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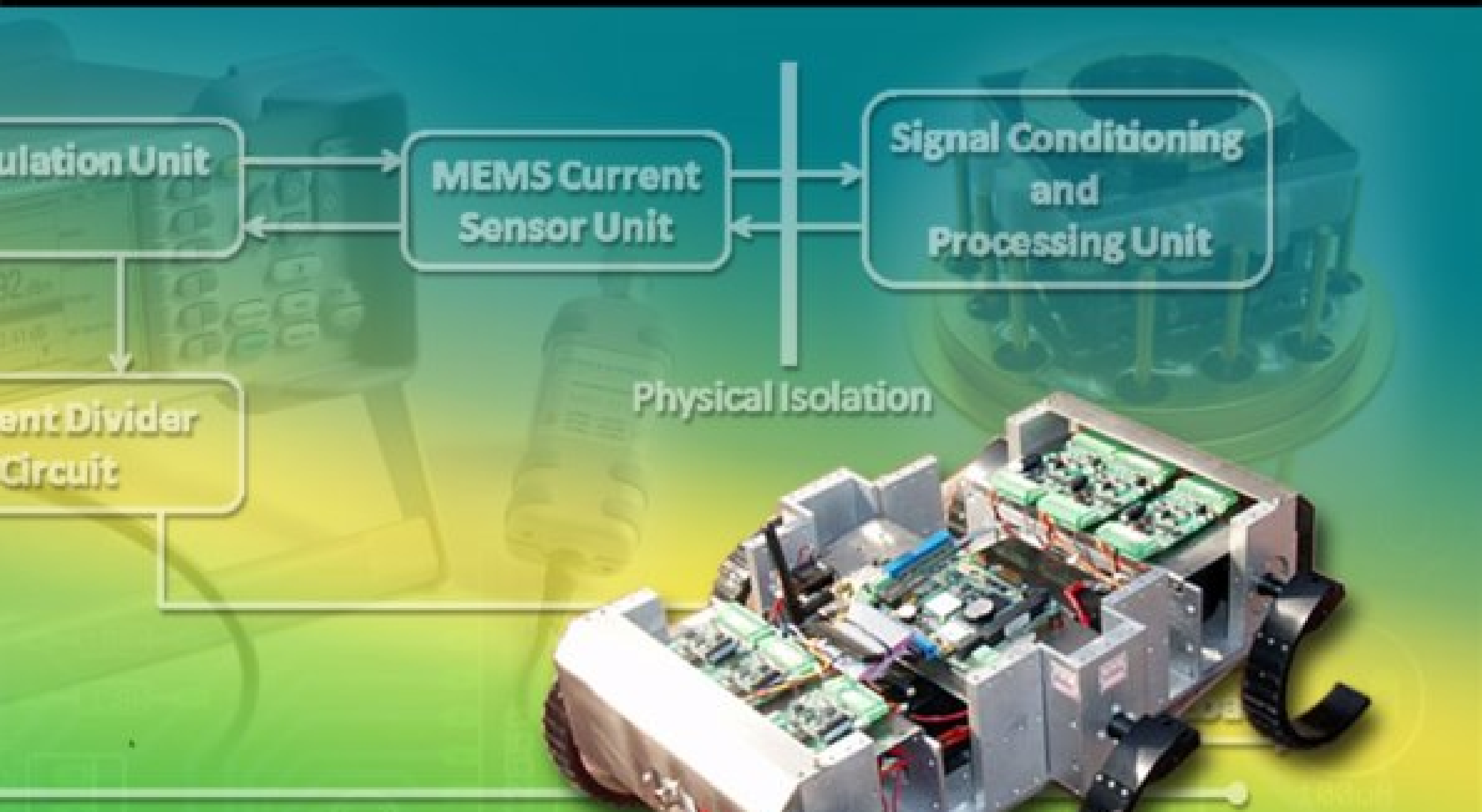

