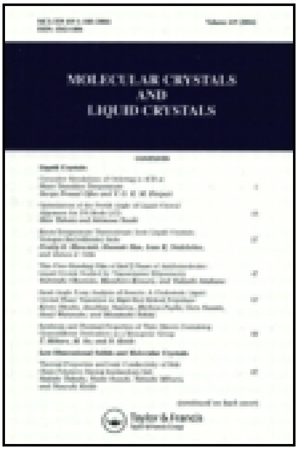

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Measurements of Lateral Ion Transport in LCD Cells

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MEASUREMENTS OF LATERAL ION TRANSPORT IN LCD CELLS

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The ions present in liquid crystal devices modulate the applied electric field and lead to deterioration of the expected good optical response. In addition to the flicker and ghost images, a boundary image-retention effect is also possible. It occurs near the edges of a stressed pixel. We have attributed this effect to ions moving in the plane perpendicular to the applied electric field. This hypothesis has been proven using a combination of electrical and optical measurements. The observed optical non-homogeneity and its evolution with stress time were explained using the new model of lateral ion transport. The physical cause of this phenomenon is subject to further study.

Keywords: image retention; ions; lateral ion transport; liquid crystal displays

1. INTRODUCTION

It is widely known that liquid crystal devices contain ions, whose origin can be traced to impurities due to the fabrication process, to the alignment

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layers or to the dissociation of the LC mixture molecules. In principle the presence of ions modulates the applied electric field and deteriorates the good electro-optical behavior of the LC cell. The magnitude of the ions' influence depends on the ion concentration, on the cell parameters (LC and alignment layer capacitances) and the driving method (constant charge or constant voltage). Active-matrix-driven displays for example are much more sensitive to the ion content than passive-matrix driven displays.

The ion effects can be short-term (during one half-period of an AC addressing pulse), which causes flicker, or long-term (after long addressing), which causes image sticking (ghost images). The basic short-term phenomenon is that under the influence of the applied electric field the ions move to the oppositely charged electrodes and create an inner electric field. The voltage over the LC layer is then being modulated, the transmission is changing during one pulse and we observe a flicker when the cell is driven with some gray-level voltage. On longer time-scales, due to a possible asymmetry in the driving or the cell itself, there may be a net separation of ion kinds towards the electrodes. This creates a DC effect in the cell, and gives rise to image retention and ghost images.

In the past decade, many theoretical and experimental studies of the effects mentioned above have been performed [1–10]. These have focused mainly on the theory, simulations and measurements of short-term ion transport and flicker [1–3], [8–9] and on long-term generation and image sticking [4–7], [10]. All of these image retention phenomena occur only in the direction of the applied field, and are independent on the lateral dimensions along the surface of the cell.

Recently we have observed a special form of image retention, which occurs on the boundaries of the stressed pixel. To our knowledge, boundary image sticking has already been reported [11]. We reproduced this phenomenon in our test cells. The highly contaminated test cell had one row ($2 \times 3\,\mathrm{cm}^2$) and three columns ($2 \times 1\,\mathrm{cm}^2$). After a longer stressing of the middle column, image retention has developed in the lateral direction, at the borders with the neighboring columns (Fig. 1). When all columns were viewed at a gray-level voltage and a frequency of 10–50 Hz, there appears a dark stripe on one edge and a bright stripe on the opposite edge (the cell is normally white). The aim of this paper is to show that this boundary image retention is caused by lateral movement of ions, a new phenomenon not previously reported.

