

3D PRINTED PYROELECTRIC LITHIUM-NIOBATE HIGH VOLTAGES SOURCE WITH PULL-IN REGULATED OUTPUT

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ABSTRACT

In this paper, a high voltage source (output voltage 1.03 kV), with low system mass density and compact size is realized for micro-robotics using 3D printed conductive polylactic acid (CPLA) polymer. The device includes both the resistive heater and an electrostatically actuated cantilever switch in tight integration with a pyroelectric crystal. A lithium niobate crystal is embedded within the heater to generate high voltages using the pyroelectric effect and the electrostatic actuator transfers this voltage at its pull-in voltage. The low density of CPLA material and the ability to integrate the voltage source and pull-in cantilever switch in the same material can potentially enable fast design capability for battery driven autonomous micro-robotics.

KEYWORDS

Pyroelectricity, high voltage supply, pull-in actuator, 3D printing electronics

INTRODUCTION

The current micro-robotics research has been limited in robot mobility as depending mostly on tethered actuation owing to a lack of small high-density power sources. Miniaturized high-voltage power suppliers are needed for micro-robotics that utilize actuators that require high voltages. Examples of such actuators include Dielectric Electrostatic Actuators (DEA) and piezoelectric actuators, to achieve high mechanical energy densities [1], [2], which limits its applications in more intelligent and complex tasks. In order to maximize mission time on a size limited micro-robot, the size, weight, and power of the power source should be minimized. As the robot dimension scales down, energy storage, delivery, and control have been hard to scale down.

The primary challenge for both DEA and piezoelectric actuators is the required high driving voltage (10s of kV) for sufficient force and displacement output. Most commercial kV supplies consist of switch-mode circuits that boost voltages using inductors [3], [4]. Researchers have developed variants of flyback converters [5], [6] which can boost voltage from 10sV up to a few kV. However, the sizes of these converters are over 1cc owing to the size of discrete components and the limit of magnetic energy volume needed to store magnetic energy in the inductors used. While there are many approaches to miniaturize such systems using CMOS electronics, getting to 2-3kV in a compact <2-3mm³ system remains a challenge due to space and weight inductors and capacitors need. Researchers in Ref. [7] developed a dual-stage flyback converter for Robobee piezoelectric actuators, which shrunk the size down to an area of 5 x 5 mm² and had a maximum output voltage of 200V. However,

implementing voltage in the kV range on this design would require larger storage capacitors and inductors and thus larger size and weight. Besides, the efficiency of the flyback conversion is highly dependent on the driving loads and switching frequency. In the case of driving capacitive loads, the active power is only during charging and discharging period, and the convertor is mostly operated at the low load, low-efficiency mode.

Pyroelectricity can generate very high voltages across a crystal within a few mm³ with low input voltage to a resistor that heats the pyroelectric material [9]. The restively heated pyroelectric crystal architecture holds the promise of building a miniaturized HV supply. The voltage generation is due to the atomic dipole realignment when temperature change happens [8]. Crystals can be connected in series to increase the output voltage or in parallel to drive bigger loads. One challenge is to be able to gate the high voltages to the transducers. If using transistors, one has to content challenges with the on-stage resistance, and the energy required at the gate capacitance to gate very high voltage transistors. Here we use an electrostatically triggered cantilever switch to deliver high voltages to the load. The gating capacitance is an air/vacuum capacitance which is small, and the on-stage resistance can be low as the switch can be made of a metallic material with very low series resistance. While pyroelectric conversion tends to suffer from low efficiency, in applications where actuation is required even with low efficiency this mode of operation can be useful. Furthermore, by using more complex conversion cycles, one can increase pyroelectric conversion cycles.

Though the generation of over 1kV voltage from a pyroelectric crystal LiNbO₃ has been demonstrated earlier [9], previous efforts suffered from reduced heating efficiencies, large size, and the time-consuming fabrication. Inconsistent heating coverage could limit the final output voltage and lower the efficiency of the generator. As the crystal is partially heated, the polarization is only changed locally at which temperature variance happens, while the pyroelectric charge generated electric field is shared across the whole crystal. Hence, the non-heated part serves as a parasitic capacitive load.