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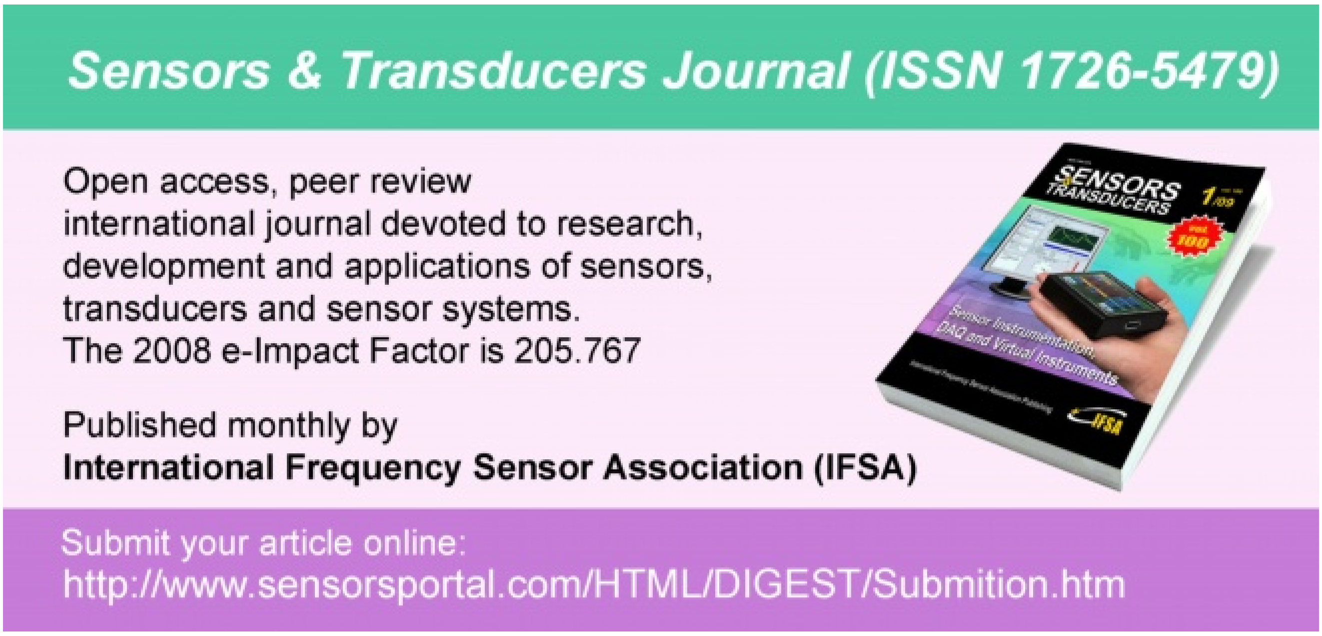
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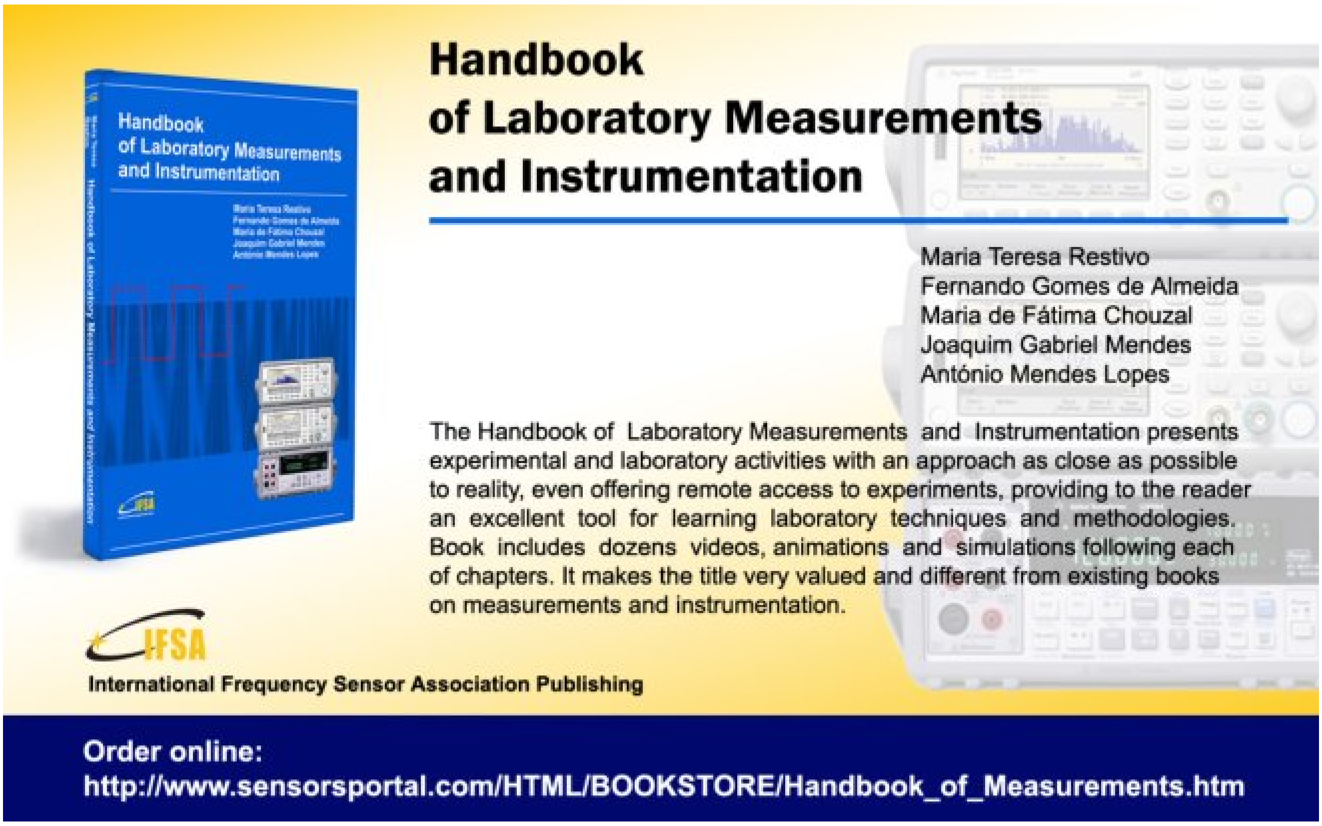
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Energy Harvesting Via Pyroelectric Transducer