2. EXPERIMENTAL METHOD

At a given gray-level voltage and a low frequency, the movement of the ions influences the optical response of the cell and causes flicker. Using the

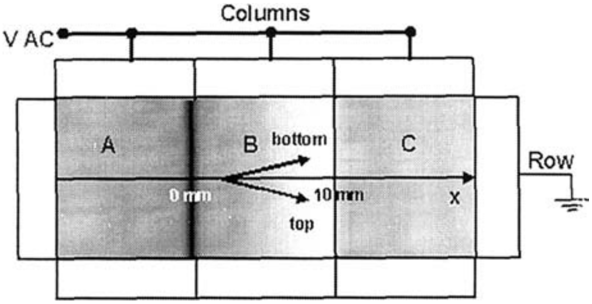

FIGURE 1 A scheme of the test cell and the observed phenomenon of image retention in the lateral direction x (viewed at 1.65 V, 20 Hz SQW). The arrows show rubbing directions on top and bottom alignment layers.

transmission through the cell, it is possible to determine a qualitative measure for the local ion density. This provides us with a tool to investigate the lateral non-homogeneity in the stressed cell. A brief account on the method used for deriving the ion content from optical measurements is given below.

Let the LCD cell be short-circuited for a time long enough to assume a homogeneous ion distribution. We then apply a square wave (SQW) with amplitude V_0. When the first pulse is applied, the capacitance of the LCD cell C_e is charged and the charge $Q_0 = C_eV_0$ is brought to the electrodes. If the voltage is above the threshold, the LC molecules will switch and there will be a displacement current, which will bring additional charge to the electrodes. The ions start moving to the oppositely charged electrodes under the influence of the present electric field. If the voltage is kept constant (passive addressing mode) the movement of the ions gives rise to an electric current in the external circuit, and additional charge is brought on to the electrodes. Although all of our measurements were performed above threshold, for simplicity in the further considerations we do not take into account the LC switching and the displacement currents.

If the voltage is applied for a time longer than the transient time of the ions, at the end of the first SQW pulse all of the present ions will be gathered near the alignment layers. We assume that the ion diffusion layer is thin, and that it can be treated as a charged plane. In the case of our cell, we have chosen 1 Hz as a suitable frequency. Assuming there is no leakage in the alignment layers, the total additional charge brought to the electrodes is equal to $Q_t = \alpha eSd_{LC}n_0$. Here e is the elementary charge, $n_0 = n^+{}_0 = n^-{}_0$ is the equilibrium ion concentration of positive and of negative ions, S is the cell surface, d_{LC} is the thickness of the LC layer and C_{LC} is the capacitance of the liquid crystal layer. $\alpha = C_e/C_{LC}$ is a factor that comes from the equivalent capacitor circuit of the LCD cell. This factor is usually very close to 1 (0.97 in our case). The equivalent capacitance of the cell is $\frac{1}{C_e} = \frac{1}{C_{LC}} + \frac{1}{C_{2AL}}$. Considering the electric fields in the alignment layers and in the liquid crystal (including the space charge) at the end of the first half-period ($T/2$) the voltage over the LC layer can be written as

$$V_{LC}(T/2)_1 = \alpha V_0 - \frac{\alpha e S d_{LC}}{C_{2AL}} n_0 \tag{1}$$

C_{2AL} is the equivalent capacitance of both alignment layers. The second term in the above equation diminishes the voltage over the liquid crystal because of the screening effect of the ions.

If at this moment the voltage is reversed (the second half-period of an SQW pulse), the applied voltage changes sign, but the ions do not move yet. The voltage over the LC becomes negative, but its absolute value becomes bigger:

$$V_{LC}(T/2)_2 = -\alpha V_0 - \frac{\alpha e S d_{LC}}{C_{2AL}} n_0 \tag{2}$$

The LC molecules suddenly feel a higher voltage and the transmission goes down (with a speed governed by the switching time of the molecules). Then the ions start flowing towards the opposite electrodes, the voltage diminishes in absolute value and the transmission increases. At the end of the period when all the ions have reached the opposite electrodes, the voltage over the cell is

$$V_{LC}(T) = -\alpha V_0 + \frac{\alpha e S d_{LC}}{C_{2AL}} n_0 \tag{3}$$

The same process is repeated when the voltage is reversed again. Therefore, during one SQW half-period, the voltage over the LC layer changes by

$$\Delta V_{LC} = V_{LC}(T) - V_{LC}(T/2) = \frac{2\alpha e S d_{LC}}{C_{2AL}} n_0 \tag{4}$$

