



The Effects of Excitation Signal on the Resolution of the Liquid Crystal Capacitive Chemical and Biological Sensors

A. Hassanzadeh^a, Y. Zou^b, R. G. Lindquist^b

^a ECE Department, Shahid Beheshti University, Tehran, Iran

^b ECE Department, University of Alabama in Huntsville, Huntsville, AL35899, USA

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ABSTRACT

In this paper excitation characteristics of the Liquid Crystal (LC) capacitive chemical and biological sensor are examined and the optimum frequency and voltage range for the sensor interface are introduced. Interdigitated capacitor has been used for the sensor capacitance measurement and two different molecular orientations, homeotropic and homogenous, have been considered. The LC sensor capacitance has been measured for different frequencies from 20Hz to 2MHz and voltages from 0.5V to 20V. In both cases, the effects of excitation on the capacitance value and the accuracy of the measurement are investigated. Simulation and experimental results support the proposed range of measurement.

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1. INTRODUCTION

Liquid Crystal (LC) sensors have proven to be good candidates for detection of chemical and biological agents. The LC molecules change their orientation when exposed to certain chemical and biological agents [1-5]. The sensor molecules can amplify small changes at the interface of the LC and the agent; therefore, very low concentration agents, in parts per million (ppm) or parts per billion (ppb) can be easily detected. Since the LC molecules show different permittivity in different directions, capacitive transduction can be used for molecular orientation change detection. Dr. Lindquist and his group at the University of Alabama in Huntsville have used capacitive technique to measure LC director axis orientation change [6, 7]. Since the sensor is passive, an excitation voltage should be applied to the sensor in order to measure the capacitance. The amplitude and frequency of the AC excitation signal are important for a high accuracy and resolution measurement. Figure 1 shows a typical differential integrated CMOS charge amplifier that has been used for the low value capacitance measurement of the LC sensor [8].

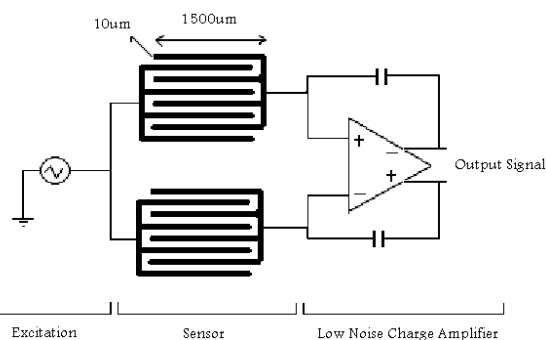


Figure 1. Integrated differential charge amplifier for LC capacitive sensors [8]

The measurement system consists of an excitation voltage, two interdigitated LC capacitive sensors and a differential charge amplifier. The excitation frequency of the LC sensor is very important for determination of bandwidth and operating frequency of the charge amplifier. One of the limiting factors in the resolution of the charge amplifier is the noise floor of the measurement system. In CMOS amplifiers, flicker noise or $1/f$ noise is dominant in the low frequencies and as the frequency of measurement decreases, this noise increases as shown in Equation (1). The first term in

*Corresponding Author Email: A_hassanzadeh@sbu.ac.ir (A. Hassanzadeh)

Equation (1) is the thermal noise and the second one is the flicker noise, which is inversely proportional to the frequency of operation. In Equation (1), k is Boltzman, constant, T temperature, g_m transistor transconductance, η a constant, K_F flicker noise coefficient, f frequency, C_{OX} oxide capacitance, W transistor width, L transistor length and k' a constant.

$$v^2_N = \left[\frac{8kT(1 + \eta)}{3g_m} + \frac{K_F}{2fC_{OX}WLK'} \right] \Delta f \quad (1)$$

Therefore, it is important to design the amplifier in a frequency that maximizes the resolution (lower noise) and accuracy of the measurement. As a result, very low parts per billion agents can be detected with an integrated sensor microchip. The voltage investigation is important because low voltages are used for sensor capacitance measurement and high voltages are used to monitor the anchoring energy for the sensor sensitivity [9]. This paper is arranged as follows. First, capacitance transduction technique is introduced, then sensor fabrication for the LC homogenous and homeotropic alignments will be discussed. Electrical and optical observations in different voltage and frequency excitations are presented afterward. Simulation results from the Finite Element Method (FEM) will be presented next. Conclusion remarks are at the end.