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Abstract: Pyroelectric transducers offer a novel approach for directly converting temporal temperature fluctuations to electric current via production of charges on the surface of the element. It is basically a thermal-electric energy convertor. The pyroelectric lithium tantalite element was characterized for electrical parameters. The modeling and simulation of energy harvesting capacity with temperation variations were investigated. The results show that the harvested energy can be compatible with use in autonomous sensor module working in low-duty-cycle switched-supply mode.
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Keywords: Pyroelectric sensors, Energy harvesting, Modeling.

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1. Introduction

Energy harvesting or scavenging is a very attractive technique for a wide variety of self-powered micro-systems such as wireless sensors, biomedical implants, military monitoring devices, remote weather stations, structure-embedded instrumentation and other nano-devices [1]. Thermal energy in the environment is a potential source of energy for low-power electronics. Large amounts of heat is wasted at pulp and paper mills, steel works, petrochemical plants, glass manufacturers, automobile factories and electric power stations including automobiles. Pyroelctric effect is one of the possible techniques to directly converting heat into electricity [2]. Pyroelectric materials produce power from temporal temperature changes. Pyroelectric materials produce charges on the surface (thus generating voltage) when the temperature is varied over time. One major advantage of pyroelectrics over thermoelectric is that many pyroelectric materials are stable up to 1200 ºC or more, enabling energy harvesting from high temperature sources and thus increasing thermodynamic efficiency [3].