The change in the voltage over the LC during one SQW frame is proportional to the ion concentration. From here, the ion concentration in the cell is

$$n_0 = \frac{1}{\alpha e S d_{LC}} C_{2AL} \frac{\Delta V_{LC}}{2} \tag{5}$$

The T-V curve of the LC cell represents the optical response (transmission) of the cell to a certain voltage that has been applied over it. At a high frequency, the electrical displacement in the cell is homogeneous. When a low frequency is applied to the cell and the ions move, the LC molecules

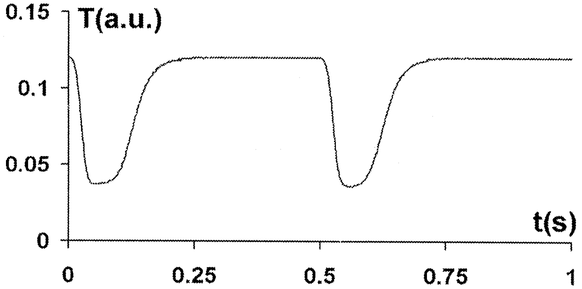

FIGURE 2 Transmission at 1 Hz, 1.65 V, changing with time due to the ion movement and field modulation.

respond to the modulation of the electric field and the transmission through the cell changes. On average, the cell responds to some effective voltage V_{eff}. The ion effect on transmission can be seen in Figure 2. The height of the optical pulse (maximum-minimum transmission) is larger if more ions are present [8]. The transmission reaches the maximum value when all of the ions have reached the opposite electrodes. Only if the ion concentration is very large, the transmission will reach a steady value before the ions have arrived because the liquid crystal has already switched off. Combining the T-V curve and the T-t response (flicker), we can derive the effective voltage V_{eff} as a function of time during one period of a SQW pulse (as shown in Figure 3). From the T-t dependency, for a given time t the transmission T is fitted between two close transmission values in the T-V curve. From the fitting, a corresponding value of V_{eff} is obtained. Because in the T-V curve we use the voltage applied on the cell rather than

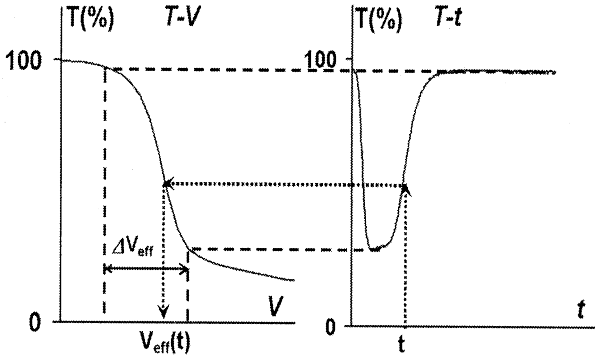

FIGURE 3 Illustration of the method used to derive the effective voltage in the cell from transmission measurements.

on the liquid crystal, we have to correct the value of V_{eff} with multiplying by α. The difference $\alpha\Delta V_{eff}$ between the maximum and the minimum value of V_{eff} is taken to be the change of the effective voltage during one SQW pulse. If the transmission varies in the linear range of the T-V curve, the optical pulse height is proportional to the change ΔV_{eff}. However, if the ion concentration is higher and the transmission reaches the non-linear part of the T-V curve, the ΔV_{eff} derived with this method represents the ion concentration better than the optical pulse height. If we put the value of ΔV_{eff} in the place of ΔV_{LC} in Eq. (5), we obtain a value for the ion concentration that is around 2 times smaller than the electrically measured one. This difference mainly lies in the fact that it is difficult to determine what this effective voltage is in comparison to the total voltage over the LC. The method is also not very accurate numerically, because a small noise in the transmission in the flat T-V part yields big numerical changes in the voltage values. Anyway, since the ion concentration value obtained in such a way is comparable to the one measured electrically, we will use it as a good indicator.

