5.3: A New Method for Measuring Ion Density in Nematic LCDs

Goran Stojmenovik, Kristiaan Neyts, Stefaan Vermael

LC group, Electronics and Information Systems Department, Ghent University,
Sint-Pietersnieuwstraat 41, 9000 Gent, Belgium
Email: goran@elis.ugent.be, Tel. +32-9-264-8951, Fax +32-9-264-3594

Alwin Verschueren

Philips Research Laboratories, WY6.52, Prof. Holstlaan 4(WY64),
5656 AA Eindhoven, The Netherlands
Email: alwin.verschueren@philips.com, Tel. +31-40-274-3867, Fax. +31-40-274-4335

Abstract

A new optical method characterizing ion content in LCDs has been developed. It utilizes T-V and optical flicker measurements. Simulations and measurements give good correspondence with previously reported methods. The method is suitable for measurements on matrix panels.

1.   Introduction

All nematic liquid crystal displays contain ions, which, if in considerable quantity, can cause flicker [1], ghost images [2-4] and change of transmission-voltage characteristics [5-7]. The basic parameter responsible for the image retention is the ion concentration. Methods have been developed to characterize the ion content of the cell [8-11] as means of understanding the ion processes that lead to image artifacts. Of the used methods, only one [11] is optical, i.e. uses the light transmission through the cell in order to extract information about the ion content. An optical method is desirable for measurements on matrix displays, because in contrast to electrical measurements we do not need to worry about cross talk and additional current coming from the other pixels due to capacitive coupling. In addition, using the transmission of a narrow laser beam we can get information about any possible non-homogeneity of ions along the cell area [12].

2.   Method

Let a square wave (SQW) be applied to a liquid crystal cell in a direct-drive mode. The ions in the cell will move and will follow the change of the voltage sign. Due to their movement, there will be a current in the external circuit that will bring additional charges to the electrodes of the cell, so the electric field in the alignment layers and the cell will change at each moment while the ions move. If the half-period of the SQW is longer than the transit time of the ions t_{tr}, at the end of the first SQW pulse all of the present ions will be gathered near the alignment layers and will have stopped moving.

Let the charge density due to the additional charges brought on the electrodes during the first pulse be σ_{el}. This extra charge density σ_{el}, together with the charge density $\sigma_0 = C_e V_0$ due to the charging voltage V_0, will produce an electric field $E_{AL} = \dfrac{\sigma_0 + \sigma_{el}}{\varepsilon_0 \varepsilon_{AL}}$ in the alignment layers. C_e is the equivalent capacitance per unit surface of the cell, $C_e = \dfrac{C_{2AL} C_{LC}}{C_{2AL} + C_{LC}}$. C_{2AL} is the equivalent

capacitance per unit surface of both alignment layers and C_{LC} is the surface capacitance of the liquid crystal layer. The voltage drop over both alignment layers will then be $V_{2AL} = 2 \int_0^{d_{AL}} E_{AL} dz = \dfrac{\sigma_0 + \sigma_{el}}{C_{2AL}}$. Having in mind that the total voltage over the cell in the passive drive remains V_0, at the end of the first half-period (T/2) the voltage over the LC layer can be written as $V_{LC}(T/2^-) = \alpha V_0 - \dfrac{\sigma_{el}}{C_{2AL}}$. The factor $\alpha = C_e/C_{LC}$ is usually very close to 1 (0.97 in our case). Since T/2>t_{tr}, at the end of the period the extra charge density will be $\sigma_{el} = \int_0^{T/2} I(t) dt = \alpha e d n_0$. Here e is the elementary charge, n_0 is the equilibrium (positive equal to negative) ion concentration, S is the cell surface, d is the thickness of the LC layer. Therefore, for the voltage over the LC at the end of the period we can write $V_{LC}(T/2^-) = \alpha V_0 - \dfrac{\alpha e d}{C_{2AL}} n_0$. 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 applied voltage is reversed, the voltage over the LC becomes negative, and its absolute value becomes bigger: $V_{LC}(T/2^+) = -\alpha V_0 - \dfrac{\alpha e d}{C_{2AL}} n_0$. Then the ions start flowing towards the opposite electrodes and the voltage over the LC diminishes in absolute value. At the end of the period when all the ions have reached the opposite electrodes, the voltage over the cell is $V_{LC}(T^-) = -\alpha V_0 + \dfrac{\alpha e d}{C_{2AL}} n_0$. 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 $\Delta V_{LC} = V_{LC}(T^-) - V_{LC}(T/2^+) = \dfrac{2\alpha e d}{C_{2AL}} n_0$. 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

$$n_0 = \frac{1}{\alpha e d} C_{2AL} \frac{\Delta V_{LC}}{2} \qquad (1)$$

If a low frequency, grey level SQW is applied to a cell, the LC molecules will respond to the changing electrical field due to the ions as explained above. This leads to transmission modulation (flicker). As seen above, the voltage over the cell is highest just after the reversal of polarity, so in a normally white cell the transmission should drop when the voltage is inverted.