In order to achieve uniform heating and reducing the device size, the 3D printing technique is used to obtain better thermal coverage and a facile integration of the cantilever switch. 3D printing leads to fast, flexible and low-cost fabrication allowing fast prototypes and enabling complex packages that can fit inside robots with different power subs-system dimension requirements. 3D printing combines the CPLA has been used for electronics applications like the prototype mechanical switch for 10s of volts modulation [10]. Circuit components such as resistors, capacitors, and inductors were also implemented

by injecting metal liquid inside 3D printed supporting structures [11]. However, the assembled structure with different electronic components in one print has not been reported. In this paper, a pyroelectric high voltage supply assembled with a 3D printed heater and mechanical switch is presented. We show the assembly of different electronic components in one print for the first time, which provides a path towards miniaturized HV generator fabrication and assembly.

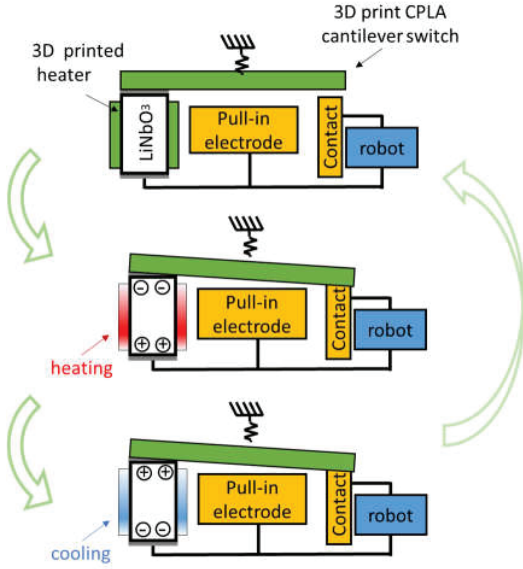


Figure 1: One operating cycle of the high voltage generation using pyroelectric LiNbO₃. When crystal is heated, a negative voltage is generated during the heating stage, which is transferred through the cantilever and actuate the robot. During the cooling stage, a positive high voltage is generated, and the robot gets actuated again.

PYROELECTRIC HV GENERATOR

Pyroelectric crystals generate a voltage when experiencing temperature change, owing to generation of dipole change per unit cell. For an unclamped pyroelectric material, the expression of generated pyroelectric charge and voltage, and the amount of energy stored on the crystal are dependent on the pyroelectric coefficient and the dielectric constant. The charge developed across a pyroelectric crystal of height h and area A with a ΔT change in temperature is

$$Q = pA\Delta T \quad (1)$$

where p is the pyroelectric coefficient (Coulombs/m²K). Since the voltage follows $Q = CV$, and $C = \frac{\epsilon_0\epsilon_r A}{h}$, the voltage across the device is

$$\Delta V = \frac{Q}{C} = \frac{ph\Delta T}{\epsilon_0\epsilon_r} \quad (2)$$

The stored electrical energy is

$$U_E = \frac{1}{2}C(\Delta V)^2 = \frac{1}{2}\left(\frac{\epsilon_0\epsilon_r A}{h}\right)\left(\frac{ph\Delta T}{\epsilon_0\epsilon_r}\right)^2 = \frac{1}{2}\frac{p^2 h A \Delta T^2}{\epsilon_0\epsilon_r} \quad (3)$$

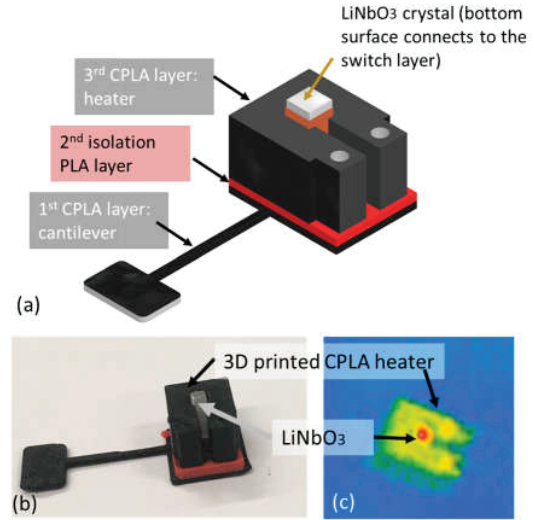


Figure 2: (a) CAD design of the assembled device. (b) The HV pyroelectric generator with heater and cantilever switch fabricated in one print. (c) Thermal profile of the device measured with an IR camera.

The equation above shows that the stored energy is a quadratic function of the pyroelectric coefficient and the change in temperature, while inversely proportional to the dielectric constant. In this paper, we used lithium niobate for its low dielectric constant, relatively high pyroelectric coefficient, a high transition Curie temperature, and high crystal quality. The crystal quality is a key reason behind highly repeatable voltage generation, which leads to high stored energy and small leakage current.