2. CAPACITANCE TRANSDUCTION OF THE LIQUID CRYSTAL SENSOR

LC molecules have different permittivity in different directions. Because of the anisotropic behavior of the LC, permittivity tensor is defined as a matrix that shows the orientation dependence of the LC permittivity, shown in Equation (2). The Nematic phase of the LC molecules is a phase that molecules have long range orientation order. Since the LC is an anisotropic material, the electric field in the LC film is governed by Maxwell's Equation (3).

$$\epsilon = \epsilon_0 \begin{bmatrix} \epsilon_{xx} & \epsilon_{xy} & \epsilon_{xz} \\ \epsilon_{yx} & \epsilon_{yy} & \epsilon_{yz} \\ \epsilon_{zx} & \epsilon_{zy} & \epsilon_{zz} \end{bmatrix} \quad (2)$$

where E is the electric field in the LC film and ϵ is the permittivity matrix.

$$\nabla \cdot (\epsilon \vec{E}) = 0 \quad (3)$$

Permittivity tensor given in Equation (2) can be written in the director axis coordinate system. Therefore, the resulting permittivity tensor will be simplified to two permittivities, $\epsilon_{||}$ for the electric field parallel to the director axis \vec{n} and perpendicular permittivity ϵ_{\perp} for the electric field perpendicular to the

director axis as shown in Equation (4). The difference between these two permittivities can be quite large and so the capacitance values change. The director axis \vec{n} represents the average of the LC molecules orientation direction.

$$\epsilon_m = \begin{bmatrix} \epsilon_{\perp} & 0 & 0 \\ 0 & \epsilon_{\perp} & 0 \\ 0 & 0 & \epsilon_{||} \end{bmatrix} \quad (4)$$

Using Maxwell's equation and the permittivity tensor, capacitance can be calculated using Equation (5) [10].

$$C = \frac{Q}{V} = \frac{\oint \vec{D} \cdot d\vec{s}}{-\int \vec{E} \cdot d\vec{\ell}} \quad (5)$$

where D is the electric displacement field and S the area of the electrode. For the interdigitated structure fringing field will be used for the capacitance measurement, and the capacitance is calculated using total charge stored on the conductors divided by the voltage difference. Figure 2 shows the interdigitated capacitive sensor that has been used for measurement of the LC capacitance change.

Although parallel plate capacitor would give higher capacitance value, but that structure does not provide easy access to the surface of the LC molecules. The agent molecules enter from the top and the interdigitated fingers are underneath for the capacitance measurement. Therefore, fringing field measurement is the preferred structure.

3. INTERDIGITATED LC CAPACITIVE SENSOR FABRICATION

In order to fabricate the interdigitated capacitors, 10nm of chromium and 40nm of gold have been deposited on a 1737 Corning glass using sputtering system (PVD). After the deposition, positive photo resist AZ MiR 701 has been spin coated on the gold and by using UV exposure interdigitated pattern has been transferred onto the surface. Wet etch is used for etching chromium and the gold and the interdigitated fingers with 10 μ m feature size have been fabricated. Figure 3 shows the fabricated interdigitated sensor that has been used for the LC deposition.

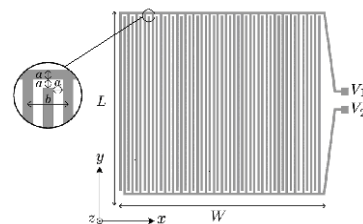


Figure 2. Interdigitated capacitor [7]