Then, as the ions move and screen the field, the transmission will rise. The electric field in the LC will be non-homogeneous, but the transmission corresponds to some effective voltage V_{eff}. On the other hand, the measured T-V curve at a higher frequency also gives the optical response of the cell to a certain effective voltage, the electric field in the cell being much more homogeneous. So, 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 (Figure 1). From the T-t dependency, we take the transmission T for a given time t. Then we find the two transmission values in the T-V curve between which T lies. Using interpolation, a voltage value that corresponds to the given transmission is found. This voltage is the effective voltage V_{eff} for the given time. The procedure is repeated for every point from the T-t curve and a $V_{eff}(t)$ is obtained. The difference ΔV_{eff} between the maximum and the minimum value of $V_{eff}(t)$ (corresponding to the minimum and the maximum of transmission, respectively) is taken to be the change of the effective voltage during one SQW pulse. If we put the value of ΔV_{eff} in the place of ΔV_{LC} in equation (1), we obtain a value for the ion concentration.
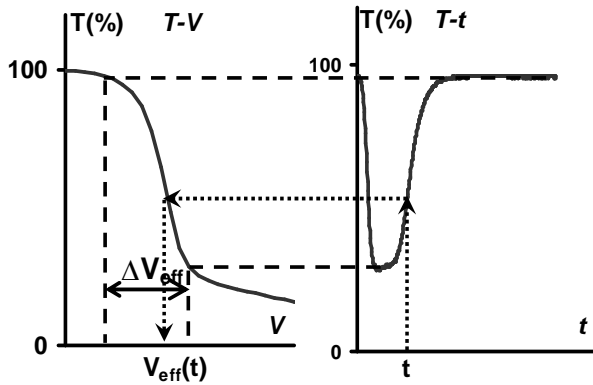

Figure 1 Illustration of the method used to derive the effective voltage over the LC

3. Simulations

In order to determine what the limits of applicability of this method are, we have performed a set of simulations with our program 'Glue' [13]. The program simulates the director switching, ion movement and optical transmission at time steps when voltage is applied. The liquid crystal parameters in the simulations are: K_{11}=12 pN, K_{22}=7 pN, K_{33}=14 pN, pitch=$7 \cdot 10^5$ rad/m, rotational viscosity η=0.2 Pa.s, $\Delta\varepsilon$=13, thickness d=5µm, pretilt θ_0=3.5°, total twist Φ_0=250°, 100 simulation slabs for LC calculation and 400-1100 slabs for ion calculation (higher ion density demands more calculation slabs). Ion mobilities along the director are $\mu^+ = \mu^- = 2 \cdot 10^{-10}$ m²/V/s. The ratio between mobility parallel and mobility perpendicular to the director is 1.8. The angles of the polarizers to the top LC director are: 160° (front) and 100° (back). There is a retarding layer under the front polarizer with an angle of 100° and retardation 800 nm.

The simulations were done in the following way: using a 20 Hz square voltage, we have simulated the optical transmission through the cell versus time at a number of voltages. The transmission of the last period is averaged to obtain a value for the T-V curve. The T-V curve has been simulated for a number of

different ion concentrations from $1 \cdot 10^{17}$ m⁻³ till $3.5 \cdot 10^{20}$ m⁻³. For every ion concentration, the transmission response (flicker) at 1 Hz, and at voltages of 1.65, 1.7 and 1.75 V has been simulated. A "flicker" frequency of 1 Hz was low enough to let the ions transit across the LC in less than half a period. Applying the method explained previously, from the flicker and the T-V, a value n_{der} has been derived. In Figure 2, the ion concentration values n_{der} derived with 1.65 V, 1.7 V and 1.8 V are shown. We conclude that the obtained value is not very sensitive to the grey-voltage used as long as the ion concentration is kept below the space charge limit ($n_{SCL} \equiv \dfrac{C_{2AL}V}{\alpha e d} \approx 3.3 \cdot 10^{20}$ m⁻³ for V=1.65 V). The derived ion concentration does not depend on the flicker frequency as long as the condition $t_{tr}<T/2$ is satisfied.
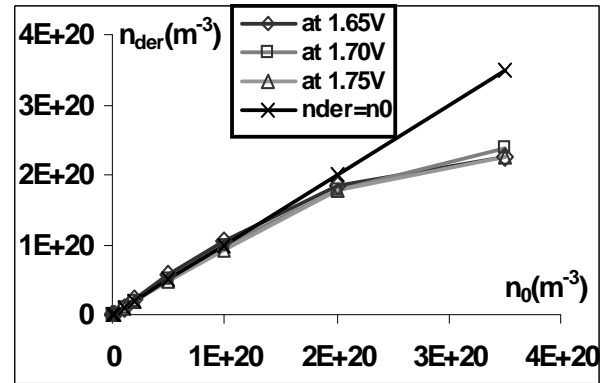