In the present work, high-temperature pyroelectric lithium tantalate was characterized for electrical properties. Lithium tantalate ($LiTaO_3$, abbreviated as LT) is an oxygen octahedral ferroelectrics (ABO_3) [4]. The neighboring oxygen octahedral is connected to each other through an oxygen ion that serves a common 'tie-end'. The symmetry of the crystal belongs to the point group 3m in the trigonal ferroelectric phase at room temperature. The symmetry changes to the point group 3/m in the paraelectric phase above Curie temperature. At room temperature, the lattice parameters of the trigonal unit cell is a = 5.4740Å, α = 56° 10'. Sometimes, it is more convenient to choose a hexagonal cell for description: with Li and Ta ions occupying two thirds of the octahedral interstices between the layers. LT also possesses a high melting point (1650 °C) and is insoluble in water. These factors make the material one of the most stable pyroelectrics with a very wide temperature range of operation. The robustness, good performance, and wide availability of this material make it a popular choice for commercial detectors including its ability to withstand high-energy infrared radiation with fast response time of 0.5ns [5]. It is generally used in single-crystal form, crystals being grown by the Czochralski method, and wafers of more than 50 mm diameter are commercially available.

Using the measured data, an effort was made to predict the voltage and power generated by using the known analytical methods [6]. An effort has also been made to examine, important parameters that affect power generation. A few unique concepts to further enhance the pyroelectric performance to increase the power output are also mentioned [7-9] via using pyroelectric materials with significantly higher pyroelctric coefficients.

2. Experimental

To fabricate a device as shown in Fig. 1, lithium niobate single crystal was polished down to 0.5 mm and area of 10 mm × 10 mm. After cleaning the sample, silver electrodes were coated on both sides of the element to form full-face electrodes. Finally, to make the samples functional, the electroded samples were poled at 100 ^{0}C with 75 kV/cm electric field for 1 hour and then cooled to room temperature with applied field. After the poling process the samples were short-circuited to remove any extrinsic charges on the sample. To perform the electrical measurements; to calculate dielectric constant, capacitance and at various temperature with an applied signal field of 10 V/cm at ac signal of 1 kHz were measured using QuadTech 7600 Precision LCR meter in a three terminal cell designed in our laboratory. All the measurements were taken during heating runs. The real part of dielectric constant (ε') was calculated by measuring parallel capacitance (C_p) as follows:

$$\varepsilon' = \frac{C_p d}{\varepsilon_0 A} , \tag{1}$$

where A is the electrode area (identical areas for the opposite electrodes were used in each sample), d is the thickness of the sample and $\varepsilon_0 = 8.854\times10^{-12}$ F/m is the permittivity of vacuum. To measure the dynamic relative pyroelectric current, direct method of Byer and Roundy was used [10]. The detailed measurement procedures of these parameters are described in our earlier publication [11]. The pyroelectric current I_p was also measured at various temperatures and the pyroelectric coefficients (p) were calculated using the relationship:

$$p = \left(\frac{I_p}{A}\right) / \left(\frac{dT}{dt}\right), \qquad (2)$$

where A is the electrode area and $\frac{dT}{dt}$ is the rate of change of temperature which was kept constant throughout the measurement. The details of both the automated set-ups are illustrated in Fig. 2.

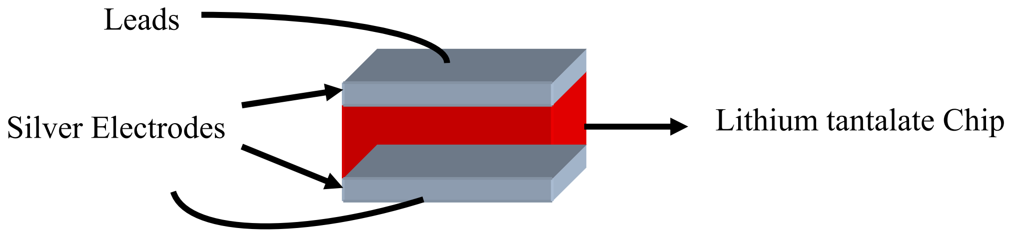

Fig. 1. Configuration of lithium tantalate-based energy harvesting device.

