A Simple Technique for Measurement of the Voltage Dependent Capacitance of Pixels in Liquid Crystal Displays

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Abstract: *A technique for measuring the voltage dependent capacitance of pixels by using a low cost integrated circuit and some common laboratory equipments is proposed. The error in measurement ranges from 1 to 2% and this technique can be used for indirect measurement of various parameters of the liquid crystals.*

Keywords: Capacitance measurement; Capacitance of liquid crystal cell; RCA CD4047B.

Introduction

Liquid crystal molecules have shape anisotropy [1]. Most of the liquid crystals that are used in displays have elongated 'rod-like' molecules. Hence several physical parameters like refractive index, dielectric constant etc., depend on the direction of measurement. For example, the dielectric constant that is measured by applying a field parallel to the long axis of the molecules can be higher as compared to that in the other two perpendicular directions. Such materials are called the positive dielectric materials and they are used in many electro-optic effects including twisted nematic (TN) and the super twisted nematic (STN) liquid crystal displays (LCDs). Molecules in these displays are aligned parallel to the surface of the liquid crystal cell (homogenous alignment in the unexcited state). As the voltage across a pixel is increased above a certain voltage called the Freedericksz threshold voltage (V_{th}), the molecules start orienting such that the long axis of the molecules are parallel to the electric field and continue to reorient till the voltage across it is higher than the saturation voltage (V_{sat}). The effective dielectric constant is higher than the unexcited state when the voltage is above the threshold voltage and it depends on the root mean square (RMS) voltage across the pixels. As a consequence, the capacitance of the pixel also varies with applied voltage. An equivalent circuit of a pixel in liquid crystal displays is shown in Figure 1. The resistance R is large (a few tens to a few thousands of kΩ) and capacitance C of the pixels increases when the voltage across the pixels in TN and STN LCDs is increased because the liquid crystal mixtures have positive dielectric anisotropy. Capacitance of the pixel can be measured by using impedance analyzer and lock-in amplifier. We propose to use a low cost integrated circuit (CD 4047) and common laboratory equipments viz., a power supply with variable output voltage and an oscilloscope to measure the voltage dependent capacitance of the pixels in liquid crystal displays.

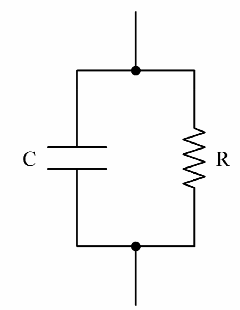

Figure 1. Equivalent circuit of a pixel in liquid crystal displays. The resistor (R) is usually high and can be neglected in most circumstances. The capacitance (C) is the variable capacitance of the pixel that depends on the electric field.

Principle

A resistor and a capacitor (RC) are used in oscillators and timing circuits. The time taken to charge the capacitor to a certain percentage of the applied voltage depends on the RC time constant and this voltage is used to trigger a circuit to control the period of oscillation. The CD 4047 B integrated circuit [2] is one such device and it can be used as an oscillator (astable multi-vibrator) to generate square waveforms. The frequency is determined by the value of the R and C used in the circuit. The liquid crystal cell can be used as the capacitor in the oscillator circuit and the capacitance of the liquid crystal cell can be determined by measuring the frequency of the astable output. The complementary metal oxide semiconductor (CMOS) integrated circuits can operate from 3 to 18 volts and the supply voltage can be varied to vary the RMS voltage across the cell. The capacitance of the cell can be calculated by measuring the frequency of oscillation of the astable multivibrator. A maximum of 5 volts (RMS) can be applied to the cell when the supply voltage to the integrated circuit is 18V, the maximum supply voltage of the integrated circuit. It is adequate because most of the liquid crystal mixtures have their threshold and saturation voltages below 5 volts. The voltage across the pixel (capacitance) is also DC free because the square waveforms that are applied to the RC (pins 1 and 2 of the integrated circuit) are 180° out of phase.