3. STRESSING, MEASUREMENT AND OBSERVATIONS

In order to study the lateral image retention, a fresh test cell with high ion contamination was prepared. The test cell was an STN cell with three columns ($1 \times 2\,\mathrm{cm}^2$) and one ground electrode ($3 \times 2\,\mathrm{cm}^2$) (Fig. 1). Each column contains around 30 pixel electrodes. The threshold voltage was around 1.5 V. The ion concentration in the cell was 9.7e19 m^{-3} and the mobilities of two ion kinds are 2.2e-10 and 0.6e-10 m^2/V.s. The ion parameters were obtained by using the transient-current technique [2]. The polarizers are aligned for a normally white mode. The rubbing directions of the top and bottom plate are indicated in Figure 1 with arrows, the angle towards the horizontal axis being around 30 degrees. The optical measurements were performed in transmission, with a He-Ne laser beam (632.8 nm) and a solar cell as a photo-detector at the back of the cell. The signal of the solar cell was read from an oscilloscope.

Before stressing the cell transmission looked homogeneous when viewed at an "evaluation" gray-scale voltage of 1.65 V and 20 Hz (applied on all columns). The electric current at each column was measured and the present charge was estimated. The electro-optical T-V curves at 20 Hz and at 1 kHz were measured at equidistant positions along the x-direction shown in Figure 1 with spacing of 0.5 mm (vertical position somewhere in the middle of the pixels). The positions were changed with a transversal shifter, with reproducibility of 0.01 mm. At each point, the transmission versus time (T-t) at 1.65 V during SQW periods at 1 Hz (flicker) and during one second of 20 Hz was also measured. The measurement at 20 Hz was used to obtain the average transmission as a function of the lateral coordinate x. The flicker measurement at 1 Hz was used to estimate the ion content at the measured point by the method explained above.

The stressing consisted of applying a square wave (SQW), 2 V_{ampl} and 100 Hz, on the middle column B, while the side columns were not connected. The applied voltage was above the cell threshold. The total stress continued for 3.5 hours. After every 30 minutes of stress, a series of measurements was performed along a lateral line (the arrow in Fig. 1) with 0.5 mm spacing. The same measurements were carried out as before the stress, i.e. T-t at 1.65 V, two pulses of 1 Hz and 1 second of 20 Hz. Each series of measurement lasted for 40 minutes. After the total stress, the current was again measured in each column and the charge estimated.

Even after 30 minutes of stress, a pattern as shown in Figure 1 was visible when the evaluation voltage was applied. A dark stripe developed near the border between columns A and B, while near the border of B and C a bright stripe could be observed. The dark stripe was mainly situated to the left of the A-B border, in the column A, and the bright stripe was present to the left of the B-C border, in column B. From the measurements at 20 Hz, the evolution of the average transmission along the x-direction could be followed. In Figure 4 we see clearly that, as the stressing time increases, the transmission in the dark band decreases and in the bright band increases. In addition, the whole of the stressed column B and the floating column to the right (C) generally becomes brighter.

The transient ion current [2–3] for every column has been integrated to yield the ionic charge ($eSd_{LC}n_0$). The comparison of the ion content in the columns before and after the stress is given in Figure 5. We can see that the total amount of ions after the stress has increased in the column A (which

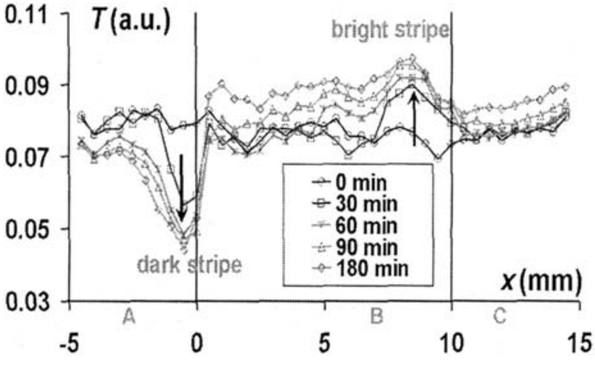

FIGURE 4 The occurrence of bright and dark bands in the cell. The average transmission at 1.65 V, 20 Hz changes with increasing the stress time.