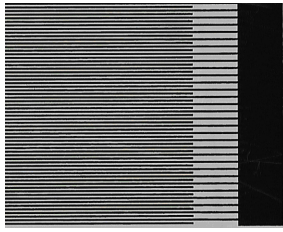


Figure 3. Fabricated interdigitated capacitive sensor

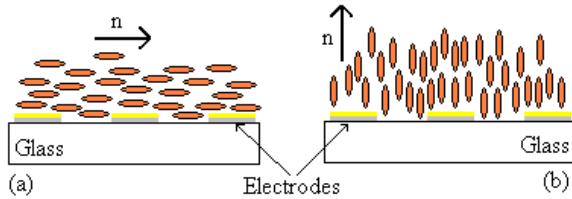


Figure 4. LC a) homogenous alignment b) homeotropic alignment



Figure 5. Optical texture of a) Homogenous alignment, b) Homeotropic alignment

Two different orientations of the liquid crystal molecules can be considered, one parallel to the substrate that is called homogenous and one perpendicular to the substrate or homeotropic orientation. These two orientations are shown in Figure 4.

In order to obtain the homogenous alignment 4% w/w PVA (Polyvinyl alcohol) in the de-ionized water was spin coated on the interdigitated sensor surface and baked for 2 min at 90°C. Then, the surface was rubbed in one direction for a few times using a cloth. After putting the LC on the surface, molecules tend to align in the homogenous orientation. From optical observation, homogenous alignment will look bright under a cross polarizer with 45° angle as shown in Figure 5a. For the homeotropic alignment 0.1% CTAB (Cetyltrimethylammonium Bromide) solution in de-ionized water is spin coated on the surface of the interdigitated capacitor. After baking at 90°C for 5 min, the LC will be spin coated on the substrate. The resulting orientation will be homeotropic and will always look dark regardless of the angle that it makes with the polarizer as shown in Figure 5b.

The E7 liquid crystal (one type of LC) has been used for the experiment measurement. The clearing point of E7 is higher than room temperature and remains anisotropic during the experiment; therefore, it has been

used in the LC chemical and biological sensing applications.

4. LC SENSOR CAPACITANCE VERSUS EXCITATION CHANGE

For the flat fingers on the substrate the capacitance measurement will be a fringing field capacitor. Usually fringing field capacitor has smaller value comparing to the parallel plate field, but it is easier for implementation of the homeotropic and homogenous alignments. Glass substrate and the top air will produce relatively constant capacitance versus frequency and voltage in the range of interest; therefore, will not be effective on the experiment. The amplitude of the excitation voltage is important for the LC molecules. If the applied voltage amplitude is below the Friedrich's voltage, then it will not cause an orientation change for the LC molecules. In this case, measurement will only depend on the existing orientation and is used for sensing applications. Increasing voltage amplitude above the Friedrich's voltage will cause LC molecules to reorient along the applied electric field direction that will cause larger capacitance change. Higher voltage excitation is used for anchoring energy investigation. The frequency of excitation also has effects on the capacitance value. Very low excitation frequency causes the LC molecules to vibrate, which is visually observable and is not desirable [11]. As the frequency increases this vibration decreases and the molecules will not respond anymore. In order to analyze the voltage and frequency dependence of the capacitor, voltage has been changed from 0.5V to 20V and frequency has been changed from 20Hz to 2MHz. Experimental results are shown in Figures 6 and 7 for the homogenous and the homeotropic alignments respectively.

For both cases of homogenous and homeotropic the capacitance value will decrease at low frequency more rapidly than higher frequencies. At the frequencies around 500 Hz to 1 kHz, there will be an approximately flat band area up to frequency around 100 kHz that capacitance does not change significantly. For frequencies higher than 100 kHz the capacitance starts to decrease again. At higher frequencies LC molecule anisotropy decreases and the LC director axis tends not to follow the applied electric field [12]. In addition higher voltage will cause the molecules to reorient and therefore, higher capacitance will be measured as shown in Figures 6 and 7.

Optical observation of the sensor change versus frequency and voltage has been performed. Figure 8 shows the sensor for different frequencies and voltages for the homogenous and homeotropic cases. Optical investigation shows that as the excitation voltage increases, sensor appears to be brighter because molecules reorient along the applied electric field. For

the homogenous case, the initial position makes zero degree angle with the polarizer. After applying voltage, as the voltage level increases molecules reorient and the film becomes bright. For the 10V excitation voltage the field is dominant and reorients the molecules for bright film regardless of frequency and initial orientation. The homeotropic alignment shows dark pattern at beginning and as the voltage increases molecules reorient and the film becomes bright.