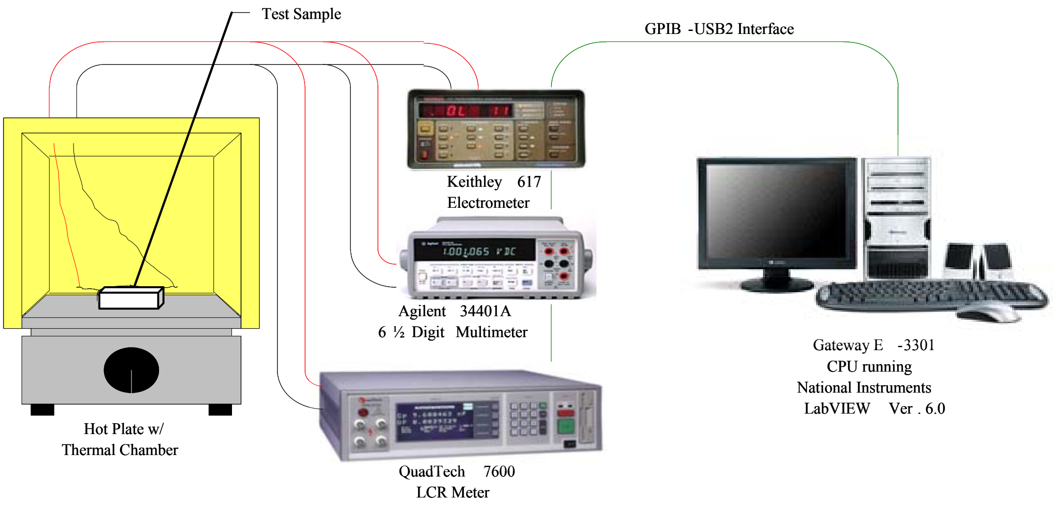

Fig. 2. Electric and pyroelectric measurement system.

An equivalent circuit diagram of a pyroelectric device is shown in Fig. 3 and utilized to model and analytically simulate so as to predict the voltage and power generated [12].

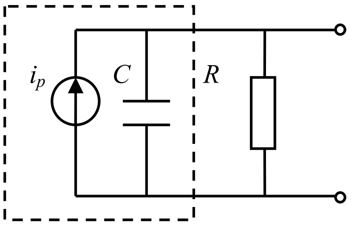

Fig. 3. Pyroelctric circuit diagram; i_p is the generated current, C is the capacitance of the pyroelectric chip and R is the external resistance.

3. Results and Discussion

3.1. Electrical Parameters

Fig. 4 and Fig. 5 show the dependence of capacitance (C) and pyroelectric coefficient (p) on temperature of LT element respectively. These parameters increase with increase of temperate as expected for pyroelectrics. In case of pyroelectric energy harvesting, the variation of electric induction is given by [12]:

$$dD = \frac{\partial D}{\partial \theta} d\theta + \frac{\partial D}{\partial E} dE, \tag{3}$$

where D is electric displacement, E is electric field and θ is the temperature.

