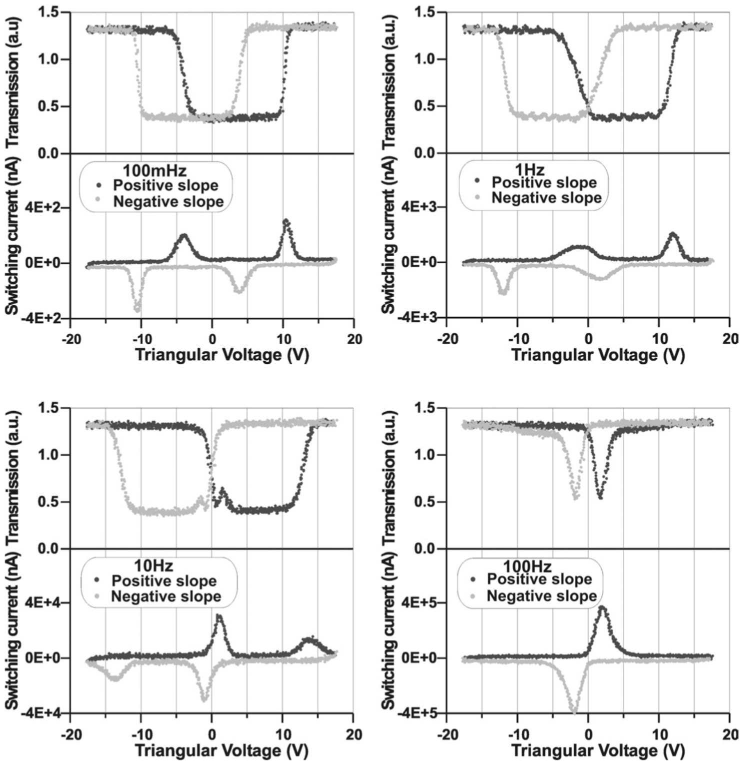

FIGURE 3 Frequency dependence of optical hysteresis and electric current in a symmetric antiferroelectric cell. Notice that logarithmic scale of the current axis changes between graphics.

distinguishes the responses for the positive and negative slopes of the triangular waveform. Triangular frequencies 100 mHz, 1 Hz, 10 Hz and 100 Hz are shown.

Two current peaks describe the field induced transitions for every slope of the triangular waveform at very low frequency. Different shape and magnitude of the two peaks reveal probably different switching speeds in transitions from antiferroelectric (AF) to ferroelectric (F+ and F–) states, and vice versa. Only one peak describes direct switching between two ferroelectric states at higher frequencies. Symmetric current profile, for the positive and negative slopes of the triangular waveform, has been demonstrated. It matches the hysteresis loop of the optical transmission.

The instantaneous polarization has been evaluated from the switching currents. Figure 4 illustrates polarization profiles of two lobes

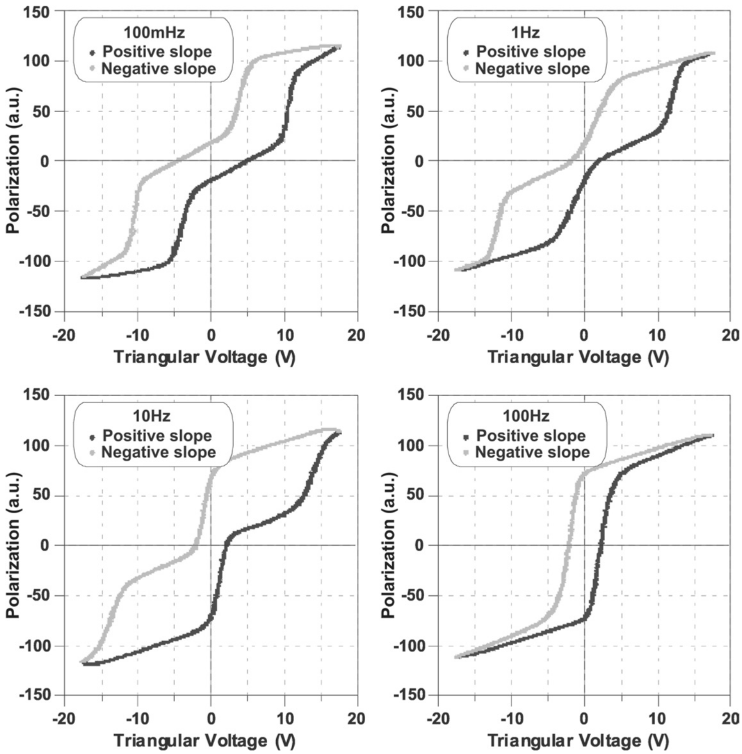

FIGURE 4 Frequency dependence of electric polarization hysteresis in a symmetric antiferroelectric cell.

reproducing the custom antiferroelectric electrooptic response, at the lowest frequencies. Only one lobe, characteristic of the ferroelectric phase, remains at the highest frequencies. The symmetry of the polarization for the positive and negative slopes suggests an equal charge distribution independently of the signal polarity applied to the sample.