A schematic diagram of the working principle of the pyroelectric generator is shown in Fig. 1. A cantilever is connected to the top side of the crystal, with a common ground at the bottom of the crystal. The pyroelectric voltage is generated in both heating and cooling stages. When a low input voltage is applied to heat the resistive heater, temperature on the crystal rises ($\Delta T > 0$). The spontaneous polarization results in a negative high voltage built up across the crystal. Similarly, a positive voltage is generated when the input turns off and the crystal cools down. The cantilever switch can be electrostatically pulling down as the pyroelectric voltage goes beyond the pull-in voltage. In the case of providing power to actuate a high-voltage robotic actuator, just one cantilever is needed to deliver voltages to the actuator as MEMS switch pull-in with both positive and negative voltages. Hence, for the same amount of input thermal energy one can get twice the electrical energy calculated in equation (3), doubling the effective efficiency.

Figure 2 shows the design of the system and the printed device. An Ultimaker 3 3D printer with dual extrusion tool is used to print two materials in one print. The heater and the cantilever switch are printed using the conductive polylactic acid (CPLA, from Proto-Plant Inc.). To isolate these two electronic components, a nonconductive PLA layer is printed in between. A pyroelectric crystal (1.25x1.25x5mm Z-cut LiNbO₃) is embedded in the heater. The heater is designed in a C shape

to form a uniform contact between the resistor and the crystal. The uniform contact area results in a uniformly heated crystal with heat diffusing into the crystal. The thickness of the CPLA heater was chosen to result in a reasonable resistance that results in good power at a low voltage. A hole is left on the isolation layer for the embedded LiNbO₃ to pass through and make a physical connection with the cantilever switch. A thin layer of silver paste was applied in between the crystal and the CPLA switch to ensure electrical contact. The cantilever is designed to pull-in at kV range to utilize the high voltage generated by LiNbO₃. The conductivity of the printed material is 115ohm-cm and can be further reduced by using other carbon-nanotube doped PLA materials to get down to a value drivable with a 1.5V battery, although here we used a 25V supply. A FLIR T300 IR camera was used to monitor the transient temperature on both the heater and the pyroelectric crystal.

EXPERIMENTAL RESULTS

The prototype 3D-printed CPLA electronics components are tested individually first and then assembled and examined as a high voltage generator. The CPLA cantilever dimension and operation states are shown in Fig. 3a and Fig. 3b. The cantilever and drain electrode were printed separately in order to test the switch performance with respect to different gaps. Although a relatively large switch was printed in this prototype design, a smaller switch within a millimeter scale can be printed using Ultimaker 3. The existence of the air gap during OFF state (Fig. 3b) ensures the absolute isolation of source and drain. As a result, very little or no leakage current can flow into the drain. When the voltage applied on the cantilever reaches the pull-in voltage $V_{PI} = \sqrt{\frac{8kg_{air}^3}{27\epsilon_0 A_{overlap}}}$, the suspended source electrode is electrostatically pulled in towards the contact drain, generating a current path for robotics actuation. The pull-in performance as a function of gap is shown in Fig. 3(c). The spring constant k is calculated using model built in Ref. [9]. The measured pull-

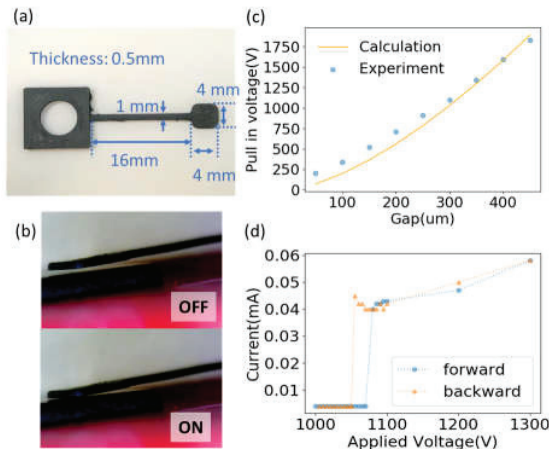


Figure 3: (a) A cantilever switch printed with CPLA. (b) Switch ON and OFF states. (c) Pull-in behavior as function of gaps (d) Switching performance of the mechanical switch. A 6.8MΩ resistor is connected in series to prevent large current.