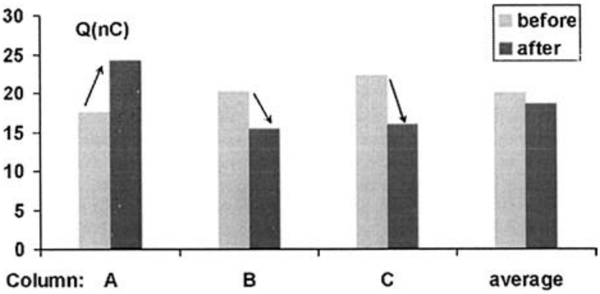

FIGURE 5 The total charge in the stressed and the floating columns before and after the stress. The change is indicated with the arrows.

became darker) and has decreased in columns B and C (which became brighter). The average amount of ions in the whole cell (all three columns) remains the same. From these observations, we could conclude that the lateral image retention had its origin in the lateral movement of ions during the stressing.

A possible answer to the fact that the ion content in the three columns is not perfectly homogeneous in the start can be traced to the non-homogeneities due to the filling of the liquid crystal. Namely, we have observed in some cells that the region next to the filling hole contains more ions than the rest of the cell. Since in our case the filling hole is at the right of the cell (next to column C), it may be possible for the column C to have initially more ions than the column A and B, and that is what we see in Figure 5.

4. LATERAL ION TRANSPORT

a) Proof

If we compare the *T*-*t* pulse after stress with the one before stress, we can see how the ion concentration at that position evolves in time. This comparison shows that in the dark band (Fig. 6a) the ion concentration has increased (the *T*-*t* pulse increases its height). In the bright band (Fig. 6c), as well as in the middle of the stressed column (Fig. 6b), the ion concentration has decreased. Using the method described above, we derived the effective voltage over the LC (proportional to the ion concentration) as a function of the lateral position x at different stress times (Fig. 7). There we can clearly see the evolution of the ion concentration along the lateral axis. Together with the electrical measurements before and after the stress (Fig. 5), this is a direct proof that during the stress of $V_{ampl} = 2$ V, $f = 100$ Hz, the ions have moved laterally to the left (negative x direction on the given figures).