Circuit for Measurement of the Capacitance

A circuit for the measuring the capacitance is shown in Figure 2. It operates as a free running astable multi-vibrator with the liquid crystal cell as the capacitor (*C*) for the oscillator. The expression for the period of the oscillation (*T*) is given in the following equation [3].

$$T = R.C \ln \frac{(V_{DD} + V_{TR})(2V_{DD} - V_{TR})}{(V_{TR})(V_{DD} - V_{TR})} \qquad (1)$$

Here, V_{TR} is the transfer voltage of the inverter in the CD4047. Unit to unit variation of the voltage V_{TR} ranges from 0.33 V_{DD} to 0.67 V_{DD} and the expression for period *T* simplifies to 2.197*RC* when V_{TR} is 0.5 V_{DD} to 2.307 *RC* when V_{TR} is either $0.33V_{DD}$ or $0.67V_{DD}$. The plot in Figure 3 shows the period of oscillation (*T*) vs. the transfer voltage (V_{TR}) normalized to the supply voltage. Hence, the CD 4047 B has a frequency stability of about $\pm 2\%$ at 100 kHz. It is due to the device-to-device variation from one batch to another. In case we can measure the V_{TR}, then the measurement accuracy could be even better than the 2% because the variation of the period with temperature is just $+0.03\% / {}^{0}C$. In fact, the transfer voltage can be measured using an oscilloscope by probing at the pin no. 3 of the device. Typical waveform that appears at pin no. 3 is shown in Figure 4. The capacitor gets charged and when the voltage reaches V_{TR}, the state of the flip-flop at the output stage is switched and the capacitor starts getting charged to a voltage of opposite polarity due to reversal in the direction of the current in the RC circuit. Typical waveforms at the pins 1 to 3 of the integrated circuit are shown in Figure 5. A discontinuity in waveform can be seen when the voltage at the junction of the resistor and the capacitor reaches the transfer voltage (see Figure 5). The capacitance can be obtained by substituting the measured values of V_{TR} and V_{DD} in the following equation.

$$C = \frac{T}{R\left[\ln\left(\frac{(V_{DD} + V_{TR})(2\,V_{DD} - V_{TR})}{(V_{TR})(V_{DD} - V_{TR})}\right)\right]} \qquad (2)$$

Verification of the technique

We have verified the technique by measuring some known capacitance using the HP 4440B Decade Capacitor. The capacitance can be varied from 40 pF to 1.2μF. The capacitance selected has an accuracy of 0.25 %, which is adequate to measure the accuracy of the experimental circuit. We have measured the capacitance over a wide range of supply voltage (4 to 18 volts) for two values of capacitance and the results are tabulated in Table 1. The error in measurement by our technique is given in Table 1. The error in the measurement was found to be always positive and the error was higher for the smaller capacitance because of the stray capacitance. The error reduces as the supply voltage is increased and it is less than 2% when the supply voltage is greater than 8 volts.

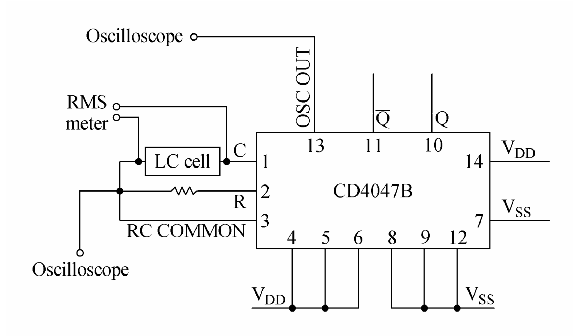

Figure 2. Schematic diagram of the circuit to measure the capacitance of the pixel using the low cost CD 4047 B integrated circuit and an oscilloscope. The RMS voltage across the liquid crystal cell, frequency of the oscillator output and the V_{TR} can be measured using an oscilloscope.