Asymmetric Antiferroelectric Liquid Crystal Cells

Similarly as in the previous study, Figure 5 shows simultaneous measurements of optical and electric responses for same frequencies.

There is a drift of the optical transmission, with regard to the zero voltage of the triangular waveform, towards positive voltages. Current peaks also drift, following the transmission changes as well as in a symmetric cell. There is a direct correspondence between the switching and relaxation optical thresholds and the current peaks. Unlike

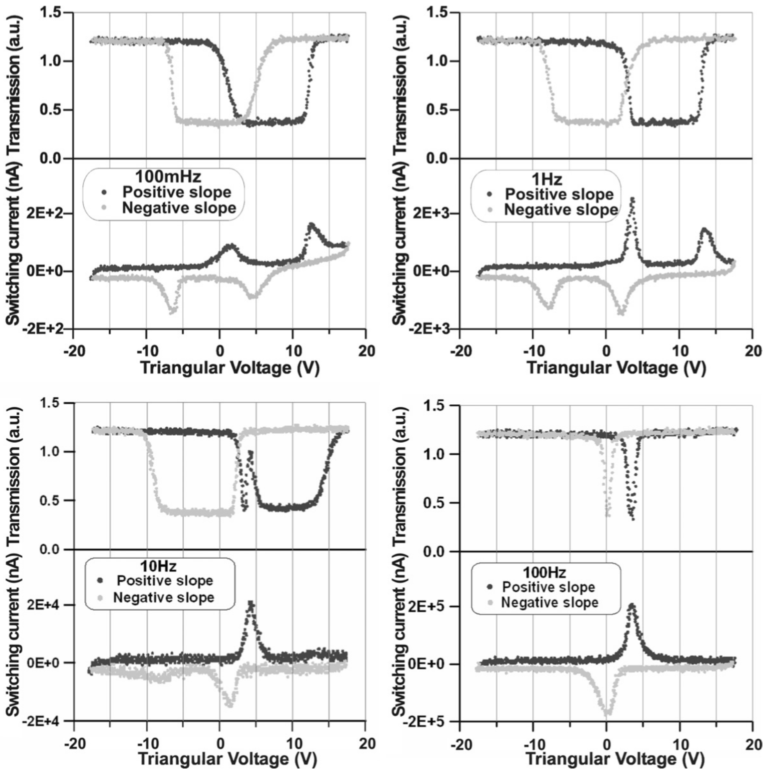

FIGURE 5 Frequency dependence of optical hysteresis and electric current in an asymmetric antiferroelectric cell.

symmetric cells, dissimilar current peaks have been reported at positive and negative slopes of the triangular waveform.

The effect of the optical shifting may cause the greyscale generation at zero voltage. The polarity of the driving signal determines the direction of the drift. The asymmetry of the response reported is slight.

Further information, that is not easily noticeable from the current profile, is going with the instantaneous polarization. At 100 mHz, during the negative slope of the signal, the polarization does not decrease in a monotonic way (Fig. 6). This anomalous profile suggests a qualitative hypothesis; an electric field with opposite sign to the external field gives rise in the inner of the cell. This voltage subtracts from the external field and two points with the same instantaneous polarization are obtained. For the rest of frequencies, the two slopes of polarization are nearly equal, but the whole response is shifted towards positive voltages. It may be supposed that there are two