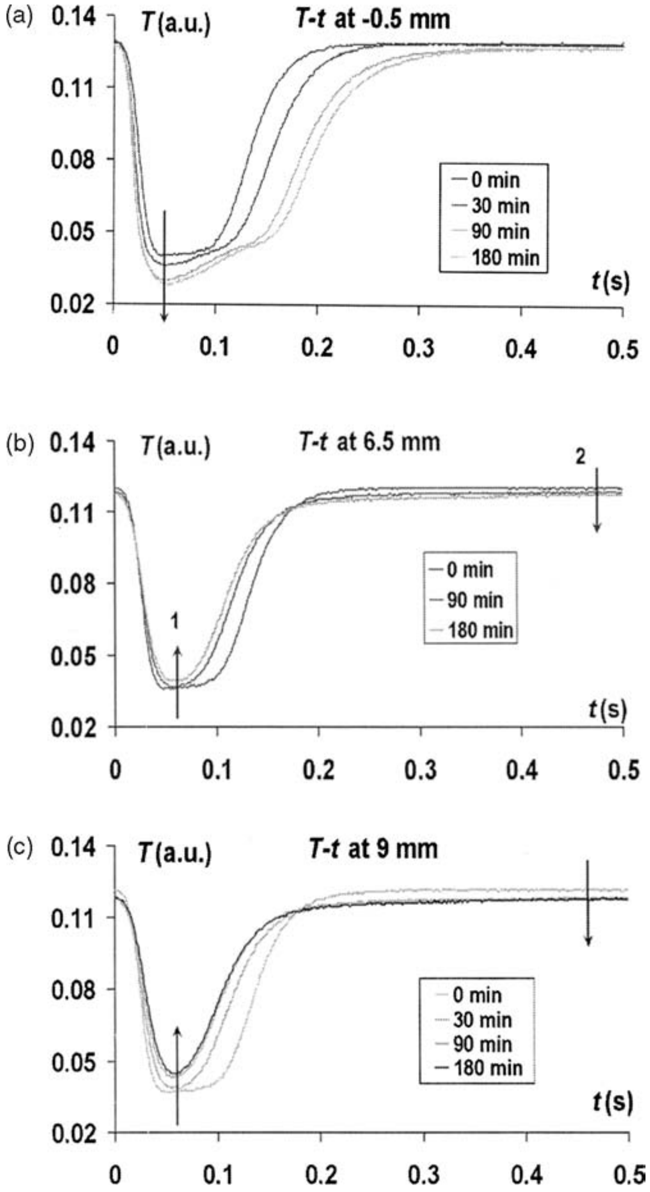

FIGURE 6 a. Transmission versus time (*T*-*t*) in the dark band. The flicker increases with time, thus ion concentration increases. b. *T*-*t*, middle of pixel B. Ion content slightly smaller with increasing time. c. *T*-*t*, bright band. Ions move away, thus the transmission dip decreases visibly.

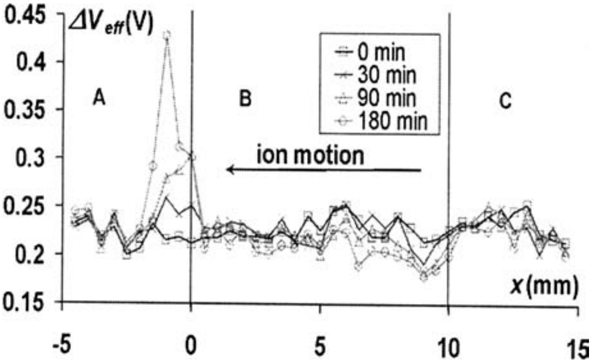

FIGURE 7 Lateral distribution of the ion concentration (proportional to the ΔV_{eff}). The ions move from right to left and pile-up after the edge of the column B.

Another issue here is the brightness of the cell. The cell is normally white, and the threshold voltage is around 1.5 V. When a voltage is applied to the cell, the ions move and build an ionic field that screens the applied field. We would expect thus that in the region with a higher ion concentration, the threshold voltage would move to higher voltages, and the cell would be brighter in that region. This is exactly the opposite of what we observe – namely, the cell turns darker where there are more ions, and brighter where the ion concentration has decreased. It turns out however that this behavior is possible. When the frequency of the applied SQW is low, the ions have time to traverse the LC and to screen the electric field long enough. This is what we see in Figure 2. The higher the ion concentration, the higher the screening effect is and then the cell becomes brighter if more ions are present. However, when the frequency is high enough an opposite effect might happen. If we apply a periodic SQW, the ions gathered by the alignment layers by the end of a pulse always enhance the electric field in the middle of the cell in the beginning of the next pulse. It is possible that, due to the complicated ion motion, the electric field remains enhanced for a longer part of the pulse. In such a way, the average effective voltage over the LC during a period is higher than the applied one, and thus the cell becomes darker at the places with more ions. To prove this, we performed some simulations on transmission through an STN cell as a function of different frequencies and ion concentrations. In Figure 8, we see that a place that contains realistic 10^{20} ions/m^{-3} turns brighter with more ions at 10 Hz, but at 100 Hz it becomes darker if the ion content increases a few times (which indeed happens in the dark band). Elsewhere [12] it was also shown that high ion content could lead to a decrease of the threshold voltage if the frequency is not too low. A more recent paper [13]

