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# Modal liquid crystal temperature sensor

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*Abstract*— **In this work, a novel liquid crystal temperature sensor is proposed. This sensor is composed by only two electrodes. A simple and easily scalable structure uses the temperature dependence of the liquid crystal permittivity as the sensing magnitude. The sensor has a high sensitivity, low voltage control, low power consumption and high linearity. The analytical modelling allows an optimization of the structure, in terms of sensitivity. Several liquid crystal has been investigated. The response improves the characteristics of previous LC sensors and even some commercial sensors (e.g. 60 mV/ºC for 10 $V_{rms}$ of applied voltage, six times more than of most silicon temperature sensors).**

***Keywords—Temperature sensing; liquid crystal; high resistivity layer.***

## I. INTRODUCTION

One of the most measured physical magnitude by the industry is the temperature. From an industrial point of view, a sensor measuring this magnitude has to be simple, small in size, low cost, to be reproducible and stable. There are many situations that require this type of measure and several research effort are still focused on this topic. Among the many sensing elements used to measure temperate, are the Liquid Crystal (LC) materials. A LC is a material that has, at least, one intermediate phase between the liquid and solid phase. This can depend on the temperature (thermotropic LC) or the concentration of a determined solvent (lyotropic). The most used is the thermotropic. They intermediate states are called mesophases. In this states the molecules do not have the positional order of a crystal but have an orientational order. This gives them anisotropic properties. There are several types of mesophases, these ones depends on the molecular positional order. For example the most common is nematic (used in displays), where all the molecules follow the same direction, and smectic, where the molecules are distributed in planes (in each plane the local order is nematic). In the smectic phase, when the molecules are perpendicular to the plane are called smectic A (SmA), if the molecules are tilted is called smectic C (SmC). Another special case occurs when the molecules are twisted perpendicular to the director, with the molecular axis parallel to the director. This mesophase is called chiral nematic phase and exhibits chirality (handedness). The common name is cholesteric because it was first observed for cholesterol derivatives. So far, this is the most used phase to measure the temperature [1] [2]. These LCs have a helical configuration that results in a material with a high light rotatory power. This is their main operation principle; for wavelengths λ = n•p, where n is refractive index and p the helical pitch, the light is selectively reflected. This type of sensors take advantage of the temperature dependence of the LC helical pitch as a sensing magnitude. The output parameter is the reflected wavelength when a white light strikes the sensor. Temperature-color transducers are usually manufactured on flexible substrates [3]. These kinds of sensors are cheap, easy to measure by means of a fiber optic link and can be used in situations requiring sensors that do not emit any kind of electrical or electromagnetic signals. They have been proposed for use in medical applications [4], food processing [5], etc.

Another option to measure the temperature is the use of nematic LC materials. Until now most of the research works have been mainly focused on take advantage of the refractive index variation with temperature. Some studies are based on phase variations of the light. The output signal is wavelenght shifts. For example, a Fabry-Perot cavity filled with a nematic LC has been studied in several works [6] [7]. Others works have used another type of structures as photonic crystal fibers [8] [9] [10]. In summary these sensors are complex to build, or take measurements (low sensitivities, a spectrum analyzer is frequently required, etc.). To solve this problem we propose the use of the permittivity change with temperature as sensing magnitude. As refractive index, this parameter has a high dependence with temperature. However few works in the literature have investigated this effect as sensing magnitude. For example, Marcos et al. used this feature to create a LC capacitor that was integrated in a multivibrator circuit [11]. The result is a temperature-frequency transducer with a variable frequency as an output signal; this kind of sensor has been demonstrated to have broad temperature range. Some disadvantages are that it also needs an interrogating circuit to measure the signal and the resulting sensitivity is directly proportional to the permittivity change with temperature, by a relationship derived from the interrogating circuit. The authors have proposed a micrometric array to solve the problem of the interrogating circuitry [12]. The problem is the complexity of the structure as well as the sensitivity optimization.

In this work a novel liquid crystal (LC) temperature sensor is proposed. This sensor is composed by only two electrodes and is easy to build (no need to high resolution photolithography). The response improves the characteristics of previous LC sensors and even some commercial sensors (e.g. 60 mV/ºC for 10 $V_{rms}$ of applied voltage, six times more than of most silicon temperature sensors).

