Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

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To cite this article: A.N. Smith *et al* 2016 *J. Phys.: Conf. Ser.* **773** 012102

TIMING A PULSED THIN FILM PYROELECTRIC GENERATOR FOR MAXIMUM POWER DENSITY

A.N. Smith[1,3] , B.M. Hanrahan[2], C.J. Neville[2] and N.R Jankowski[2]

[1]U.S. Naval Academy, Annapolis, Maryland, USA, 21402
[2]U.S. Army Research Laboratory, Adelphi, Maryland, USA, 20783

Abstract. Pyroelectric thermal-to-electric energy conversion is accomplished by a cyclic process of thermally-inducing polarization changes in the material under an applied electric field. The pyroelectric MEMS device investigated consisted of a thin film PZT capacitor with platinum bottom and iridium oxide top electrodes. Electric fields between 1-20 kV/cm with a 30% duty cycle and frequencies from 0.1 – 100 Hz were tested with a modulated continuous wave IR laser with a duty cycle of 20% creating temperature swings from 0.15 - 26 °C on the pyroelectric receiver. The net output power of the device was highly sensitive to the phase delay between the laser power and the applied electric field. A thermal model was developed to predict and explain the power loss associated with finite charge and discharge times. Excellent agreement was achieved between the theoretical model and the experiment results for the measured power density versus phase delay. Limitations on the charging and discharging rates result in reduced power and lower efficiency due to a reduced net work per cycle.

1. Introduction

Pyroelectric thermal-to-electric energy conversion is accomplished by a cyclic process of thermally-inducing polarization changes in the material under an applied electric field. The energy density of this process depends on the strength of the applied field and the amount of polarization change realized from a given temperature change, described by the pyroelectric coefficient of the material. High power density is achieved by frequent cycling, which is easy to realize with a low thermal mass, thin film active material. Only recently have these devices been operated at the frequencies required to produce reasonable power densities [1]. The synchronization of heating/charging becomes critical when thermodynamic cycles are realized on real systems [2]. In this work, we examine the timing of the various processes within the pyroelectric energy conversion (PEC) cycle in order to maximize the power density of a thin-film pyroelectric generator.

The PEC cycle consists of charging the pyroelectric film, heating the material under an applied field, discharging the material while hot, then cooling the material back to the original state (figure 1). There are variations in the specifics of these processes that will strongly influence cycle efficiency and energy densities. For example, the difference between an Ericsson and Brayton cycle is whether the charging processes are performed isothermally or adiabatically, respectively. It has been hypothesized that the Brayton cycle, which includes instantaneous adiabatic charging is ideal for thin film systems [3], while the Ericsson cycle is commonly accepted as the best cycle for bulk pyroelectrics [4-6]. Practically, there

[3] Corresponding Author <ansmith@usna.edu>

are resistive losses during the charge/discharge processes that scale deleteriously with cycle frequency and applied field. The charge/discharge losses will ultimately limit the rise time of the electric field, preventing the realization of an adiabatic processes and increasing the duty cycle of the electric field. The ideal duty cycle for both the heat addition and electric field is very short for two reasons (1) thermal losses continue during the heating event since the device remains in contact with the substrate and (2) leakage losses increase when the system is held charged [7].

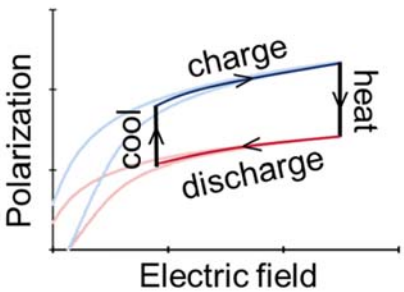


Figure 1. Pyroelectric energy conversion cycle where the enclosed area represents the energy density of the cycle.

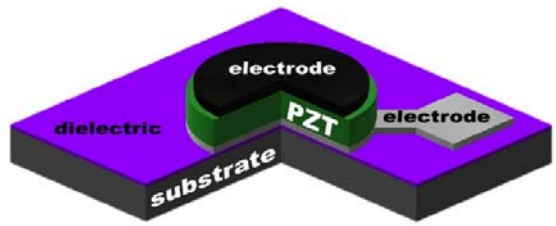


Figure 2. The pyroelectric MEMS device utilizing thin film 60:40 PZT capacitors with platinum (bottom) and IR-absorbing iridium oxide (top) electrodes.