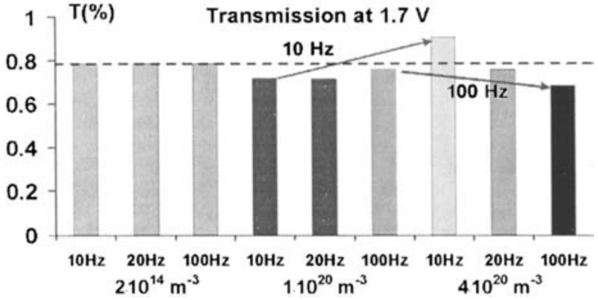

FIGURE 8 Simulations on cell transmission at 1.7 V for different frequencies and ion concentrations. For some frequency range, the cell looks *darker* if more ions are present.

gives extensive simulations on the ion influence on the frequency dependence of the threshold voltage. It also leads to a conclusion that in a certain frequency range the ions' presence shifts the *T*-*V* to the left (lower transmission at same voltage), but the paper extends this conclusion even to lower ion contents.

In our case thus, we consider that the ions' presence yields this effect, and that the cell (viewed at a mid-grey voltage, 20 Hz) becomes darker if there are more ions. In this light, we can look at the transmission at 20 Hz to be a direct indicator (though not yet a quantitative one) of the ion concentration. Then, Figure 4 shows us the evolution of the lateral ion distribution in the cell even clearer than Figure 7 (because it is subject to lesser experimental errors).

b) Discussion

The purpose of this paper is to show that the observed boundary image sticking in STN LCDs has its origin in lateral movement of ions. The reason why the ions move perpendicular to the applied field, though, is still unclear. The fringe fields between the pixel electrodes might help to move the ions over the inter-electrode gap, but how do the ions travel through the bulk along one pixel still remains a question, since there are no fringe fields under the pixel. We believe that the answer must lie in the anisotropy of the liquid crystal and the ion conduction. However, the STN cell has a complicated structure, and added the high ion concentration that modifies the field (and thus the director), we cannot yet come to a straightforward conclusion.

Anyhow, using this phenomenon, we can explain the observed image retention. During the stress of the middle column (B, Fig. 1) the ions travel towards its left edge. As soon as they enter the adjacent column (A) they stop, because the column is not stressed and the lateral speed in it is zero. The ion concentration to the left of the edge increases rapidly as new ions arrive, because all the ions concentrate in a very narrow region. The piled-up ions diffuse to the left in the non-stressed column (A) contributing to the spreading of the 'dark band' (Fig. 4). On the other side of the column, close to the edge (B-C), the ions move to the left, and no new ions come from the right, because column (C) is not stressed. Therefore, the ion concentration in the stressed column (B), left of the edge (B-C), decreases. With increasing the stress time, the brighter region (fewer ions) spreads to the left because ions gradually move away from it. This explanation corresponds well with the measured transmission (Fig. 4) and the ion distribution (Fig. 7).

The boundary image retention tends to disappear with time, if the cell is not stressed. After 1 week from the measurement, the dark band (as viewed at 20 Hz, 1.65 V) is not strongly visible anymore, and the cell appears more homogeneous. This is because the diffusion of ions levels-out the ion concentration throughout the cell. Of course, since large distances are involved, the time necessary for the diffusion will take days.

5. CONCLUSION

When we stressed a column of our test cell for a longer time, image retention has occurred near the borders with the adjacent non-stressed columns. We have assumed that the origin of the boundary image retention is the lateral transport of ions. This assumption has been proven in this paper using a combination of electrical and optical measurements. The paper gives also an illustration of a new method for deriving local ion concentrations and of the impact of the ions on the optical response of the cell. The general trend of the measured lateral ion distribution agrees with our explanation of the ion motion. In our opinion, the physical cause of this phenomenon lies in the anisotropy of the liquid crystal and the ion conductivity. However, the mechanism and the conditions that lead to the lateral ion motion are not clear at this moment and are subject to further investigations.

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