

AA Size Micro Power Conversion Cell for Wireless Applications

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This paper presents the preliminary design and experimental results of a standard AA size vibration-induced micro power generator which is integrated with a power-management circuit. The transducer is a spring mass system which uses SU-8 molding and MEMS electroplating technologies fabricated copper springs to convert mechanical energy into electrical power by Faraday's Law of Induction. We have shown that when the micro energy transducer is packaged into an AA battery size container along with a power-management circuit that consists of rectifiers and a capacitor, it is capable of producing ~2V DC when charged for about one minute. Potential applications for this micro power generator to serve as a power supply for a wireless temperature sensing system was proved to be possible with input frequencies at about 70 Hz with amplitude of approximately 250 microns.

Keywords: micro power generator, micro energy transducer, power-management circuit.

I. INTRODUCTION

Traditional alkaline battery has been used for almost a century, and has brought dramatic revolutions to human life. However, shelf life, replacement accessibility and potential hazards of chemical are some of the problems when chemical batteries are used. Our ongoing work is to develop a brand new power supply with unlimited shelf life and is environmentally safe. Three main advancements in engineering technology in the last 20 years allow possible applications for magnetic-induction based micro energy transducers: 1) increase in magnetic flux density of rare-earth-magnets; 2) continual reduction of power consumption of low-power circuits and sensor; 3) MEMS fabrication technology that allows precise and low cost production of spring-mass system.

Research on micro power generator have been done by various groups throughout the world. Williams and Yates developed an electromagnetic micro generator to produce $0.3\mu\text{W}$ in 1997 [1], Amirtharajah & Chandra-Kasan used a vibration-based power generator to drive a signal processing circuitry in 1998 [2]. Nevertheless, neither of the groups was able to demonstrate a micro power generator capable of producing enough power to drive an off-the-shelf wireless circuit. Our group later demonstrated a 1cm^3 vibration-based energy converter capable of powering an off-the-self IR transmitter [3] (2000) and RF transmitter [4] (2002). In that

work, the energy converting transducer was made of copper (Cu) springs fabricated using a Nd:YAG laser micromachining system, which limited the reduction and precision of the spring dimensions. In this paper, we will present our recent results in creating an energy transducer using MEMS compatible SU-8 fabricated high-aspect-ratio copper springs to amplify input mechanical vibrations from the transducer's environment. Thus far, we are able to get ~2.2V peak to peak AC from two micro power transducers connected in series and vibrating at about 70Hz, and capable of producing ~40 μW when connected with the power management circuit and a 100 k Ω resistor.

II. GENERATOR PRINCIPLE AND DESIGN

The prototype micro power generator consists of five main components: 1) inner and outer housing which is used to carry the resonating structure and the power generating system, respectively, 2) a SU-8 based MEMS resonator with spring constant k , 3) a N45 grading rare earth permanent magnet of mass m and magnetic field strength B , 4) copper coil of length l , and 5) a power-management circuit for output voltage step up and energy storing purpose. The resonating spring is attached to the magnet and packed by the inner housing. The orientation of inner housing, magnet and the resonating spring is shown in Figure 1a, and the illustrative drawing of AA size micro power generator is shown in Figure 1b.

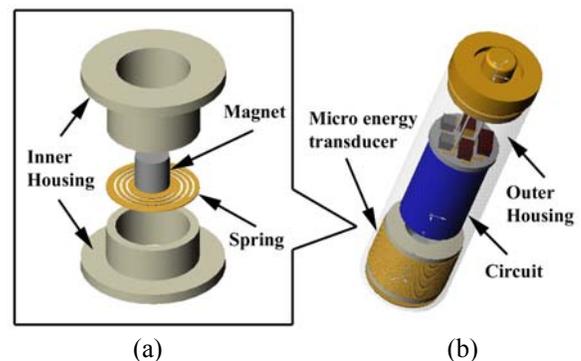


Figure 1. Illustrations of: (a) Inner structure of the micro power generator; (b) the AA size micro power generator which is integrated with a power-management circuit.

