Electrostatic Unsteady Thermal Energy Harvester Using Nematic Liquid Crystal

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Abstract: A novel electrostatic unsteady thermal harvester is proposed using nematic liquid crystal as the temperature-sensitive dielectric. With its large anisotropic permittivity and relatively high resistivity, an early prototype is made using fluorinated liquid crystal BCH-5F.F. Temperature change of the liquid crystal induces its permittivity change, thereby output voltage is obtained. An effective circuit model is developed and the simulation results are compared with the experimental data for designing harvester with better performance.

Keywords: Electrostatic, Thermal energy harvesting, Nematic liquid crystal, Resistivity

1. Introduction

Energy supply for low-power electronics is a big challenge with increasing demand of portable and wireless devices. Thermal energy harvesting can be a promising solution for self-powered electronics such as wireless sensing node [1], which is one of the essential components of the Internet of Things. Conventional thermal energy harvesting mostly utilizes constant temperature gradient based on the Seebeck effect [2]. More recently, time-dependent fluctuating ambient temperature has been reported to be an alternative thermal energy source for energy harvesting [3, 4].

We previously proposed electret-based unsteady thermal generator utilizing permittivity change of ferroelectric material [5]. By using potassium tantalate niobate (KTN) crystal, output power of 572 nJ has been obtained in 300 s [6]. However, relatively high operation temperature and long recovery time are the main drawbacks of the KTN-based system, which limit the actual application of unsteady energy harvester working in the room temperature range with rapid but small temperature fluctuations.

In this paper, nematic liquid crystal with anisotropic permittivity is, for the first time, studied as temperature sensitive dielectric in the electret-based unsteady thermal energy harvester to improve the temperature sensitivity and fast-response to temperature variation.

2. Working Principle

The basic working principle of electret-based unsteady thermal harvester using liquid crystal is shown in figure 1a, where the electret, the liquid crystal cell and the external load are connected in series. The electret serves as the permanent voltage source. There will be induced charge in both the electret capacitor $C_e$ and the temperature-sensitive capacitor $C(t)$. Figure 1b depicts the phase change of the nematic liquid crystal from the nematic to isotropic phase over the clearing temperature $T_{NI}$. Temperature variation of surrounding environment around liquid crystal’s clearing temperature will lead to the permittivity change from phase change. The permittivity change during the phase transition
can be utilized as the source of thermal-to-electrical energy conversion. The induced charge of capacitor will be redistributed as the result of capacitance change and output power can be obtained. Compared with our previous model based on KTN [6], the leakage current through the temperature-sensitive dielectric cannot be neglected due to the limited resistivity of liquid crystal. As shown in figure 1c, the liquid crystal cell can be modeled with the dielectric and the resistor. Based on the Kirchhoff’s law, and the charge conservation, we get

\begin{align}
V_{lc} &= I_{leak}R_{ln}, V_E = I_{load}R_{load}, \\
I_{total} &= I_{load} + I_{leak}, \\
\Delta Q_{lc} &= \int I_{load}dt, \Delta Q_E = \int I_{load}dt,
\end{align}

where the $V_{lc}$ and $R_{ln}$ are the voltage and internal resistance of the liquid crystal cell. $V_E$ and $R_{load}$ are the voltage and resistance of the external load, while $Q_{lc}$ and $Q_E$ are the induced charge of liquid crystal capacitor and electret. $I_{total}$, $I_{load}$ and $I_{leak}$ are the current of liquid crystal capacitor, external load and internal resistance, respectively. Output voltage can be estimated based on this model.

In order to reduce energy loss by the leakage current, liquid crystal with high resistivity is required. Fluorination of liquid crystal has been reported as a sufficient method to increase the resistivity and to maintain the anisotropic permittivity [7]. Compared with commonly-used nematic liquid crystal such as 5CB, BCH-5F.F.F is a typical fluorinated liquid crystal with low polarizability and high polarity, which result in high resistivity and high anisotropic permittivity. The detailed dielectric property will be discussed in the next section.