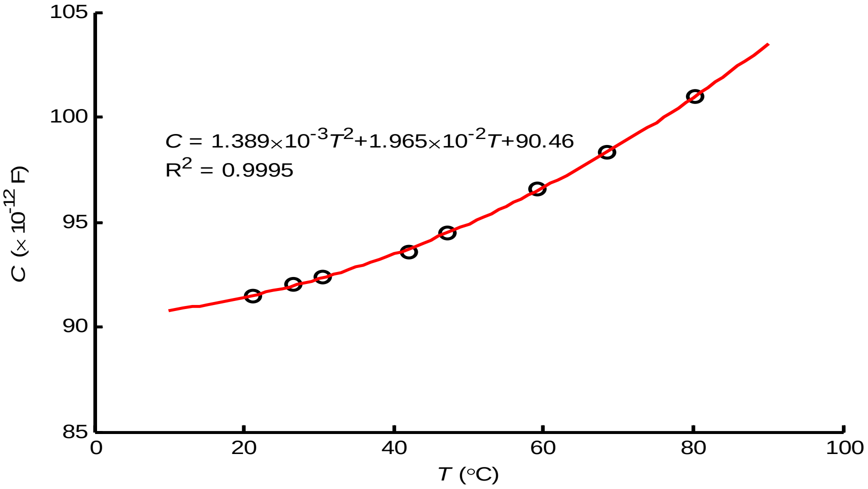

Fig. 4. Measured capacitance (*C*) versus temperature of the LT-based device.

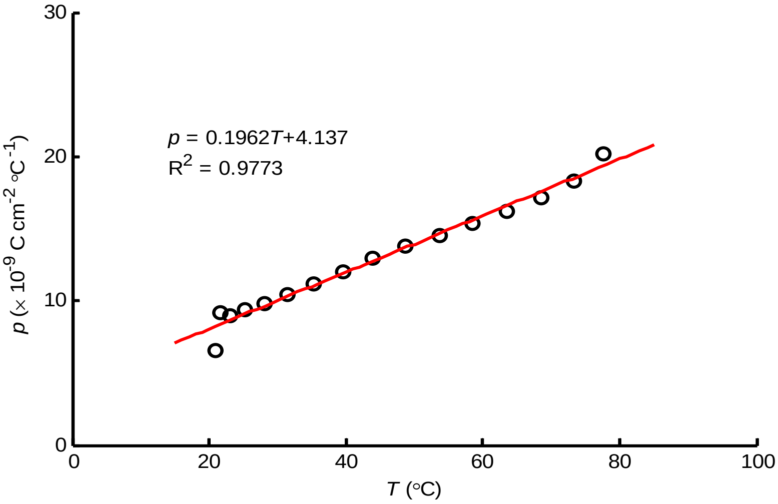

Fig. 5. Measured pyroelectric coefficient (*p*) versus temperature LT-based device.

We can replace derivative $\frac{\partial D}{\partial \theta}$ by p *(pyroelectric coefficient)* and $\frac{\partial D}{\partial E}$ by ε (relative permittivity, considering a linear behavior of pyroelectrics,

$$D = p\theta + \varepsilon E, \tag{4}$$

where D is the variation of the electric induction, θ is the variation of temperature around the working temperature, and E is the variation of electric field around a possible static field Eo. By optimizing the conditions such as resistance in the charge-storage circuit, we can define the harvested power per unit cycle per unit volume in the pyroelectrics as [13]:

$$P\max = \frac{p^2\theta^2}{2\pi\varepsilon}, \tag{5}$$

From Eq. (5), we can define a new pyroelectric Figure-of-Merit (FOM) for energy harvesting via electrocaloric effect as:

$$\frac{p^2}{\varepsilon}, \tag{6}$$

where p is the pyroelectric coefficient and ε is the relative permittivity. The extrapolated/predicted value of FOM up to 200 ºC is shown in Fig. 6. It increases with the increase of temperature (working temperature).