When the generator housing is vibrated with an amplitude of $y(t)$, the magnet will vibrate with a relative amplitude of $z(t)$. This relative movement of the magnet results in the varying amount of magnetic flux density cutting through the coil. According to Faraday's law of electromagnetic induction, a voltage is induced in the loop of coil. The average power output of the vibration-induced power generating system can be derived as [5]:

$$P = m\xi_e Y_0^2 (\omega / \omega_n)^3 \omega^3 / \left(\left[1 - (\omega / \omega_n)^2 \right]^2 + (2\xi\omega / \omega_n)^2 \right) \quad \text{Eq.1}$$

where ξ_e is the electrical damping factor, Y_0 is the input vibration amplitude, ω is the input vibration frequency (angular), ω_n is the resonance frequency of the spring-mass system and ξ is the sum of electrical damping factor and mechanical damping factor of the system. From the above equation, at resonance, the average power and voltage output is maximized:

$$P = m\xi_e Y_0^2 \omega^3 / 4\xi^2 \quad \text{Eq.2}$$

$$V = BLY_0 \omega_n / 2\xi \quad \text{Eq.3}$$

Based on the above equations, the power generator will have maximum power and voltage output when vibrating in resonance frequency with maximum amplitude and electrical damping factor.

In practice, we may need larger current in order to widen our potential applications. Experiment have proved that connecting two micro power transducers together in parallel will give a larger current output, whereas larger voltage could be obtained when connected in series. Therefore, we are able to adjust the performance of the AA size micro power generator to accommodate for different purposes. The dimensions and composition of the components inside the AA size "power-conversion cell" is given in Figure 2.

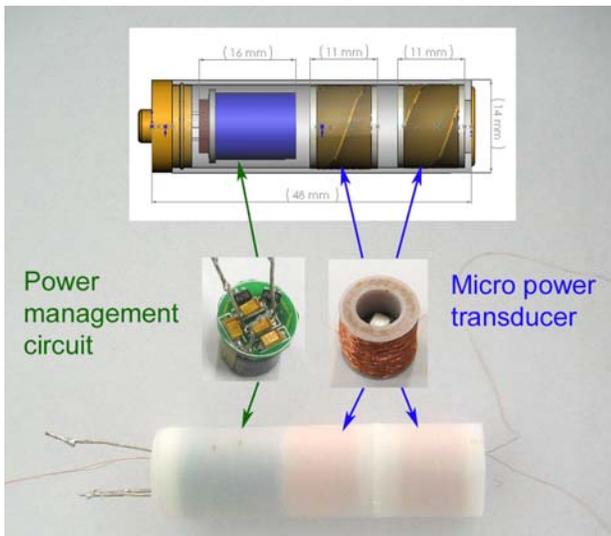


Figure 2. The AA size micro power generator which consists of two transducers and a power management circuit

III. DESIGN OF RESONATING STRUCTURE

The resonance frequency of the spring-mass system depends on the materials used for the resonating structure, and hence, the choice of spring material will affect the performance of power generator. Copper was chosen to be the material for the resonating structure because of its relatively low Young's modulus and high yield stress when compared to Silicon (See [7]). Some other materials such as brass, titanium and 55-Ni-45-Ti can also be considered, depending on the

TABLE 1: POTENTIAL MATERIALS FOR THE RESONATING SPRING [6].

	Young's modulus (GPa)	Yield Stress (MPa)	Ultimate Stress (MPa)	Fatigue Limits (MPa)	Fatigue Ratio
Aluminum	70	270	310	21	0.30
Brass	96 – 110	70 – 550	200 – 620	98 – 147	0.31
Copper	130	55 – 760	230 – 830	63	0.29
Nickel	200	100 – 620	310 – 760	109	0.35
Titanium	120	760 – 1000	900 – 1200	364	0.59
55-Ni-45-Ti	83	195 – 690	895	---	---
Silicon	160(ave)	---	---	---	---

operation environment. For instance, titanium should be used if the power generator is designed to vibrate in extremely large displacement, as its yield stress is higher than copper. We have experimentally verified that brass and 55-Ni-45-Ti resonating structures could obtain a lower resonance frequency than copper due to their lower Young's modulus. The material properties of some potential metals which may be suitable to fabricate the resonating spring are compared in Table 1.