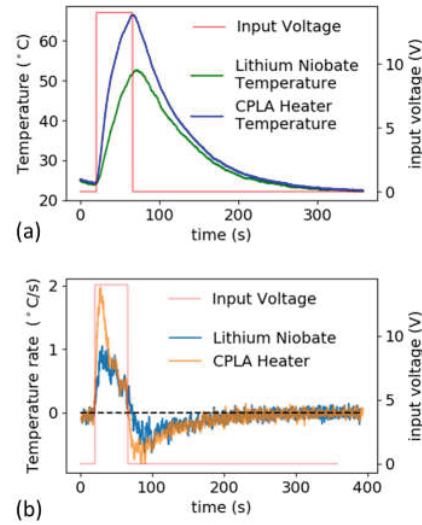


Figure 4: LiNbO₃ and the heater (a) transient temperature responses and (b) temperature changing rate.

in voltages lie close to the theoretical calculation. Discrepancies observed at small gaps is most likely due to the imperfect clamping of the cantilever at the base, and the nonlinear behavior of soft plastics. The disparity between measured and predicted pull-in voltages become smaller when gaps increase and can be ignored at $V_{PI} = 1-2kV$ range. The repeatability of the printed switch is shown in Fig. 3d by testing the pull-in voltage with fixed gap at 300μm. The abrupt switching is observed for both forward and backward curves, indicating good switch performance and low leakage current. The pull-in voltage for forward curve is 30V higher than the backward curve, which could be caused by the softening of the cantilever material.

Characterization of the CPLA heater is shown in Fig. 4. A 30s input pulse with voltage 14V was applied to the CPLA heater. The temperature responses of the heater and the crystal embedded inside were monitored by the IR camera (Fig. 4a, sampling rate 6.4Hz). The changing rate of the temperature is plotted in Fig. 4b with a rolling average of 30 samples averaged together. As the current drive of the heater is on, the temperature change follows the logarithmic growth on both the heater and the crystal. A temperature change rate of 1°C/s is reached on LiNbO₃ after being heated for 7s. After which the heat on the crystal begins to saturate and the changing rate starts decreasing. After the input is off, the temperature on the heater drops immediately, while the crystal keeps being heated up for 6s until the temperature change rate falls under zero. The delayed reaction is caused by the bulk design of the heater used in this prototype, mainly limited by the low conductivity of the material. By using a highly carbon doped PLA, a much thinner heater wall can be implemented and a faster response is expected.

In Fig. 5, we show the combined voltage generation and switch system, along with the actuation performance. The testing circuit is plotted in Fig. 5a. A power supply is used to supply the input voltage to the CPLA heater. The surface of the pyroelectric crystal is electrically connected

to the CPLA switch. The gap of the switch is fixed at $280\text{ }\mu\text{m}$, corresponding to a pull-in voltage of 1030V . Output currents from the switch are fed into an SR570 current amplifier to record the contact events. For the LiNbO_3 crystal used, $E = \frac{1}{2} CV^2 = 44\text{ nJ}$ of energy is stored on LiNbO_3 when pull-in happens. In Fig. 5b, a 25V input is applied to the heater, and the thermal and electrical response of the system is plotted as a function of time. The output from the TIA shows multiple contacts at pull-in. In practice no stiction was observed even after 10+ switching events. Different voltage polarizations are observed during heating and cooling session. Multiple actuation can be realized by connecting several crystals in parallel.

Currently the crystal has been heated up from room temperature to $50+^\circ\text{C}$ and experienced a temperature change of $\sim 25^\circ\text{C}$. The needed temperature change for actuation can be reduced by further optimization of the device to reduce heat lost to the environment and electrically isolating the crystal from the resistive heater. Furthermore, higher voltages can be realized by a serial connection of several crystals connected by the CPLA connectors that will provide both mechanical and electrical functions. The CPLA resistance will be further reduced to lower resistive losses by using carbon nanotube doped plastics, already available from several vendors. Furthermore, different pyroelectric materials will be explored to operate at more efficient pyroelectric cycles [12]. Lastly, the power system is to be integrated with soft robotic actuators, those made from non-3D printed