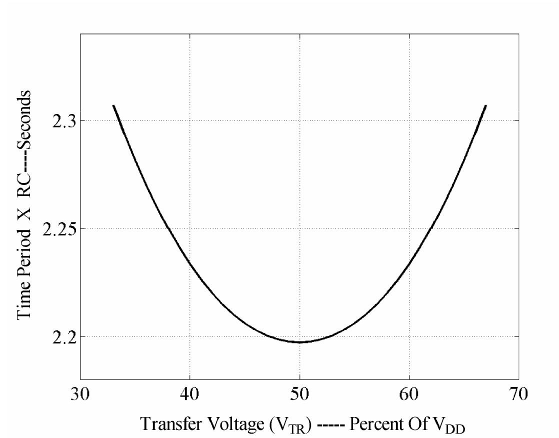

Figure 3. The period of oscillation depends on the transfer voltage (V_{TR}) as shown in the graph.

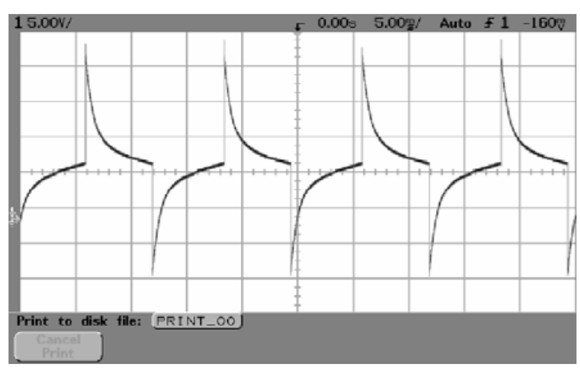

Figure 4. Waveform at RC common Point (pin 3) as observed in the oscilloscope. The V_{TR} is obtained by locating the voltage at which the waveform has a discontinuity.

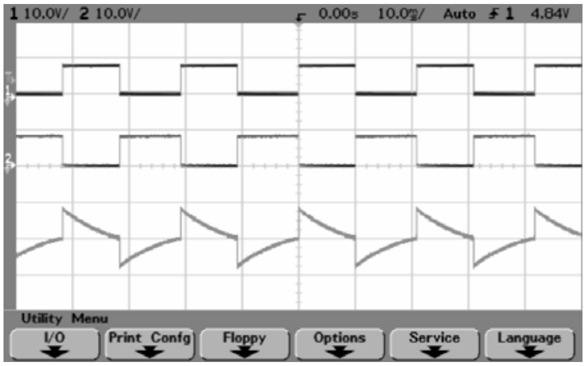

Figure 5. Typical waveforms at the pin numbers 1 to 3 of the integrated circuit (CD-4047).

Table 1. The Percent error when 10.04 nF and 50.04 nF were measured using the experimental setup.

Voltage V_{DD} in Volts	V_{TR} in Volts	V_{RMS} in Volts	Percent Error (10.04 nF)	Percent Error (50.04 nF)
4	2.16	1.16	5.933	3.329
5	2.72	1.55	3.978	2.188
6	3.25	1.92	2.867	1.761
7	3.78	2.19	2.313	1.475
8	4.28	2.48	1.994	1.536
9	4.81	2.73	1.810	1.396
10	5.34	3.01	1.600	1.401
11	5.84	3.30	1.633	1.434
12	6.34	3.59	1.470	1.298
13	6.84	3.88	1.489	1.172
14	7.34	4.16	1.317	1.333
15	7.88	4.47	1.309	1.178
16	8.41	4.75	1.119	1.017
17	8.75	4.99	1.191	1.089
18	9.25	5.34	1.009	1.093

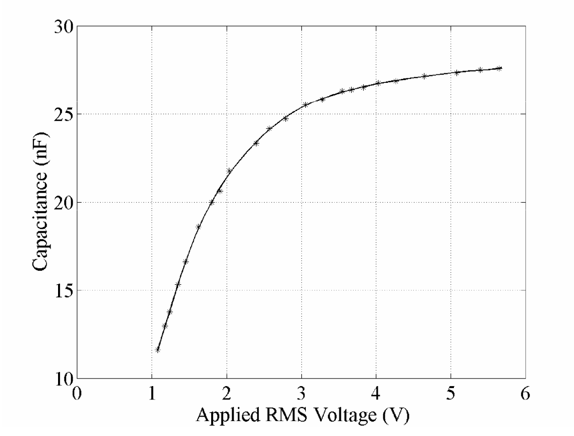

Figure 6. Voltage dependent capacitance of a liquid crystal cell filled with the RO-TN-403 mixture.