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## II. STRUCTURE AND PRINCIPLE OF OPERATION

### *A. Structure*

The structure is composed of two electrodes that act as an integrated interrogating circuitry (see Fig. 1). The structure and dimensions of the LC device are determinant in order to have a high enough voltage output. Two electrodes are designed: The first one has a comb shape and acts as voltage source (Comb 1). The other electrode is placed between the two fingers of Comb 1. This one measures the voltage drop at the central point between two teeth. The device conductivity is increased by depositing a high resistivity layer (modal control). This technique was used to fabricate liquid crystal lenses [13] some years ago. Several materials can be employed, depending on the necessary sheet resistance ($R_{sq}$), for instance, Titanium Oxide (TiO2), PEDOT, thin films of ITO or Nickel, etc. The resistivity of these materials ranges from 0.1 to 10 MΩ/sq. Thanks to a high resistivity layer, $R_{sq}$, the structure produces a high voltage output that does not need any type of amplification circuitry. The high impedance of the LC produces very low power consumption. In consequence, the self-heating is negligible. Although the thickness is not a critical parameter, the lower the thickness, the highest the response time. The LC molecules have an elongated shape that causes different molecular polarizabilities between the long and short axis. The effective permittivity depends on the angle of long axis of the molecules. For this reason, a homeotropic alignment layer is necessary to exploit the extraordinary dependence of the LC permittivity with temperature. This can be done, for example, by using a $SiO_x$ layer over the high resistivity layer [14]. The molecules arrange perpendicular to these layer when the cell is filled.

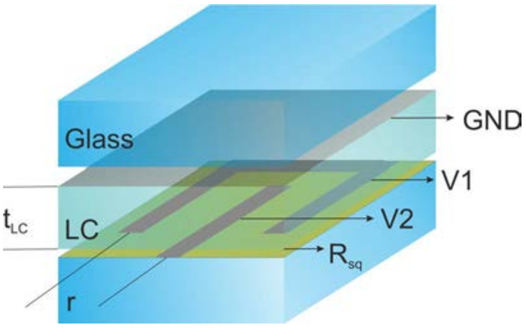

Fig. 1 Structure. Note drawings are not to scale.

### *B. Theoretical background*

The governing equations of the proposed structure can be derived from the transmission line theory [15]. Considering a driving voltage that comprises only one harmonic ($V(x, t) = V(x)\, e^{i\omega t}$) and $V(x = -r) = V(x = r) = V_1$, and $V(x = 0) = V_2$ (r is the distance between electrodes), the governing equation is,

$$V_2(T) = \frac{V_1}{\cosh\left(\sqrt{\dfrac{R_{sq}\cdot\omega\cdot\varepsilon_0\cdot\varepsilon_{LC}(T)}{t_{LC}}}\cdot r\right)} \qquad (1)$$

where $\varepsilon_0$ is the vacuum permittivity, $t_{LC}$ the LC thickness and $\varepsilon_{LC}$ the average real effective permittivity in the perpendicular direction, $\omega$ is the angular frequency of the applied voltage ($2\cdot\pi\cdot f$). From (1) we can predict the offset value for the sensor; this value is directly proportional to $V_1$. The parameter that gives the sensor sensitivity is $\varepsilon_{LC}$. This term is multiplied by some structural parameters and is inside of a cosine hyperbolic function. So considering these facts, it would be very important to know the maximum sensitivity response of the proposed structure. This is proportional to the structural parameters (2).

$$Coeff = \sqrt{\frac{R_{sq}\cdot\omega\cdot\varepsilon_0\cdot\varepsilon_{LC}(T)}{t_{LC}}}\cdot r \qquad (2)$$

For a determined relation between the coefficients the sensitivity of the structure will be maximum. This can be estimated by the derivative of the (1) with respect to (2). As can be seen on Fig. 2 this value is around 0.9. This is an approximation and further studies will be focused on the derivative of (1) with respect to the permittivity. This parameter is a function of temperature so it will be considered as an independent function. But this study is beyond the scope of this paper. The present study is focused on demonstrate the behavior of two electrodes LC sensor. When the structural parameters follow the relation shown in Fig. 2, the output voltage has a maximum sensitivity.

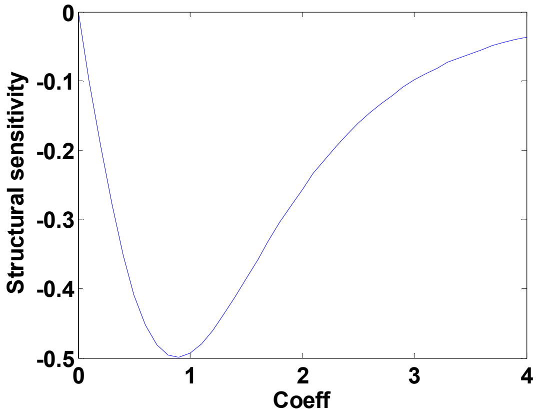

Fig. 2 Structural sensitivity.