5. SIMULATION RESULTS

In order to verify the measurement results a finite element program has been developed to calculate the capacitance value at different frequencies and voltages. The dielectric permittivity of the LC from [13], and the fabricated sensor dimensions have been used for the calculations. For the external applied voltage, the director deformation is altered by an external electric field. The analysis of the electric field-induced director deformations above the Friedrich's threshold can be tracked by capacitive measurement. First, the LC director and potential profile are solved by minimizing the total energy in the LC sensor. The energy density is given by:

$$F_{unit} = F_{elastic} + F_{electric} + F_{anchoring} \tag{6}$$

The elastic energy is:

$$F_{elastic} = \frac{1}{2} K_1 (\nabla \cdot \vec{n})^2 + \frac{1}{2} K_2 (\vec{n} \cdot \nabla \times \vec{n})^2 + \frac{1}{2} K_3 (\vec{n} \times \nabla \times \vec{n})^2 \tag{7}$$

where K_1 is the splay constant, K_2 the twist constant, K_3 the bend constant of the LC material and \vec{n} the LC director vector. The electric energy density that contributes to free energy is given by [14].

$$F_{electric} = -\frac{1}{2} \vec{D} \cdot \vec{E} \tag{8}$$

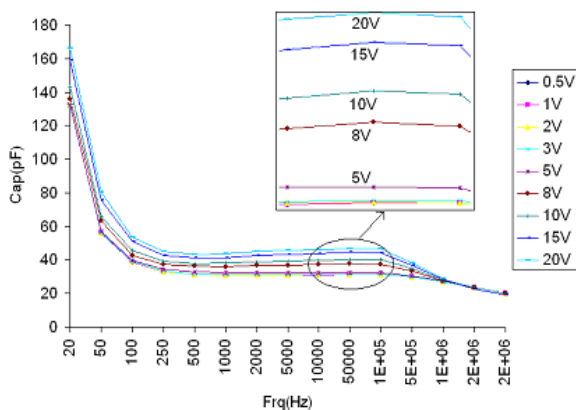


Figure 6. LC capacitance vs frequency (Homogenous)

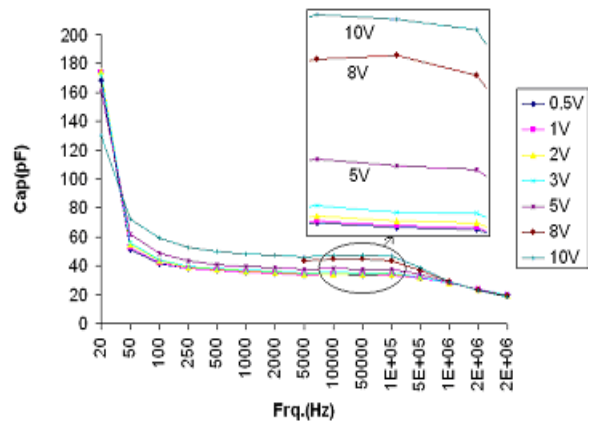


Figure 7. LC capacitance vs frequency (Homeotropic)