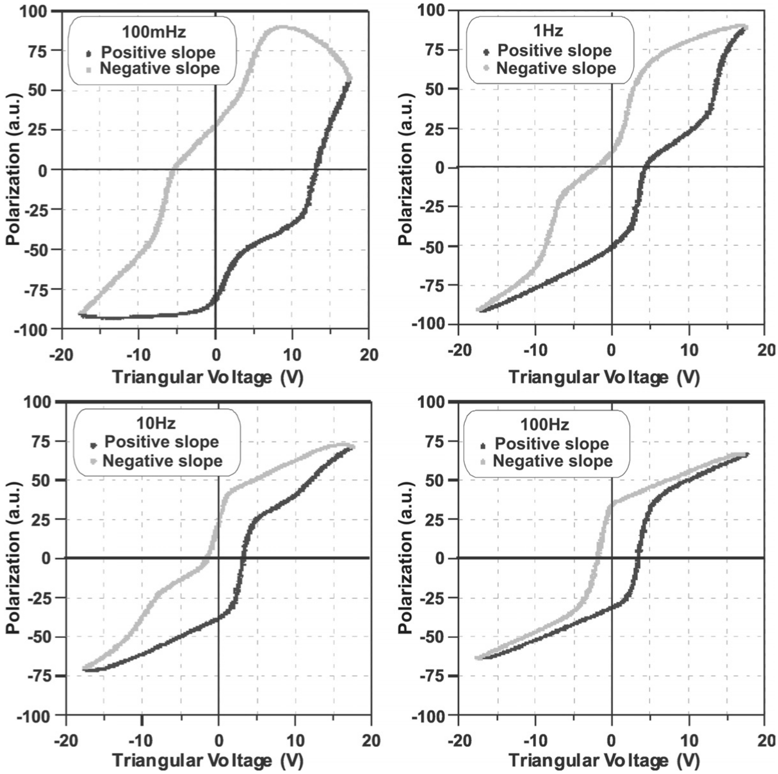

FIGURE 6 Frequency dependence of electric polarization hysteresis in an asymmetric antiferroelectric cell.

different charge contributions; charges that only appear at low frequencies and, on the other hand fixed charges in the device.

Frequency Dependence of Current Peak Magnitude

Electric current measurements have been the initial point for knowing the evolution of peaks as frequency changes, with the values detailed previously. The magnitude of the current peaks versus frequency is showed in the graphics of Figure 7 (Note that both axes are in logarithmic scale). Every graph corresponds to one slope of the triangular waveform. Symmetric and asymmetric cells are compared. Two dotted lines are represented: rhombus line corresponds to AF $\rightarrow$ F transitions and circle line corresponds to F $\rightarrow$ AF transitions.

In the range 30 mHz to 10 Hz, current shows two transitions. The peak for the AF $\rightarrow$ F transition becomes smaller and smaller and

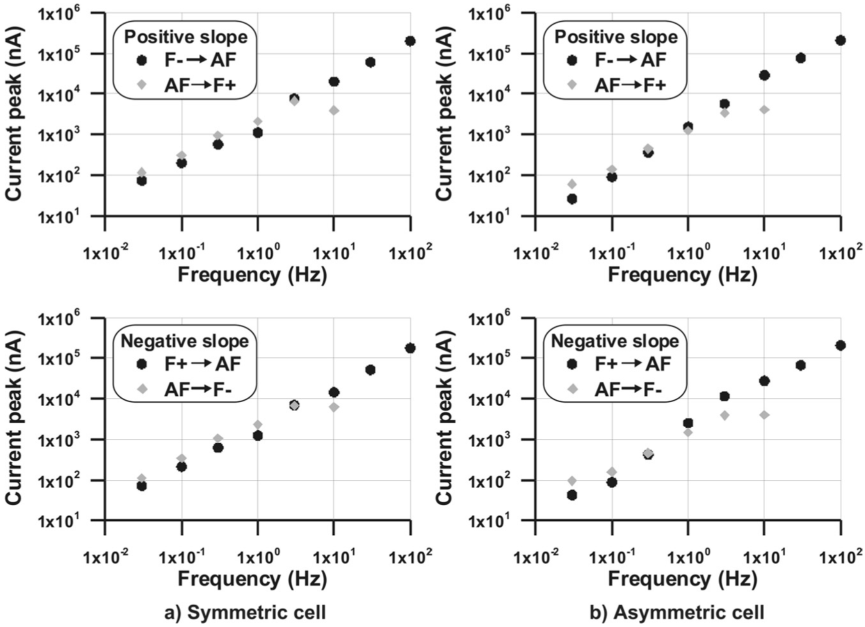

FIGURE 7 Frequency dependence of current peak magnitude. Notice that both axes are in logarithmic scale

disappears at 30 Hz and 100 Hz. This fact happens because the liquid crystal relaxation is slow enough compared to the triangular speed. In this situation, the peak left strictly would correspond to a direct transition between ferroelectric states.