## III. RESULTS

The result of the structure optimization is studied to bring the optimum design of the sensor. There are many free parameters to achieve this value. This makes the fabrication process a no critical step. The result of filling the structure with three different LC has been estimated. Two different voltages are displayed in Fig. 3. From the study applying a 1 $V_{rms}$ signal, the sensitivity as function of the applied voltage can be measured (V/V/ºC). Another signal of 10 $V_{rms}$ is displayed in order to see how the sensitivity can be changed with the applied voltage. The high output voltage make the device very easy to measure. No special equipment or signal amplification

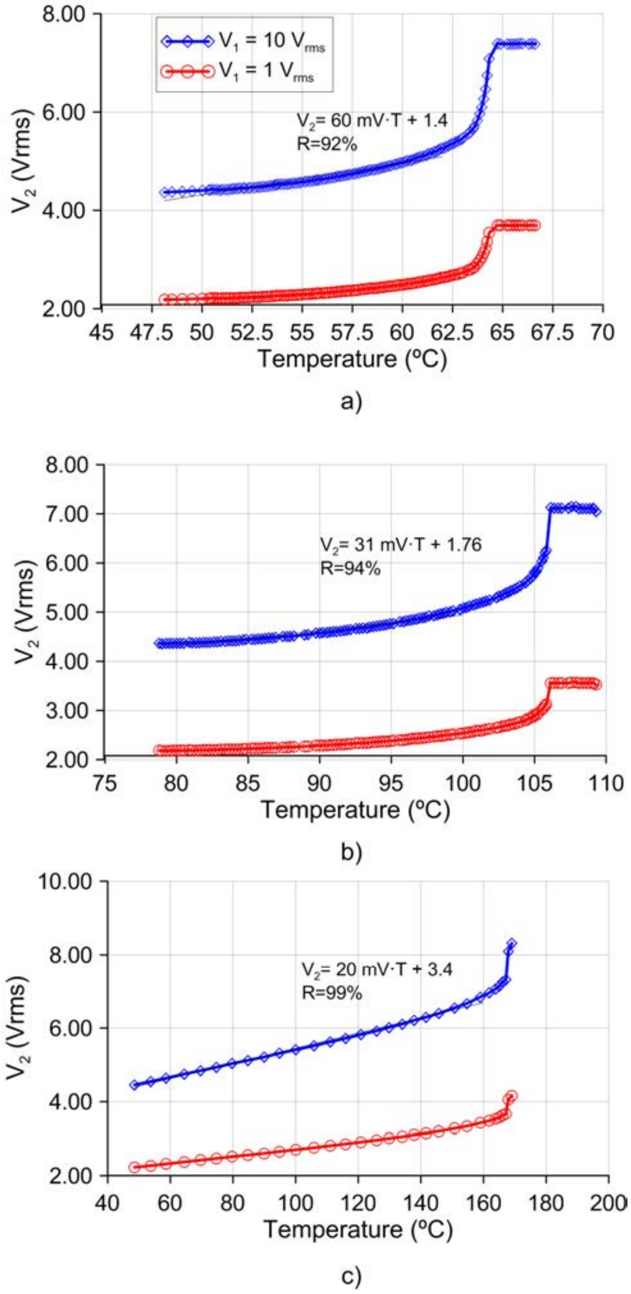

Fig. 3 Voltage output for several LC, a) TN132, b) TN201 and c) fluorinated terphenyl liquid crystal

is required. There is a great difference between the three LC. This can be an advantage because the sensor response can be selected as a function of the required application. The highest sensitive response is also the less linear. The highest sensitivity is observed for the TN132. An unexpected sensitivity of 60mV/ºC has been estimated. The higher linearity can be found for other compounds at the cost of lower sensitivities. For example, in Fig. 3 (c), the sensitivity of 22 mV/ºC has a regression coefficient of 99%. The dependence of the sensitivity with the applied voltage produce a total control over this parameter.

A sensitivity of 22 mV/°C is obtained for a temperature range from 60 ºC to 95 ºC. This range could be useful in some specific applications. For example, LCD displays that are used in extreme environments (outdoor, avionics display, military aerospace display). The sensor could follow the temperature with high sensitivities in this specific range. Even more than the typical used silicon sensor (LM35). The other temperature ranges and sensitivities can find a great number of different applications.