Figure 2 Comparison of the derived ion concentration with the one used for simulations

In Figure 3, the values obtained from optical simulations for 1.65 V have been compared to the values obtained by integrating the simulated transit ion current and to the initial value n_0 used in the simulations. We see that this optical method gives as good results as the electrical method when the ion concentration is smaller than the space charge limit for the flicker voltage (marked in Figure 3 with dashed lines).
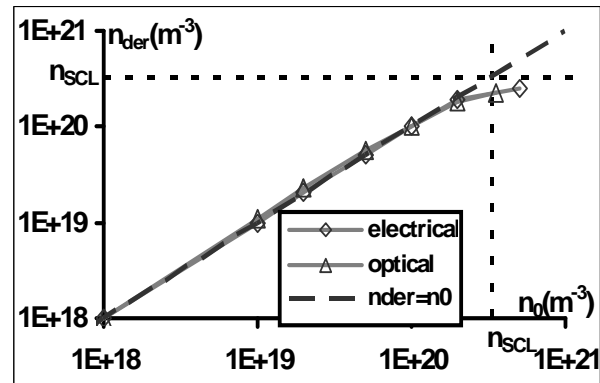

Figure 3 Comparison of the ion concentration derived from optical simulations at 1.65 V, electrically at 1 V and the one used in simulations (n_0)

Any of the two methods cannot yield ion concentrations higher than the SCL because by definition, this is the limit concentration at which the electrical field in the cell is completely screened, and any ions left in the bulk will not move anymore. The optical method, however, has a further limitation. Namely, when the ion concentration is high enough, the transmission at the end of the SQW pulse reaches almost 100%, i.e. is in the horizontal part of the *T-V* curve. There, the determination of the voltage becomes difficult and is subject to experimental errors. Small noise in the transmission can lead to big change of the voltage. The simulations do not have this drawback, so, in principle, the optical method is rather accurate for $n \ll n_{SCL}$ as seen in Figure 3 and can be used for characterization of the ion content in an LCD cell.

4.   Measurements

Our test cell has similar characteristics as the parameters used in the simulations (250° twist STN, 5μm cell gap). The ion concentration has been measured electrically with a current amplifier and an oscilloscope, to obtain a value of $8.8 \cdot 10^{19}$ m^{-3} when 1 V was applied. For optical measurements, the transmission of a laser beam (632.8 nm) through the LC cell has been detected with a photo-diode and read from an oscilloscope by a computer. For every 20 Hz voltage between 1 and 2 V (step 25 mV) applied on the cell the transmission during 20 periods is read from the oscilloscope and averaged to obtain the *T-V* curve. While we used 1 Hz for the flicker simulations, we needed to use a much smaller frequency for the measurements (0.1 Hz) because the cell contained slow ions, and for a successful application of this method, the half-period of the square wave needs to be larger than the transient time of all ions. Using the method explained above, from the *T-V* and the flicker (0.1 Hz, 1.65 V) the change of the voltage ΔV_{eff} was obtained (Figure 4), and using formula (1) ion concentration of $5.6 \cdot 10^{19}$ m^{-3} derived. This value is around 64 % of the value obtained electrically.
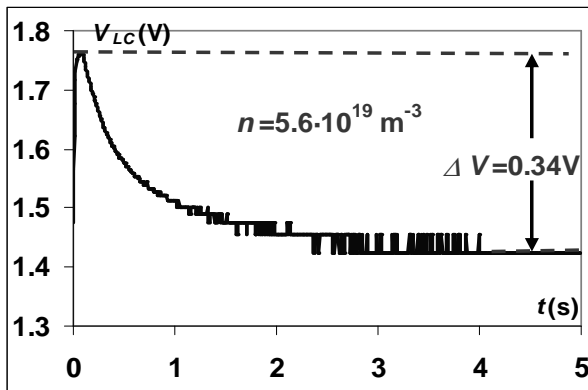

**Figure 4 The effective voltage over the LC
and the ion concentration derived herewith**

There can be various reasons for this discrepancy. The main difficulty in the experiment is the measurement noise. When the transmission reaches an almost horizontal level at the end of the SQW pulse, the transmission is subject to digitization from the oscilloscope, as well as to normal noise. This leads to errors in determination of ΔV_{eff}. Further, when the applied DC pulses are long enough, (longer than 0.5-1 s), processes like generation and leakage become important in the cell. These processes have a different influence on the electrical than the optical behavior of the cell. This may give rise to a difference in the ion content

obtained by different ways. Still, the obtained ion concentration is acceptable, because most of the times we are mostly concerned about the order of the ion contamination of an LCD cell.