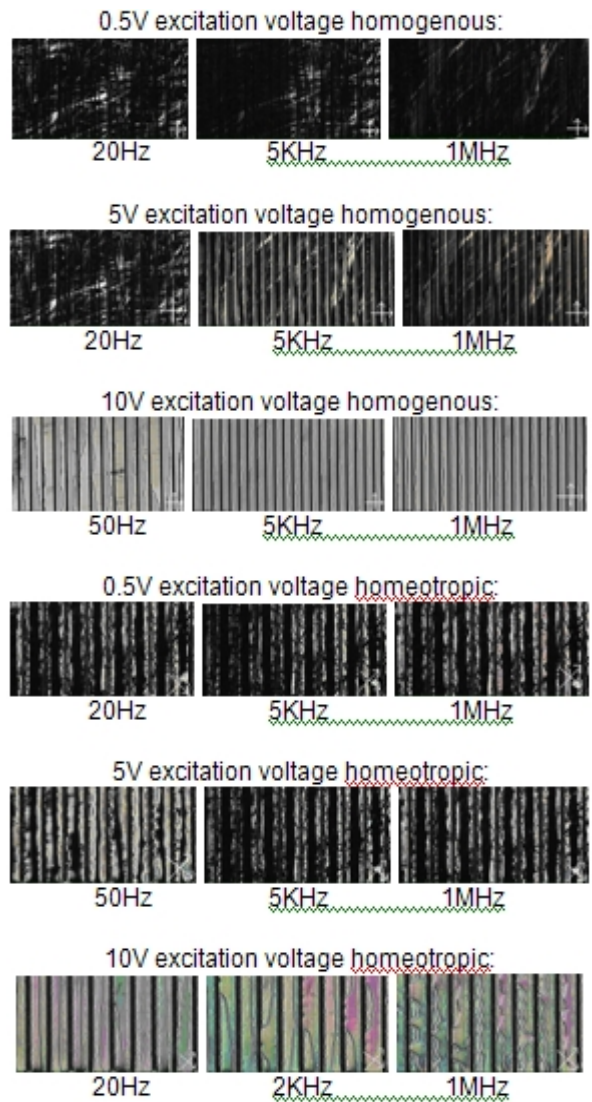


Figure 8. Optical characteristic of the LC sensor at different voltages and frequencies (Homogenous are 0° and homeotropics are 45° with respect to the polarizer)

In the last term of Equation (6), the anchoring energy in the Rapini-Papoular form is given by:

$$F_{anchoring} = \frac{1}{2} W_n (\vec{n} \cdot \vec{n}_0)^2 \tag{9}$$

where W_n is anchoring energy coefficient and \vec{n} is easy axis of the LC director. Once the LC director and electrical field distribution in a LC sample are decided using Finite Element Method (FEM), the capacitance can be calculated using Equation (5).

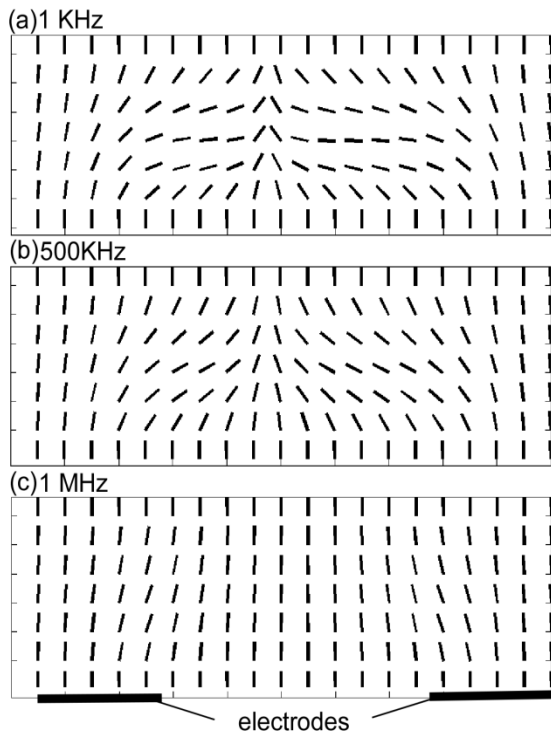


Figure 9. Simulation results of the LC director distribution within one 10 μm periodic domain at 10 V_{rms} applied voltage. (a) 1 KHz (b) 500 KHz and (c) 1 MHz.