## IV. CONCLUSIONS

A novel idea in the research field of temperature sensors has been presented. The analytical study reveals an interesting response in terms of sensitivity. The structure can be optimize by using the derivatives of the analytical functions. This sensor demonstrates some advantages over other related LC temperature sensors. Even it has a better response than some commercial temperature sensors. For example, it has higher sensitivities than silicon sensors (for certain supply voltages). Also, a great linearity has been observed to a broad range of temperatures. Some problems of self-heating can be avoided due to the high resistance of the deposited layer. This makes it very efficient in terms of power consumption. The high voltage output allows measures without the need of any type of amplification circuitry. The proposed structure can be easily scalable depending on the required application. The applications cover a wide range of market products as LCD displays, LCD projectors and portable equipment with low power requirements, among others.

## REFERENCES

[1] Brown, V. R. Colorimetric temperature sensor. US3651695A 1970;

[2] Mulder, D. J. and Schenning, A. P. H. J. and Bastiaansen, C. W. M., "Chiral-nematic liquid crystals as one dimensional photonic materials in optical sensors," J. Mater. Chem. C, 2014.

[3] Davies, D.J.D.; Vaccaro, A.R.; Morris, S.M.; Herzer, N.; Schenning, A.P.H.J; Bastiaansen, C.W.M. A Printable Optical Time-Temperature Integrator Based on Shape Memory in a Chiral Nematic Polymer Network. Adv. Funct. Mater., vol. 6, pp. 100–110, 2013.

[4] Luk, C.M. Liquid crystal temperature indicator for measuring human body temperature. US4302971A 1981.

[5] Balasubramaniam, V. M.; Sastry, S. K. Use of liquid crystals as temperature sensors in food processing research. J. Food Eng., vol. 26, pp. 219–230, 1995.

[6] H. R. Kim, Y. Wook Lee; E. Jang, J. Im, B. Lee, S. D. Lee, "Electro-optically detectable temperature sensor using a nematic liquid crystal Fabry-Perot resonator," Lasers and Electro-Optics Society, 2003. The 16th Annual Meeting of the IEEE, vol.1, pp.95-96, Oct. 2003.

[7] H. R. Kim, E. Jang, and S. D. Lee, "Electrooptic temperature sensor based on a Fabry-Perot resonator with a liquid crystal film," *IEEE Photon. Technol. Lett.*, vol. 18, no. 18, pp. 905-907, April 2006.

[8] Y. Wang, M. Yang, D. N. Wang, and C. R. Liao, "Selectively Infiltrated Photonic Crystal Fiber with Ultrahigh Temperature Sensitivity," *IEEE Photon. Technol. Lett.*, vol.23, no.20, pp. 1520-1522, Oct. 2011.

[9] D. J. J. Hu, J. L. Lim, Y. Cui, K. Milenko, Y. Wang, P. P. Shum, and T. Wolinski, "Fabrication and Characterization of a Highly Temperature Sensitive Device Based on Nematic Liquid Crystal-Filled Photonic Crystal Fiber," *IEEE Photon. J.*, vol. 4, no.5, pp. 1248-1255, Oct. 2012

[10] Y. Peng, J. Hou, Y. Zhang, Z. Huang, R. Xiao, and Q. Lu, "Temperature sensing using the bandgap-like effect in a selectively liquid-filled photonic crystal fiber," Opt. Lett. , vol. 38, pp. 263-265, 2013.

[11] C. Marcos, J. M. Sánchez-Pena, J. C. Torres, J. I. Santos, "Temperature-Frequency Converter Using a Liquid Crystal Cell as a Sensing Element," Sensors, vol. 12, pp. 3204-3214, 2012.

[12] J. F. Algorri, V. Urruchi, N. Bennis, J. M. Sánchez-Pena, “A Novel High-Sensitivity, Low-Power, Liquid Crystal Temperature Sensor,” Sensors, vol. 14, pp. 6571-6583, 2014.

[13] G. D. Love and A. F. Naumov, “Modal liquid crystal lenses,” *Liq. Cryst. Today*, vol. 10, no. 13, pp. 1–4, 2000.

[14] E. Otón, S. López-Andres, C. Carrasco-Vela, B. Cerrolaza, N. Bennis, J. M. Otón, “Dynamics and Electrooptics of Vertically Aligned Nematics With Induced Pretilt on SiOx,” J. Display Technol., vol. 6, pp. 263–268, 2010.

[15] V. Urruchi, J. F. Algorri, C. Marcos, and J. M. Sánchez-Pena, “Electrical modeling and characterization of voltage gradient in liquid crystal microlenses,” *Rev. Sci. Inst.*, vol. 84, no. 11, pp. 116105, Nov. 2013.