Characterization of fluorinated nematic liquid crystal for high-power electrostatic energy harvester

K. Kittipaisalsilp\textsuperscript{a1}, T. Kato\textsuperscript{2}, and Y. Suzuki\textsuperscript{1}

\textsuperscript{1}Department of Mechanical Engineering, The University of Tokyo, Japan
\textsuperscript{2}Department of Chemistry and Biotechnology, The University of Tokyo, Japan

Email: kasidis@mesl.t.u-tokyo.ac.jp

Abstract. The use of fluorinated nematic liquid crystal (NLC) as the medium in between the stator and the rotor of electrostatic vibration energy harvester is proposed for output power enhancement. Fluorine terminal group of 3,4,5-Trifluoro-4’-(trans-4-pentylcyclohexyl)-1,1’-biphenyl (BCH-5F.F.F) offers high resistivity that is two-order-of-magnitude higher than that of 5CB used in our previously study. In a power generation experiment, output power as high as 490 µW is obtained at 10 Hz and 1.00 mm\textsuperscript{peak-peak} vibration, while keeping the leakage current as low as a few µA.

1. Introduction

Energy harvesting \cite{1, 2} attracts much attention for powering low-power-consumption electronics. Electrostatic/electret vibration energy harvester (EH) has good compatibility with MEMS technologies, and is advantageous in power generation under low vibration frequencies and in small dimensions \cite{2-4}. However, the output power is very sensitive to the parasitic capacitance ($C_p$) between interdigitated electrodes, and its reduction is crucial for the electrostatic/electret EH \cite{5-7}.

Chen et al. \cite{7} propose a model of $C_p$ for current-collector electrodes, and demonstrate improvement of the output power by using a MEMS-based suspended electrode structure with low effective permittivity of the substrate. In general, $C_p$ consists of 2 parts; the capacitance through the substrate (permittivity: $\varepsilon_j$) and through the dielectric in the gap (permittivity: $\varepsilon_2$) as shown in Figure 1. When a high permittivity fluid is filled inside the gap between the rotor and the stator, the vertical permittivity ($\varepsilon_{||}$) is increased, so that the capacitance change during the vibration is increased. However, with isotropic permittivity material ($\varepsilon_{||} = \varepsilon_L$), $C_p$ also becomes large, which leads to deterioration of the output power. To address this issue, we previously proposed the use of nematic liquid crystal (LC) with positive anisotropic permittivity ($\Delta \varepsilon = \varepsilon_{||} - \varepsilon_L > 0$) \cite{8}. Figure 2 shows the concept of liquid-crystal-enhanced electrostatic generator. The rod-shaped molecules filling the gap between the rotor and the stator align its longitudinal axis parallel with electric field. With high $\varepsilon_{||}$ and low $\varepsilon_L$, the output power is much increased, while the increase of $C_p$ is suppressed. We demonstrated this concept using conventional nematic LC (4-Cyano-4’-pentylbiphenyl, 5CB). However, 5CB has large amount of ionic impurities as high as $10^{14}$ cm\textsuperscript{3} \cite{9}, such that the resistivity tends to be low and the leakage current is very large. This makes it very difficult to obtain repeatable experimental data.
To reduce the leakage current, nematic LC with high resistivity and reasonable anisotropic permittivity is needed. According to Hard [10] and Kirsch [11], fluorine substituent in LC molecule modifies the LC properties depending on the number of substituents and their location such as, the melting point, the mesophase range, the anisotropic permittivity, and the resistivity. In addition, fluorine has the highest electronegativity among elements in periodic table, making high polarity for C-F bonds. In the present study, we propose fluorinated NLC as a new anisotropic permittivity liquid for power enhancement of electrostatic energy harvesters.

2. Fluorinated Nematic Liquid Crystal

In this study, we employ 3,4,5-Trifluoro-4’-(trans-4-pentylcyclohexyl)-1-1’-biphenyl (BCH-5F.F.F, Ark Pharm) as the representative of fluorinated NLC. Figure 3 shows the molecular structures of 5CB used in our previous study, and BCH-5F.F.F. The major difference between these two NLC is their terminal groups. Dipole moment by the cyano substituent (C≡N) in 5CB exhibits high polarity and high polarizability. On the other hand, three fluoro substituents at the end of aromatic rings in BCH-5F.F.F exhibits low polarizability, while maintaining high polarity. High polarity ensures the anisotropic permittivity. Polarizability describes the ease of electron cloud distortion by external influences. In other words, lower polarizability confers higher resistivity [10-11]. The resistivity of BCH-5F.F.F in our impedance measurement is $7.4 \times 10^9 \text{\Omega m}$, which is two-order-of-magnitude higher than that of 5CB ($1.3 \times 10^7 \text{\Omega m}$).

![Figure 1. Schematic diagram of electrostatic energy harvester and origin of parasitic capacitance.](image)

![Figure 2. Concept of liquid-crystal-enhanced electrostatic energy harvester.](image)

![Figure 3. Molecular structures of (a) 5CB, and (b) BCH-5F.F.F.](image)

![Figure 4. Comparison of relative permittivity between 5CB and BCH-5F.F.F as a function of temperature.](image)
Figure 4 shows the comparison of relative permittivity as a function of temperature. A glass cell with a 5 μm gap is used, and the permittivity is measured at 1 kHz. For both NLCs, the horizontal alignment is used, and the transverse permittivity $\varepsilon_{\perp}$ is measured with a low applied AC voltage. When the applied AC field is higher than 2 V/μm, the orientation of NLCs is changed from horizontal to vertical, so that the axial permittivity $\varepsilon_{||}$ can be measured. Although the axial permittivity $\varepsilon_{||}$ of BCH-5F.F.F is lower than that of 5CB, its $\varepsilon_{\perp}$ is also lower. Thus, the ratio of $\varepsilon_{||}/\varepsilon_{\perp}$ is 3 in both NLCs. The nematic range of BCH-5F.F.F is 29 – 56 °C, which is wider than that of 5CB (22 - 34°C), leading to wider operation temperature range of liquid-crystal-enhanced electrostatic energy harvester.