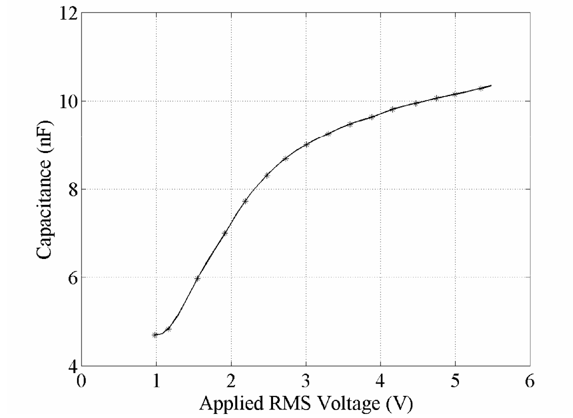

Figure 7. Voltage dependent capacitance of a liquid crystal cell filled with the RO-TN-605C mixture.

Results and Discussion

We have measured the voltage dependent capacitance of two cells filled with two different liquid crystal mixtures after calibrating the measurement technique with two values (10.04 nF and 50.04 nF from the standard decade capacitor unit) of capacitances. The measurements were performed by increasing the supply voltage from 4 to 18 volts in steps of 1 volt. The RMS voltage (V_{rms}) across the liquid crystal cell was in the range of about 1V to 5V. The plot of the capacitance vs. RMS voltage across the cell for the cells filled with RO-TN-403 and RO-TN-605C are shown in Figures 6 and 7 respectively. We have also verified that the DC voltage across the cell is negligible. The molecules in a liquid crystal display starts orienting to the electric field at a voltage that is lower than the threshold voltage (optical threshold that is measured from the change in light transmission through the cell). The threshold voltage (V_{th}) of the two cells are 1.33 and 1.75 volts for the liquid crystals RO-TN-403 and RO-TN-605C respectively. The effective dielectric constants ($\varepsilon_{effective}$) of the cells were computed using the following equation.

$$\varepsilon_{\text{effective}} = \frac{C\,.d}{\varepsilon_0\,.\,A} \qquad (3)$$

Here, *C* is the capacitance of the cell, *d* is the cell gap (gap between the two electrodes) and *A* is the area of cross-section of the electrodes. The effective dielectric constants of the two cells are shown in Table 2. The $\varepsilon_\perp$ and ε_{ll} of the RO-TN-403 liquid crystal mixture are 5.6 and 24.8 respectively. Similarly, the dielectric constants of RO-TN-605C are 5.3 ($\varepsilon_\perp$) and 18.5 (ε_{ll}). The $\varepsilon_{effective}$ near the threshold is close to $\varepsilon_\perp$ because the molecules are perpendicular to the electric field in the OFF state. The $\varepsilon_{effective}$ will be equal to ε_{ll} when the RMS voltage is above the saturation voltage of the electro-optic characteristics. The resistance R in the circuit has to be in the range of 10 KΩ to 1 MΩ for reliable operation of the oscillator. The minimum value of capacitance that can be measured by this circuit is 100 pF.

Conclusion

The technique proposed in this paper has sufficient accuracy for a wide range of applications. The technique can be used for indirect measurement of the cell gap (*d*) using the following equation.