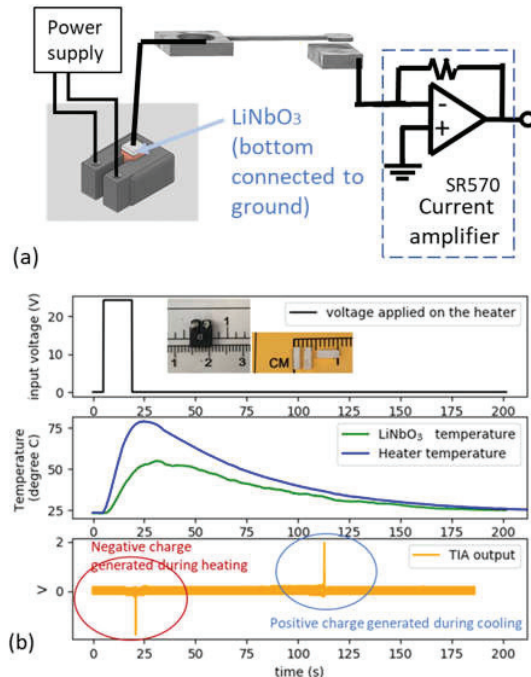


Figure 5: Combined voltage generation and switch system testing. (a) Experiment setup: The heater is connected to a power supply (Tektronix CPS250). After pull-in happens, pyroelectric charges are drained to the contact and are measured with a current amplifier (SR570). The pull-in voltage is set at 1030V . The sensitivity of the TIA is 5 nA/V . (b) The HV actuation performance with pyroelectric LiNbO_3 .

structures, and those made with 3D printing in the same process flow as the one used to make the HV generator and switch.

CONCLUSION

In this work, we report a 3D printable HV source utilizing the 3D printing technique and high voltage generation from pyroelectricity. By heating a LiNbO_3 crystal, voltages as high as 1.03 kV is generated with a temperature change of 25°C , and then delivered to a load using an electrostatically actuated switch. 3D printing was used to fabricate the heater and switch in one print, which enables flexible assembly design and simplifies the manufacturing process. The HV source developed has the advantages in low mass, compact size and fast fabrication, which shows promising applications in supplying power to micro robotics.

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REFERENCES

- [1] N. T. Jafferis *et al.*, "Untethered flight of an insect-sized flapping-wing microscale aerial vehicle," *Nature*, vol. 570, no. 7762, pp. 491–495, 2019.
- [2] E. Acome *et al.*, "Hydraulically amplified self-healing electrostatic actuators with muscle-like performance," *Science (80-.)*, vol. 359, no. 6371, pp. 61–65, 2018.
- [3] EMCO High Voltage Corporation
- [4] Pico Electronics, High Voltage DC-DC Converters
- [5] F. Zhang and Y. Yan, "Novel forward-flyback hybrid bidirectional DC-DC converter," *IEEE Trans. Ind. Electron.*, vol. 56, no. 5, pp. 1578–1584, 2009.
- [6] J. Elmes, C. Jourdan, O. Abdel-Rahman, and I. Batarseh, "High-voltage, high-power-density DC-DC converter for capacitor charging applications," *Conf. Proc. - IEEE Appl. Power Electron. Conf. Expo. - APEC*, pp. 433–439, 2009.
- [7] M. Karpelson, G. Y. Wei, and R. J. Wood, "Driving high voltage piezoelectric actuators in microrobotic applications," *Sensors Actuators, A Phys.*, vol. 176, pp. 78–89, 2012.
- [8] C. R. Bowen, J. Taylor, E. Le Boulbar, D. Zabek, A. Chauhan, and R. Vaish, "Pyroelectric materials and devices for energy harvesting applications," *Energy Environ. Sci.*, vol. 7, no. 12, pp. 3836–3856, 2014.
- [9] D. Ni, K. B. Vinayakumar, V. Pinrod, and A. Lal, "Multi Kilovolt Lithium Niobate Pyroelectric Cantilever Switched Power Supply," *Proc. IEEE Int. Conf. Micro Electro Mech. Syst.*, vol. 2019-January, no. January, pp. 970–973, 2019.
- [10] Y. Lee *et al.*, "Three-Dimensionally Printed Micro-electromechanical Switches," *ACS Appl. Mater. Interfaces*, vol. 10, no. 18, pp. 15841–15846, 2018.
- [11] S. Y. Wu, C. Yang, W. Hsu, and L. Lin, "3D-printed microelectronics for integrated circuitry and passive wireless sensors," *Microsystems Nanoeng.*, vol. 1, no. June, pp. 1–9, 2015.
- [12] Bowen, C.R. *et al.*, "Pyroelectric materials and devices for energy harvesting applications". *Energy & Environmental Science*, 7(12), pp. 3836-3856, 2014.

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