An electroactive polymer energy harvester for wireless sensor networks

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Abstract. This paper reports the design, fabrication, and testing of a soft electroactive polymer power generator that has a volume of 1 cm\textsuperscript{3}. The generator provides an opportunity to harvest energy from environmental sources to power wireless sensor networks because it can harvest from low frequency motions, is compact, and lightweight.

Electroactive polymers are highly stretchable variable capacitors. Electrical energy is produced when the deformation of a stretched, charged electroactive polymer is relaxed; like-charges are compressed together and opposite-charges are pushed apart, resulting in an increased voltage.

Although electroactive polymers have impressively displayed energy densities as high as 550 mJ/g, they have been based on films with thicknesses of tens to hundreds of micrometers, thus a generator covering a large area would be required to provide useful power. Energy harvesters covering large areas are inconvenient to deploy in a wireless sensor network with a large number of nodes, so a generator that is compact in all three dimensions is required. In this work we fabricated a generator that can fit within a 11x11x9 mm envelope by stacking 42, 11mm diameter generator films on top of each other.

When compressed cyclically at a rate of 0.5 Hz our generator produced 300 uW of power which is a sufficient amount of power for a low power wireless sensor node. The combination of our generator’s small form factor and ability to harvest useful energy from low frequency motions provides an opportunity to deploy large numbers of wireless sensor nodes without the need for periodic, costly battery replacement.

With applications such as sensors monitoring the health of a building or transducers to monitor wildlife populations, wireless sensor networks provide an opportunity to obtain an enhanced awareness of both our local and remote environments. The major advantage of a wireless sensor network is that the cost and inconvenience of wiring between nodes is eliminated [1, 2].

The advantages of wireless sensor networks can be offset if frequent battery replacement is required. One solution is to integrate a compact energy harvester into the wireless sensor nodes. If hundreds or thousands of sensor nodes are to be deployed, energy harvesting devices become impractical if they are too large, thus there is a drive for energy harvesters that fit within a 1 cm\textsuperscript{3} envelope [3].

Dielectric elastomers (DE), a class of electroactive polymers, are highly deformable variable capacitors that show great promise for sub-cm\textsuperscript{3} scale energy harvesters. Electrical energy is produced when the deformation of a stretched, charged DE is relaxed; like-charges are compressed together and opposite-charges are pushed apart, resulting in an increased voltage (see Figure 1). DE lend themselves well to low complexity, small-scale energy harvesters because the energy harvesting mechanism is theoretically scale invariant, they can be directly coupled to rectilinear motions [4], they can produce high energy densities [5, 6], and can harvest energy efficiently from a wide range of frequencies.
Figure 1: The DE energy harvesting cycle. 1) Mechanical energy is used to stretch the generator; 2) The generator is electrically charged; 3) the generator is mechanically relaxed which pushes opposite charges apart and compresses like charges together, this action boosts the electrical energy of the charges; 4) the charges are extracted in this higher energy state.

Although DE have displayed energy densities as high as 550 mJ/g [5], they have been based on films with thicknesses of tens to hundreds of micrometers [4-6], thus a generator covering a large area would be required to provide useful power. Furthermore, the thin film structures often require additional rigid frames to maintain their desired shape. The framing reduces the generator’s energy density, deformability, simplicity, and introduces potentially catastrophic stress concentrations.

In this paper we present a stacked membrane generator configuration which allows self-supporting generators to be fabricated that do not require rigid frames. The stacked configuration also allows a large quantity of generator material to be fabricated onto a much smaller footprint than that achievable using a single thin membrane.

Our generator consisted of 42, 40 um thick, 11mm diameter DE layers stacked on top of each other and electrically connected in parallel. The generator stack was then sandwiched between 3mm thick silicone end caps (see Figure 2). The end caps were included because the most convenient mechanism for coupling a stack to a load is to adhere the ends of the stack between two structures. The constrained ends do not deform as much as the center of the stack. And as described in Figure 1, the generator harvests energy by displacing electrical charges using mechanical deformation. Thus, the constrained end-cap regions would not provide much additional energy. In fact, if the end-caps were substituted for DE layers, they would reduce the overall proportional change of the generator’s capacitance, which could reduce energy production [7].

Figure 2: The stack DE generator is coupled to a mechanical energy source by adhering its ends between two bodies that move relative to each other. The active generator zone is deformed when the stack is compressed. The end caps do not deform as much as the active zone because of the fixed boundary condition between the generator stack and the mechanical energy source.
An overview of our fabrication process is given in Figure 3. Our generator’s silicone membranes (Sylgard 186, Dow Corning) were cast on to a polyimide backing using a Zehntner ZAA2300 film applicator. Electrodes consisting of 90% by weight Sylgard 186, Ketchenblack EC-300J carbon black (Akzo-Nobel) (5% by weight), and Cabot Black Pearl 2000 carbon black (5% by weight) were applied to the membranes using a TPM-101 pad printer from Teca-Print. A Diener Zepto plasma system was then used to bond the layers together with a short exposure to an oxygen plasma, until a stack of 42 active membranes was formed. A Trotec Speedy 300 laser cutter was used to cut the stack to shape before the polyimide backing film was removed. LSR-20 silicone (factor 2) endcaps were then bonded to the stack. The layers were then interconnected using the silicone/ketchenblack/cobalt carbon black electrode mix.

The stack generator was tested using the energy harvesting circuit illustrated in Figure 4. The generator transfers charge from a priming source up to a higher voltage where the energy was supplied to a load. Thus our energy harvester provides a gain in electrical energy by boosting the voltage of the charge before it is delivered to a load. We replicated the approach of Huang et al. who used a zener diode array as the load. When the voltage reaches the breakdown voltage of the zener array, charge is transferred from the generator to the zener load. We used an array of 9 200 Volt zeners (1N5388BG). The generator was primed to 1400 Volts using an EAP controller power supply (www.biomimeticslab.com). The voltage across the DE generator was measured using a 5 GΩ: 5MΩ resistor ladder. The charge on the generator was measured using a 1 µF current integration capacitor.

![Figure 3: An overview of the process which was developed for fabrication of stacked DE generators.](image-url)
The generator was cyclically compressed by 3 mm at 0.5 Hz using an Instron 3342 dynamic test rig. The measured voltage versus charge relationship from one cycle is given in figure 4. As described by Huang et al. the energy produced by the generator in a single cycle was found by computing the area within the Voltage-charge envelope. When primed at 1400 Volts and delivering charge to the load at 1800 Volts, our generator produced 600 µJoules in a single cycle. Since the Instron cyclically deformed the DE generator at 0.5 Hertz, this energy production corresponds to a power output of 300 µWatts.

The production of 300 uW is a sufficient for powering a low power wireless sensor node. For instance, Rhee et al. developed a wireless sensor network with transmitting nodes that consumed 300 uW to send 1 packet of sensor data per second [2]. Furthermore the power output of electroactive polymer energy harvesters scales linearly with frequency, so power hungry wireless sensor nodes could be powered using our generator if a higher frequency energy source was available.

The combination of our generator’s small form factor and ability to harvest useful energy from low frequency motions provides an opportunity to deploy large numbers of wireless sensor nodes without the need for periodic, costly battery replacement. The ability to harvest from low frequencies opens the possibility to harvest from a wide range of energy sources. For instance, we previously used electroactive polymers to harvest energy from a tree branch swaying in the breeze [8]. Our generator coupled to swaying branches could, for example, power wireless sensor nodes that provide an alarm if a forest fire develops.
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