3. Power Generation Experiment Setup
The experimental setup for power generation experiments can be found in Ref. [8]. The interdigitated Cr/Au electrode was patterned on a Tempax substrate using MEMS technologies. The width of a pair of electrode fingers is 0.5 mm with the interdigitated gap of 0.05 mm. The electrode area is 20 mm $\times$ 20 mm. Figure 5a shows the finished substrates with the interdigitated Cr/Au electrodes.

Schematic of the experimental setup and its photo are shown in Figure 5b and 5c, respectively. Briefly, two substrates with the interdigitated electrodes are set in parallel on the top and the bottom stages with the gap of 100 μm. The top electrode is connected to a source meter unit (2410, Keithley) for the bias voltage of -400 V, while the bottom one is connected to an external load. The vibration frequency and amplitude are 10 Hz and 1.00 mm peak-peak, respectively. BCH-5F.F.F is filled in the dielectric gap with an estimated amount of 40 μL, and its temperature is kept at around 32 °C. The leakage current with BCH-5F.F.F is as low as 6 μA, which is much lower than that for 5CB.

To avoid an unwanted effect of the parasitic capacitance of the read-out circuit, the output current is connected to a programmable current amplifier (CA 5350, NF) through an external load, by which the current is converted to a DC voltage with the gain of $10^6$ V/A. Then, the output voltage is measured and the data are stored by a data logger unit (NR-600, Keyence).

![Image](image-url)

Figure 5. (a) Microfabricated Cr/Au interdigitated electrode on Tempax glass, (b) Schematic diagram of experimental setup for power generation, and (c) photo of the setup.

4. Experimental Results
Figure 6 shows the output voltage waveforms at optimal load resistance of the air and the fluorinated-NLC-filled gap. The number of positive and negative peaks corresponds to number of times that top and bottom electrodes fully overlap with each other in one oscillation period. The peak-to-peak voltage for BCH-5F.F.F reaches 210 V, which is much higher than that of the air gap (50 V peak-peak). The output power versus the load resistance is shown in Figure 7. For the air gap, the optimal load is 35 MΩ, and the maximum output power $P_{\text{max}}$ at the matched impedance is 4.98 μW. On the other hand, for the BCH-5F.F.F-filled gap, $P_{\text{max}}$ is as high as 490 μW at 7 MΩ, which corresponds to 100 times higher output power compared to that of the air gap.
5. Conclusion
In this paper, we have proposed the use of fluorinated NLC for liquid-crystal-enhanced electrostatic energy harvester, which has higher resistivity than conventional NLC with cyano terminal. With BCH-5F.F.F, which has wide temperature range of the liquid crystal phase, the resistivity has been increased by 570 times if compared with 5CB. On the other hand, the ratio between the permittivities in the two orthogonal directions is almost the same at around 3. In preliminary vibration power generation experiment, the output power has been increased by 100 times ($P_{\text{max}} = 490 \mu W$) compared with the device with an air gap.

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References
[1] S. Roundy, P. K. Wright, and J. Rabaey, “A study of low level vibration as power source for wireless sensor nodes,” Comput. Commun., vol. 26, pp. 1131-1144 (2003).
[2] Y. Suzuki, “Recent progress in MEMS electret generator for energy harvesting,” IEEJ Trans. Electr. Electron. Eng., vol.6, pp 101-111 (2011).
[3] C.P. Le, and E. Halvorsen, “MEMS electrostatic energy harvesters with end-stop effects,” J. Micromech. Microeng., vol. 22, 074013 (2012).
[4] P. Basset et al., “Electrostatic vibration energy harvester with combined effect of electrical nonlinearities and mechanical input,” J. Micromech. Microeng., vol. 24, 035001 (2014).
[5] T. Masaki et al., “Power output enhancement of a vibration-driven electret generator for wireless sensor applications,” J. Micromech. Microeng., vol. 21, 104004 (2011).
[6] U. Bartsch et al., “Influence of parasitic capacitances on the power output of electret-based energy harvesting generators,” Power MEMS 2009, Washington DC, pp. 332-335 (2009).
[7] R. Chen, and Y. Suzuki, “Suspended electrode for reducing parasitic capacitance in electret energy harvesters,” J. Micromech. Microeng., vol. 23, 125015 (2013).
[8] K. Kittipaisalsilpa, T. Kato, and Y. Suzuki, “Liquid-crystal-enhanced electrostatic vibration generator,” IEEE MEMS 2016, Shanghai, pp. 37-40 (2016).
[9] H. Mada, and M. Ryuzaki, “Ion influence on nematic liquid crystal cell impedance at low frequency,” Jpn. J. Appl. Phys., vol. 34, pp. 1134-1136 (1995).
[10] M. Hard, “Fluorinated liquid crystals – properties and applications,” Chem. Soc. Rev., vol. 36, pp. 2070-2095 (2007).
[11] R. Kirsch, “Fluorine in liquid crystal design for display applications,” J. Fluorine Chem., vol. 177, pp. 29-36 (2015).