Before direct ferroelectric transitions happen, at the lowest frequencies, switching peak magnitude prevails; then relaxation peak magnitude prevail. The frequency of change occurs near 3 Hz in the symmetric cell and 300 mHz in the asymmetric one. This result may be due to a weaker anchoring of the asymmetric alignment.

In all cases, current peak magnitude increases one order of magnitude as the frequency increases one decade, and its sign is opposite in the positive and negative slopes. Frequency dependence of peaks is similar in symmetric and asymmetric cells.

Alignment Dependence of Driving Voltages

Current peaks, due to the field induced transitions, appear at different voltages according to the triangular frequency. Figure 8 shows the

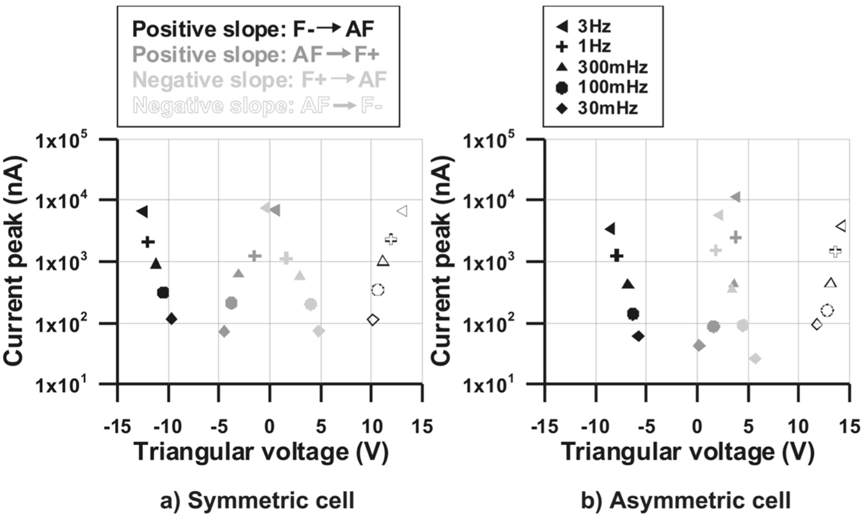

FIGURE 8 Alignment dependence of driving triangular voltages.

magnitude of the peaks versus the driving triangular voltage, for the symmetric cell and the asymmetric one. Every symbol refers to a frequency, 30 mHz, 100 mHz, 300 mHz, 1 Hz and 3 Hz.

The graph on the left shows that driving voltages in a symmetric cell are nearly symmetric with regard to zero voltage. Switching voltage magnitude increases as frequency increases (outer lines). Relaxation voltage magnitude decreases as frequency increases (inner lines). These values tend to meet at zero voltage for the positive and negative slopes. The graph on the right shows driving voltages in an asymmetric cell. Frequency dependence is like the symmetric cell. However, the whole response is shifted toward positive voltages and, in contrast to symmetric cells, relaxation curves for positive and negative slopes meet at a positive value.

Detailed inspection of the asymmetric cell curves, reveals that voltages of every transition are modified in a different way. Black curve shifts about 5 V, from the symmetric to the asymmetric cell. The lowest frequency, in the dark grey curve, shifts about 5 V; the highest one shifts only 3 V. The shift in the grey curve is variable and less than 2.5 V. Finally, the white curve is shifted less than 2 V.

This result supports again the supposition of the internal generation of some voltages which depend on the frequency and polarity of the signal.

CONCLUSIONS

Simultaneous measurements of optical transmission and electric current have been carried out in symmetric and asymmetric aligned cells and a comparative analysis has been realized. A direct correspondence between switching and relaxation optical thresholds and current peaks has been checked for both kinds of cells. Current peaks follow the changes of the optical transmission and its magnitude increases one order of magnitude as the frequency increases one decade.

Optical transmission shifts, with regard to the zero voltage of driving signal, have been achieved by creating asymmetric surface anchoring conditions upon cell manufacturing. This effect may cause the greyscale generation at zero voltage and make possible the simplification of driving waveforms.

Evaluation of instantaneous polarization reveals an anomalous behaviour at low frequencies. The reason of this effect may be on a charge contribution that arises then. Also, a fixed charge is suspected to be involved in the switching of the device. Finally, non-homogeneous voltage drifts in asymmetric cells support the last proposal.

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