$$d = \frac{\varepsilon_0 \,.\varepsilon_{effective}\,.A}{C} \tag{4}$$

The cell gap may not be uniform and the variation in gap beyond certain percentage will show up as change in color if the cell is optimized for the first minimum corresponding to the product ($\Delta n.d$) or change in contrast. The response time is also highly dependent on the cell gap (d) and it is advisable to reject the cell if the variation in the cell gap is beyond some limit. We have considered two profiles to show that the accuracy of the technique is adequate to detect variation in cell gap beyond 5% easily as evident from Table 3. The cell gap could be uniformly higher or lower than the desired value and even in such cases the technique can easily detect a deviation above 2%. The technique can be used to measure the cell gap of empty cells or those filled with liquid crystal mixtures and hence could be used for measuring cell gap in panels where in, the cell is filled using drop fill technique. In case it is used in quality control to accept or reject the cell then the experimental setup can be further simplified by using another CD 4047 as a frequency discriminator [3] and one can eliminate the need of an oscilloscope in the test setup. Orientation of the director [4] (the average direction of the long axis of the liquid crystal molecules) can be obtained using the equation in (5).

$$\theta = \sin^{-1}\sqrt{\left(\frac{(\varepsilon_{effective} - \varepsilon_{\perp})}{(\varepsilon_{||} - \varepsilon_{\perp})}\right)} \tag{5}$$

A plot of angle subtended by the director with reference to the surface of the cell vs. RMS voltage across the pixel is shown in Figure 8.

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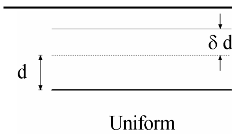
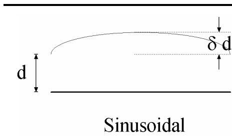
References

1. S. Chandrasekhar, "Liquid Crystals," second edition (Cambridge University Press, 1992).
2. CMOS Integrated Circuits Data book, RCA Solid State Data book Series (1983).
3. J. Paradise, "Using the CD4047A in COS/MOS timing applications," Digital Integrated circuits Application Note RCA ICAN-6230.
4. H. J. Deuling, "Deformation of Nematic Liquid Crystals in an Electric field," *Molecular Crystals and Liquid Crystals*, Vol. 19, pp. 123-131, 1972.

Table 2. Effective dielectric constant of the liquid crystal cell measured at different RMS volatges.

Voltage V_{DD} in Volts	V_{RMS} in Volts	$\varepsilon_{effective}$ (RO-TN-403)	$\varepsilon_{effective}$ (RO-TN-605C)
4	1.16	11.052	8.463
5	1.55	13.030	10.452
6	1.92	15.899	12.257
7	2.19	18.239	13.530
8	2.48	19.717	14.544
9	2.73	20.905	15.220
10	3.01	21.860	15.770
11	3.30	22.491	16.209
12	3.59	23.570	16.596
13	3.88	23.991	16.866
14	4.16	24.650	17.179
15	4.47	24.821	17.416
16	4.75	25.131	17.614
17	4.99	25.268	17.773
18	5.34	25.479	18.008

Table 3. Percentage change in the capacitance of the liquid crystal cell when the variation in the cell gap is a) uniform and b) sinusoidal.

Cell gap (d) variation profile	Percentage deviation in d (δd in %d)	Percentage deviation in C (δC in %C)
	5	4.76
	10	9.09
	20	16.6
	5	3.06
	10	5.90
	20	11.03

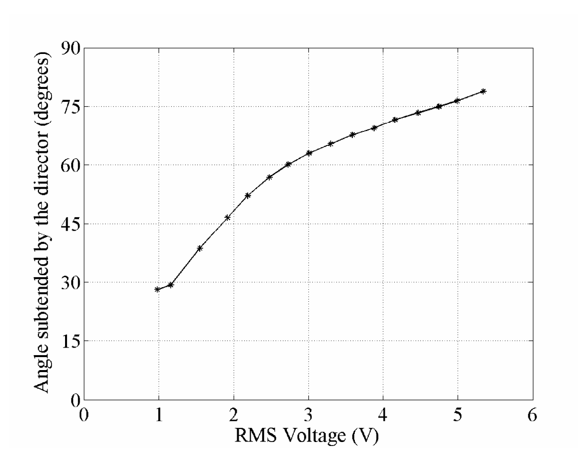


Figure 8. Plot of the angle subtended by the director (average direction of the liquid crystal molecules) Vs. the RMS voltage.