2. Experimental Results

The pyroelectric MEMS device used in this investigation consisted of thin film lead zirconate titanate (PZT) with a 60:40 ratio of Zr:Ti cations in a capacitor structure with platinum bottom and iridium oxide top electrodes (figure 2). Figure 3 shows experimental data that illustrates the cycle timing, showing both the applied electric field responsible for charging and discharging the device along with the transient temperature response to the heating event. The temperature response is determined from the pyroelectric current where the pyroelectric coefficient has been independently measured.

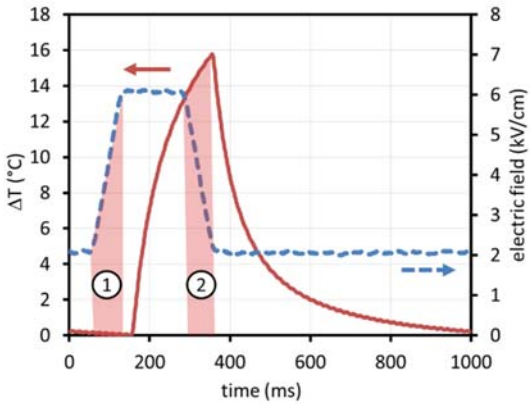


Figure 3. Electric field and temperature response of a 1 Hz pyroelectric energy conversion cycle. Regions 1 and 2 represent the times when the cycle deviates from ideal operation.

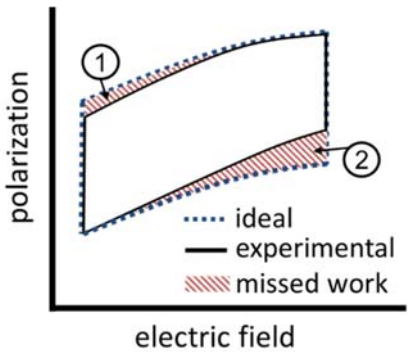


Figure 4. The time required for charging and discharging lowers the specific work of the cycle. Regions 1 and 2 represent deviations from ideal, also shown in figure 3.

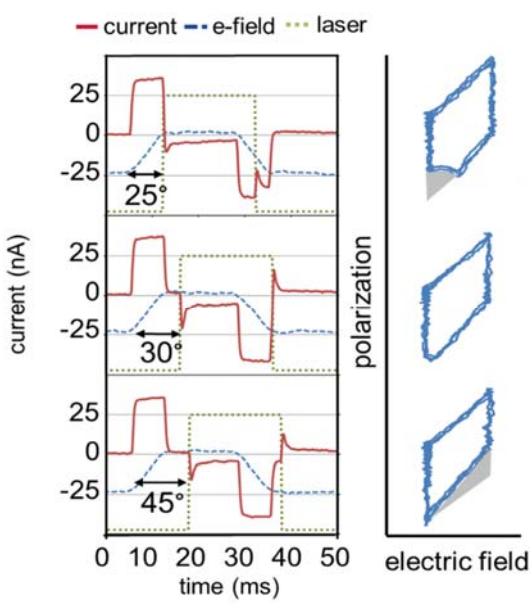
The electric field had a duty cycle of 30% and was applied with a rise time that represented 7% of the cycle period while the laser heating duty cycle was 20%. Practically the substrate remains in thermal contact with the device. During the laser heating period the system exponentially approaches a steady state "on" value, and once the heat source is removed the system exponentially approaches the substrate temperature. The thermal time constant of the device is a function of the thermal mass and the thermal impedance between the device and the substrate; and governs the performance of the device at high

frequencies [3]. The thermal time constant for the device in this study was determine to be 100 ms by comparing the measured temperature response shown in figure 3 to a thermal model for the heating and cooling. Figures 3 & 4 show how the finite rise leads to a reduction in net work per cycle. Ideally cooling would only occur at the minimum electric field and heating would only occur at the maximum electric field.

Figure 5 shows experimental results with phase delays of 25°, 30° and 45° between the initiation of charging and heating. The pyroelectric current, applied electric field, and laser power are shown along with a plot of the measured polarization versus electric field for the adjacent timing, where the lost work is illustrated by the shaded area. At a 25° delay the lower left corner is shaded because the system temperature is allowed to decrease before the electric field has been fully lowered. At a 45° phase delay heating continues after the field has been removed, therefore less heating has occurred while the field was raised reducing the length of the heating line and cooling lines on the right and left side respectively. The optimal power density occurs around 30° phase delay, which roughly aligns the peak temperature with the end of the electric field pulse due to the 10% difference in duty cycles.

3. Thermal Model

The thermal model based on a simple heating/cooling lumped capacitance model was useful in explaining the behavior observed in the polarization plots as shown in Figure 5. The predicted transient temperatures were combined with the electric field values and used to predict the polarization based on the assumption of a constant pyroelectric coefficient, $p = -0.03\ \mu C/cm^2K$ and dielectric constant, $\varepsilon = 0.2\ \mu C/kV\cdot cm$. Figure 6 shows the predicted polarization versus electric field at different phase delays, where the same shaded regions seen in Figure 5 are evident and a phase delay of 36° has the highest net work per cycle.