Using ANSYS to simulate the resonating structures, it was found that springs with spiral geometry have lower spring constant and stress concentration than other designs, such that a larger displacement can be obtained [7]. We have used a Q-switch Nd:YAG (1.06 μ m wavelength) laser to micromachine the spiral resonating spring as shown in Figure 3a and b. A copper spring with diameter of 8mm and 0.1mm thickness will be used for the AA size micro power generator.

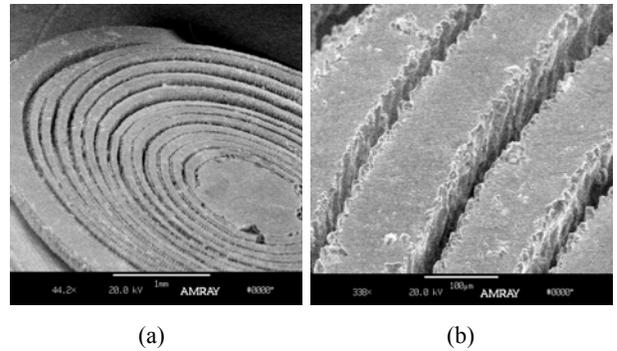


Figure 3. SEM pictures of : (a) a laser-micromachined copper spring with diameter of 5mm; (b) close up of the copper spring; width of the spring is ~100 μ m.

IV. SU-8 BASED MEMS RESONATOR

Using laser-micromachining to fabricate the copper spring is direct and fast, but the cutting resolution is not ideal (see Figure 3b). We have developed another process which involves high-aspect-ratio electroplating of copper using lithographic techniques. The fabrication process is shown in Figure 4. First of all, a seed layer is sputtered on the silicon wafer. Then, a SU-8 photoresist is coated and baked to form the desired thickness of spring. After that, the SU-8 photoresist is exposed to transfer the desired pattern from the mask to SU-8. The mold for the resonating spring can then be formed after developing the SU-8 photoresist. Then, copper is electroplated on the mold. Finally, the SU-8 photoresist and seed layer are stripped and the desired dimension of copper spring can be obtained. The fabricated copper resonator and its close up pictures are shown in Figure 5.

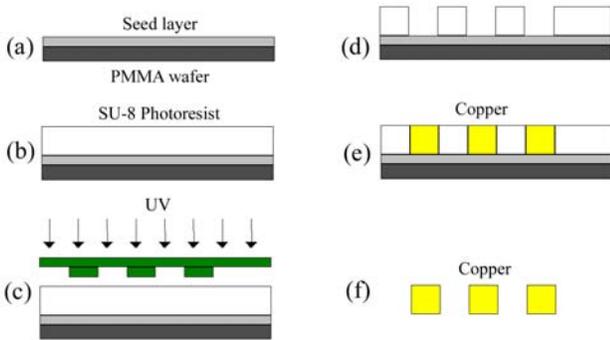


Figure 4. SU-8 based copper resonator fabrication process. (a) Sputter Cr/Au seed layers on PMMA substrate; (b) coat thick SU-8 negative PR and soft bake; (c) expose SU-8 PR with spring pattern mask using UV light source; (d) develop in SU-8 developer; (e) electroplate copper into the SU-8 mold; (f) strip SU-8 and PMMA substrate by MicroChem Remover.

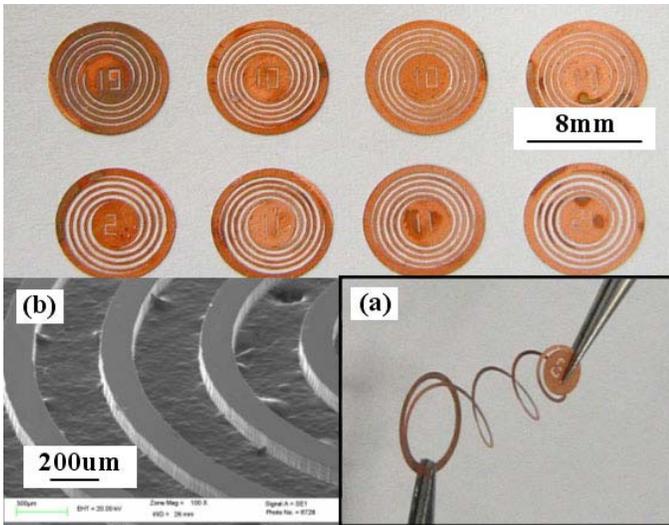


Figure 5. Batch fabricated copper resonators. Inset (a) shows a spring being stretched. Inset (b) shows an SEM picture of a SU-8 fabricated resonator.