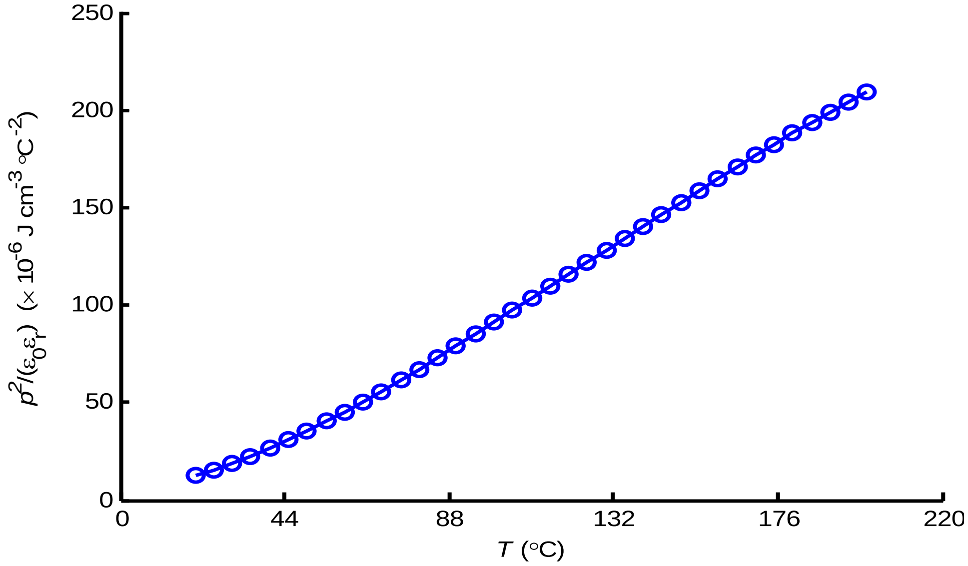

Fig. 6. Figure-of-Merit for energy harvesting of LT-based device obtained via 5 ^{o}C/sec heating rate from 20 ºC-200 ^{0}C.

It is evident that depending of the working temperature available, one can achieve FOM / efficiency of energy harvester accordingly.

3.2. Energy Harvesting Capacity through Modelling and Numerical Simulation

The pyroelectric current generator is modeled as current source with a capacitance and resistor in parallel with a current source (Fig. 3). The current is generated within an element with the change in temperature. The circuit in Fig. 3 can be modeled with the following first order differential equation:

$$C(T)\frac{dV}{dt}+\frac{V}{R}=i_p=p(T)A\frac{dT}{dt}\ , \tag{7}$$

where $C(T)$ is capacitance as a function of temperature, R is the resistance, V is voltage, i_p is pyroelectric current, A is cross sectional area of the sample, $\mathrm{d}T/\mathrm{d}t$ is temperature gradient and $p(T)$ is pyroelectric coefficient as a function of temperature.

This equation is then numerically solved with a given temperature profile using Runge-Kutta 4th order numerical integration technique as follows:

$$V_{i+1}=V_i+\frac{1}{6}\left(k_1+2k_2+2k_3+k_4\right)h \tag{8a}$$

$$\begin{gathered} k_1=f\left(t_i,V_i\right);\ k_2=f\left(t_i+\frac{1}{2}h,V_i+\frac{1}{2}k_1h\right);\ k_3=f\left(t_i+\frac{1}{2}h,V_i+\frac{1}{2}k_2h\right); \\ k_4=f\left(t_i+h,V_i+k_3h\right), \end{gathered} \tag{8b}$$

where, $f(t,V)=\frac{A}{C(T)}p(T)\frac{dT}{dt}-\frac{V}{RC(T)}$ and h = Δt is the step size. The capacitance and the pyroelectric coefficient as functions of temperature were obtained from the experiment and shown in Fig. 4 and Fig. 5 respectively. For the purpose of the simulation, the temperature is chosen as a linear function of time. At various time instances, the temperature is calculated and the corresponding values of p and C are obtained from Fig 4 and Fig. 5 respectively. The Eq. (7) is then numerically solved using Eq. (8). Fig. 7 shows the simulation results: the voltage and power generated as a function of time for R = 40 MΩ.