![Figure 1. a) Working principle of electret-based thermal energy harvester, b) Circuit model of unsteady harvester considering the leakage current of liquid crystal.](image1.png)

![Figure 2. a,b) Photo and structure of liquid crystal cell used in the current study. c) Setup for power generation experiment.](image2.png)
3. Material Characterization and Experimental Results

As shown in figures 2ab, a cell with a 6 mm x 6 mm ITO electrode area and with a 5 μm gap is used for both material characterization and power generation experiments. Detailed experiment setup is shown in figure 3c. A light bulb is used to heat up the liquid crystal cell. In this report, the electret is replaced with a ceramic capacitor with a priming voltage for preliminary experiments. The components are firstly connected in series, and then the liquid crystal cell is heated up. The temperature information and the output voltage of the external load are recorded via a data logger. An impedance analyzer from Solartron is used to precisely measure the impedance of the liquid crystal cell. It is found that the volume resistivity of BCH-5F.F.F at around 26 °C is $7.4 \times 10^9$  $\Omega \cdot m$. Since the resistivity of 5CB is around $3 \times 10^7$  $\Omega \cdot m$, BCH-5F.F.F has 250 times higher resistivity than 5CB.

The transverse and axial permittivities of BCH-5F.F.F at different temperatures from 25 – 60 °C are measured by using a liquid crystal cell with homeotropic alignment. The permittivity measured with low AC voltage (0.5 $V_{\text{RMS}}$) corresponds to the transverse permittivity, while, with high AC voltage (20 $V_{\text{RMS}}$ = 4 $V_{\text{RMS}}$/μm), the liquid crystals should be aligned perpendicularly to the substrate, so that the axial permittivity is measured. As shown in figure 3, the axial permittivity is as large as 13 at 25 °C, and decreased with increasing temperature. The clearing temperature where phase transition occurred is around 56 °C.

In the present study, the priming voltage of ceramic capacitor is chosen as 50 V. The external load is 810 MΩ. Figure 4 shows the permittivity change of BCH-5F.F.F when heated up with the lamp during power generation experiment. It is found that the permittivity drops at around 50 s when the liquid crystal phase changes from nematic to isotropic.

Figure 5 shows the output voltage for different capacitances of the ceramic capacitor. As the temperature of liquid crystal increases, voltage increases due to decreasing internal resistance, and clear positive voltage peak around 50 s is observed as the result of steep permittivity change during the phase transition of BCH-5F.F.F. Then, the voltage drop follows because of the charge dissipation. Also, higher voltage output can be found for the higher initial charge with higher capacitance. For the capacitance of 4.7 nF, voltage peak around 2.3 V is obtained during heating. Based on the experimental results, we can verify the electrostatic working mechanism utilizing permittivity change of liquid crystal phase transition.

![Figure 3. Permittivity change for both transverse and axial direction for 25-60 °C.](image1.png)

![Figure 4. Permittivity and temperature change of liquid crystal cell during heating in experimental setup.](image2.png)
Figure 6 shows comparison between the experimental data and the simulation results for $C_{\text{char}}=4.7\text{nF}$. The simulation results especially the positive voltage peak during the phase transition are in good accordance with the experimental data. The shift of leakage peak around 100 s between simulation and experimental is possibly from the measurement error of resistance of liquid crystal cell.

Based on the results above, it is found that, even with BCH-5F.F.F, the leakage current is still a dominant part of the current generated from the temperature variation; the priming charges are leaked out through the liquid crystal layer. Figure 7a shows the output voltage for higher internal resistance of the liquid crystal cell. With increasing internal resistance, the negative output voltage due to the leakage current decreases dramatically, and the positive voltage peak increases. As shown in figure 7b, maximum of 23 nJ can be expected during one heating cycle when the internal resistance is as large as 100 GΩ.
4. Conclusion
A novel electret-based unsteady thermal energy harvester using nematic liquid crystal is proposed for the first time. Fluorinated nematic liquid crystal BCH-5F.F.F is chosen as the temperature-sensitive permittivity material with high resistivity. Output voltage by the temperature fluctuations is examined and compared with an effective circuit mode. A sharp output current peak is observed, while the leakage current is still dominant. Much higher internal resistance is needed to reduce the energy loss. Maximum of 23 nJ can be expected with a liquid crystal with 100 GΩ internal resistance.

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