5.   Discussion

This method has been used in [12] to characterize the ion content at different positions in the cell. There only the basic idea of the method has been put forward without further elaboration or support. The only other publication about an optical method for ion characterization known to the authors is [10]. In order to use that method, one must first perform simulations on flicker of the measured cell at various ion concentrations, using all the LC and cell parameters. Then, the measured flicker of the cell is related to an ion concentration value via the simulated 'calibration' curve. The method we propose here does not have this inconvenience since the optical parameters are excluded from consideration by the transition from the flicker via the *T-V* curve (Figure 1). Using the model of field screening, we are able to determine a value for ion concentration directly by two measurements (*T-V* and flicker at a grey-level voltage), knowing only two parameters of the cell (alignment layer capacity per surface C_{2AL} and cell gap d).

In laboratory conditions, we can use any test cell and connect the electrodes in such a way to prevent cross talk. However, in real matrix displays, the measurement of ion concentration of a single pixel or of a small block using the transient technique (electric way, [8-9]) is impossible due to cross talk. Namely, due to capacitive coupling, the pixels not directly addressed will feel some voltage and will contribute to the total measured current. This will lead to over-estimation of the ion concentration. The method proposed in this paper is not influenced by how the other pixels are addressed – using a suitable small laser beam one could measure the ion concentration fast and in any point of the display, with knowing just 2 parameters of the cell.

In the case when constant charge is applied to the electrodes, it is the capacitance of the liquid crystal, rather than the alignment layer capacitance, that plays a role in the field screening. In active addressing schemes with a TFT, an extra storage capacitance C_s is connected in parallel to the pixel. Thus, in formula (1) the C_{2AL} has to be replaced with $C_{LC}+C_s$:

$$n_0 \approx \frac{1}{ed}(C_{LC} + C_s)\frac{\Delta V_{LC}}{2} \qquad (2)$$

Since $C_{LC}+C_s$ is much smaller than C_{2AL}, the space charge limit for the active addressing is also smaller, and so is the maximal obtainable ion concentration. However, in active matrix displays the ion concentration can be up to two orders lower than the concentration in passive matrix displays, so in principle, the method described in this paper is suitable for both types of addressing (with carefully calculating the capacitances in the case of a TFT circuit).

Our simulations and measurements have been performed in transmission, but because of the independence of the method from the optical parameters, measurements in reflection are also possible.

6.   Conclusion

A new optical method for measuring ion density in nematic LCDs has been developed. Via optical measurements (flicker and T-V), information is extracted about the inner effective voltage and hence the ion concentration. The method is independent on the

optical configuration (polarizers, retardation films, transmission or reflection measurements). Simulations confirm the validity of the method for a wide range of ion concentrations, when compared to the electrical method and to the ion density used in the simulations. The method is cross talk independent and can also be used for measuring inhomogeneities in the ion density along the display.

7.   Acknowledgements

8.   References

[1] K. H. Yang, J. Appl. Phys. **67** (1990), pp. 36-39.

[2] A. Lien, C.-J. Chen, H. Inove and Y. Saitoh, SID 1997 Digest, 14.3, pp. 203-206

[3] H. De Vleeschouwer, B. Verweire, K. D'Have and H. Zhang, Mol. Cryst. Liq. Cryst **331** (1999), pp. 567-574

[4] H. De Vleeschouwer, F. Bougrioua and H. Pauwels, Mol. Cryst. Liq. Cryst **360** (2001), pp. 29-39

[5] C. Colpaert, B. Maximus and C. M. Groeneveld, IDRC 1994, pp. 191-194

[6] A. Sawada, H. Sato, Y. Nakazono, S. Naemura and A. Manabe, SID 1999 Digest, 16.1, pp. 190-193

[7] A. R. M. Verschueren, P. A. E. J. Machiels, SID 2003 Digest, 50.3, pp. 1386-1389

[8] B. Maximus, C. Colpaert, A. De Meyere and H. Pauwels, Liq. Cryst.,**15** (1993), pp. 871-882

[9] C. Colpaert, B. Maximus and A. De Meyere, Liq. Cryst., **21** (1996), pp. 133-142

[10] A. Sawada, K. Tarumi and S. Naemura, Jpn. J. Appl. Phys., **38** (1999) pp.1423-1427

[11] N. Sasaki, Mol. Cryst. Liq. Cryst **367** (2001), pp. 671-679

[12] Measurements of lateral ion transport in LCD cells, G. Stojmenovik, K. Neyts, S. Vermael, A. Verschueren, R. van Asselt, submitted for publication in the proceedings of the 19th ILCC, Edinburgh 2002 in Mol. Cryst. Liq. Cryst.

[13] C. Colpaert, A. De Meyere, B. Maximus, SID 1996 Digest, 20.3, pp. 301-30