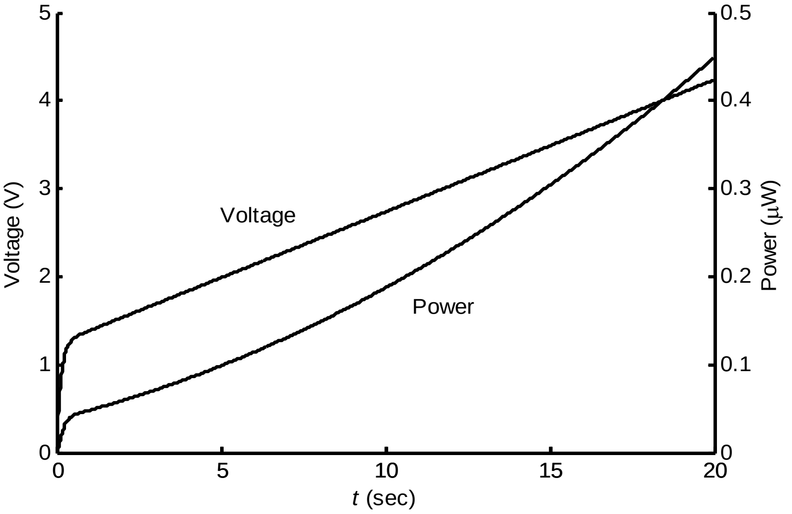

Fig. 7. Predicted (simulated) voltage and power generated versus time by LT-based device during heating at 5 °C/sec.

Utilizing propose model and analysis, it is possible to optimize the rate of heating and circuit resistance to obtain maximum power generation. In order to investigate the effect of heating rate of the device on the voltage generated, the variation of these parameters with time is depicted in Fig. 8.

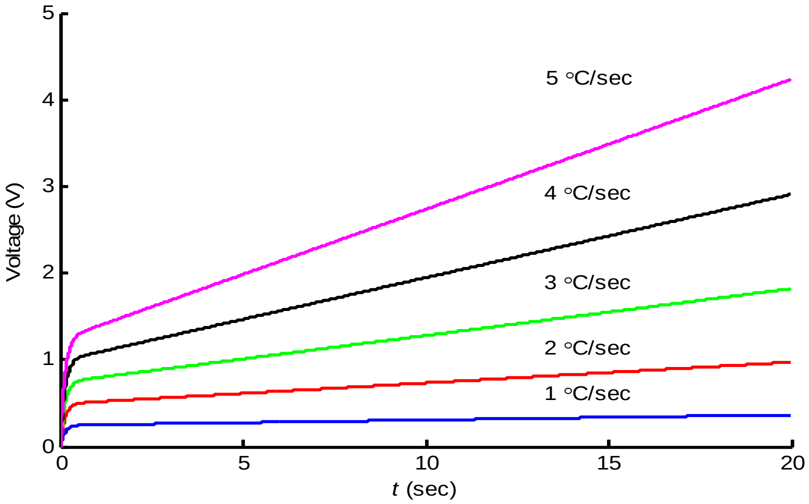

Fig. 8. Predicted (simulated) voltages generated as a function of time at different heating rates of the LT-based device.

Enhancing the voltage-generated in pyroelectric energy harvesters is still a main challenge via increasing the pyroelectric coefficients. Following unique techniques for enhancing the performance can be explored. It has been demonstrated by incorporation of these techniques, infrared detector responsivity can be increased many fold: i) by adopting Multilayer Structures/Bimorphs of pyroelectrics, Lang and Alexe showed that their response can be increased more than one hundred folds [7]; (ii) by fabricating compositionally graded structures, it has been shown that effective pyroelectric coefficient can increase by nearly two orders of magnitude than those observed from conventional pyroelectric thin-film devices [8]; (iii) by fabrication of porous films of PZT, it has been shown that performance increased by nearly four times; and (iv) by embedding silver nano-particles in pyroelectric composites: P(VDF-TrFE):$LiTaO_3$, Batra et al. have preliminary demonstrated vast increase in pyroelectric coefficient [9].

4. Conclusions

Pyroelectric device based on based on lithium tantalate (LT) was fabricated, characterized for relevant parameters, and simulated as thermal energy harvester via analytical modelling. It is evident that the power extracted from a pyroelectric element is typically low to guarantee a continuous operation for low-power autonomous sensors. It is proposed that the converted energy can be accumulated into a storage capacitance by proper power management techniques [14-15], and then transferred to the load during time intervals of short duration.

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