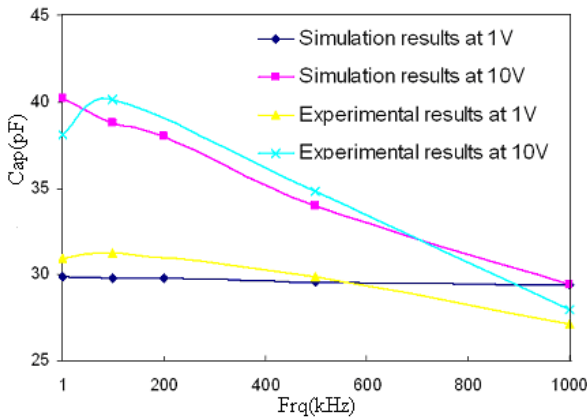


Figure 10. Simulation result of capacitance versus frequency at different applied voltages

For the interdigitated sensor structure, the analytic form of minimizing the total energy of Equation (6) by calculus of variation is almost impossible due to the nonlinearity and the coupled elastic and electric energies. The problem of the coupled differential elastic and electrical equations can be solved by an iteration process [15]. The nonlinear differential equation can be solved numerically by the Finite Element Method (FEM) [16]. At first, the electrical potential profile is acquired by solving the Laplace equation based on the known initial LC director distribution and the applied voltage. Then, the LC director distribution is updated based on the known potential profile. The iteration is continued until the time frame or the equilibrium is reached. Finally, Equation (5) is used to calculate the capacitance. The electric responses to different voltages and frequencies have been simulated. The parallel dielectric permittivity $\epsilon_{||}$ and the perpendicular dielectric permittivity ϵ_{\perp} are 19.1 and 5.1 at 1kHz, 18.0 and 5.1 at 100kHz, 17.4 and 5.1 at 200kHz, 14.3 and 5.1 at 500kHz, 11.5 and 5.1 at 1MHz, which are used for the simulation [16]. Simulation results are shown in Figures 9 and 10. The parameters of the LC and the LC cell are the same as the above experiments and the thickness of the LC film is assumed to be 3.5 μm. Figure 9 shows the LC director distribution at different frequencies. At the 10V applied voltage, as the frequency increases, the dielectric anisotropy becomes small. Thus, the LC director has less distortion at higher frequencies. The capacitance calculated matches measurement results as shown in Figure 10. At 1MHz excitation, because the LC anisotropy has decreased, the director axis does not respond properly to the excitation voltage.

6. CONCLUSION

Performance of the LC capacitive sensor versus applied excitation characteristics has been investigated for proper range of operation. It is found that the sensor shows higher capacitance for low frequency excitation rather than high frequency, but the low frequency excitation voltage causes the LC molecules to vibrate. The proper band for excitation is the flat band that capacitance does not change very much versus frequency in the range of 100 Hz to 100 kHz. Although the higher frequency would provide less flicker noise for the amplifier, available bandwidth is also important for the rms input noise that should be considered for the amplifier design. At high frequencies, LC loses its anisotropy that is not good for sensor applications. For sensor measurement applications low excitation voltage below Friedrich’s voltage should be used and high voltage values are used for anchoring energy investigations. Therefore, the proper range of measurement is the range that anisotropy is dominant.

7. ACKNOWLEDGMENT

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A. Hassanzadeh^a, Y. Zou^b, R. G. Lindquist^b

^a ECE Department, Shahid Beheshti University, Tehran, Iran

^b ECE Department, University of Alabama in Huntsville, Huntsville, AL35899, USA

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در این مقاله مشخصات سیگنال تحریک سنسور (حس گر) های خازنی برای آشکارسازی مواد بیولوژیکی و شیمیایی مورد بررسی قرار گرفته و فرکانس و ولتاژ بهینه برای تحریک سنسور به دست آمده است. از خازن شانه‌ای برای اندازه‌گیری سنسور خازنی در دو ساختار هموزن و هوموترایپیک استفاده شده است. خازن سنسور برای دامنه‌ی فرکانسی ۲۰ هرتز تا ۲ مگاهرتز و ولتاژهای ۰/۵ تا ۲۰ ولت اندازه‌گیری شده است. در هر دو حالت اثر سیگنال تحریک روی مقدار خازن و دقت اندازه‌گیری بررسی شده‌اند. نتایج شبیه‌سازی و اندازه‌گیری‌های آزمایشگاهی محدوده‌ی بهینه‌ی سیگنال تحریک به دست آمده را تایید می‌کند.

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