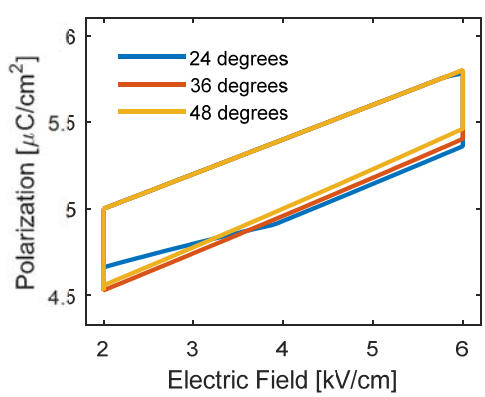


Figure 6. (Above) Polarization versus electric field for the 24°, 36° and 48° phase delays where 36° has the highest energy density.

Figure 5. (Left) 10 Hz pyroelectric energy conversion cycles with various phase lag between charging/discharging and heating/cooling cycles

4. Maximizing the Power Density

The thermal model was then used to examine the impact of the charging rates on the net work per cycle. Figure 7 shows the optimal phase delay of the heating pulse where the solid line represents the phase delay that would align the end of the laser and electrical field pulses. Given a laser and electric field duty cycle of 20%, instantaneous charging requires a 0% rise time while the minimum charging rate is given by a triangular pulse for a 20% rise time. Increasing the rise time reduces the net work per cycle.

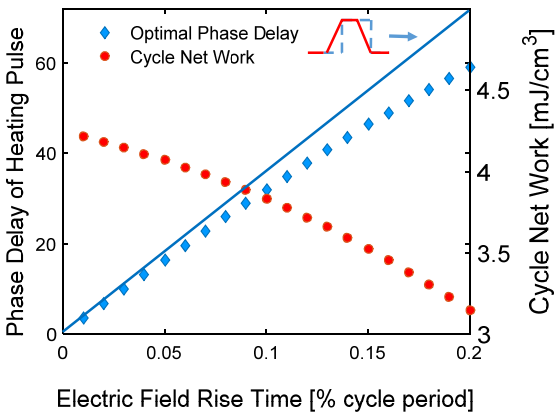


Figure 7. Optimal Phase delay of heating pulse and net cycle work over a range of electric field rise times (charging rates) for a 1 Hz cycle

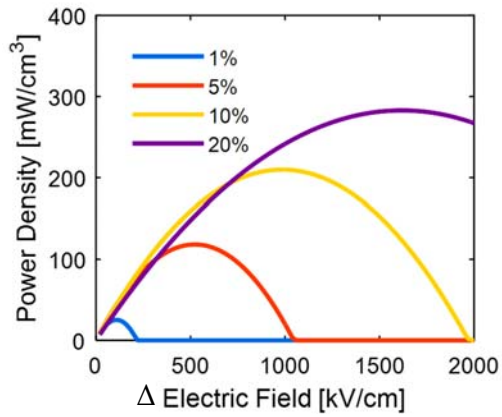


Figure 8. Calculated power density for 1 Hz cycles over a range of applied fields at different charging rates, where C=3 nF and $\tan\delta$ =*0.1%*

With the optimum phase for each rise time established, the electrical power loss during the charge and discharge cycles can be added to the model to find a maximum power density for a give applied field and charging rate. The electrical power loss is calculated as,

$$P_{loss} \approx \frac{\boldsymbol{C}\Delta V^2 f \tan\delta}{\pi(\%t_r)} \qquad [1]$$

where C is the capacitance, ΔV is the change in voltage, f is the frequency, $\tan\delta$ is the dissipation factor, and *%tr* is the faction of the cycle period used to linearly increase the electric field. Depending on the values of $\tan\delta$, it was unexpectedly found that longer rise times can be advantageous despite a reduction in the net work per cycle.

5. Conclusions

Dissipative losses that occur during charging and discharging can place a practical limit on the rise time of the electric field and hence the charging current. Finite rise times lead to a situation where the phase delay must be optimized to produce the maximum net work per cycle and power density. If the heating pulse terminates too early then the temperature drops while the electric field in still rising and potential work is lost. If the heating pulse terminates too late, heating occurs while the electric field has been reduced which is wasteful and lessens the portion of the heating pulse that is actually utilized. Longer rise times may have the potential to be more power dense due to reduced charge/discharge losses.

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