V. RESONATOR CHARACTERISTICS

The motion of the spring-mass under a mechanical input vibration is similar to those reported in our prior work for laser-micromachined springs [4], i.e., 3 distinctive modes of resonance were observed. These 3 different modes of resonant vibration were captured using a digital video camera and analyzed. A strobe light was used to synchronize the vibration motion of the mass. Sample frames from the digital movies are shown in Figure 6 which shows the 3 modes of vibration. The 1st mode is a vertical resonance. For the 2nd and 3rd modes, the mass appeared to cyclically rotate about an axis parallel to the plane of the coil. Most interestingly, the voltage output at the 2nd and 3rd modes of resonance for the generator is higher than the 1st mode resonance. Physically, this can be explained by the fact that Faraday's Law predicts the voltage output to be proportional to the rate of changing magnetic flux, and hence, faster the movement of the mass, the greater the current induction. It was observed that the vibration amplitude of the rotation was very small compared to the vertical vibration at the 1st mode resonance. Hence, if the a spring can be designed to vibrate in a horizontal plane with rotation, rather than to vibrate in a vertical direction relative to a coil, the voltage output can be increased and the stress on the spring can be reduced.

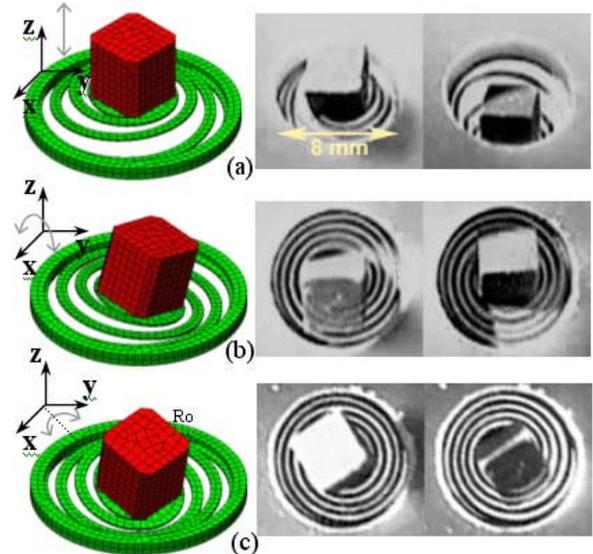


Figure 6. Simulation and experimental results for 3 different resonance vibration modes are matched: (a) 1st mode vibration (vertical); (b) 2nd mode vibration (horizontally along x axis); (c) 3rd mode vibration (horizontally along an axis between x and y axis);

VI. SIMULATION AND MODELING

FEA Modeling of the MEMS Resonators

Finite element analysis was used to study the vibration characteristics of different geometric configurations and spring designs. The copper resonating spring and magnet were modeled using ALGOR as shown in Figure 6a. With the use of linear modal analyses, the vibration resonances of the micro spring-mass were extracted from the simulation. Vertical translation vibration was observed in the first mode as

indicated in Figure 6a. In the second and third modes, horizontal rotational movements were observed (Figure 6b and c).

Micro Power Generator System Modeling

To model different behaviors of the micro power generator due to electro-mechanical coupling effects, basic principles of electromagnetic theory are adopted. According to the Faraday's Law of induction, a voltage is induced in a coil when there is a change of magnetic flux through the loop of coil. This induction behavior is contributed by the mass-spring resonator structure in the micro transducer, where a magnet is attached to a spring and moves through a coil which is fixed on the housing of the device. This is depicted in Figure 7.

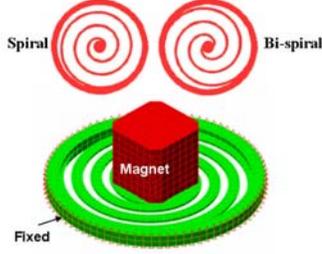


Figure 7. Finite element model of the micro resonating spring.

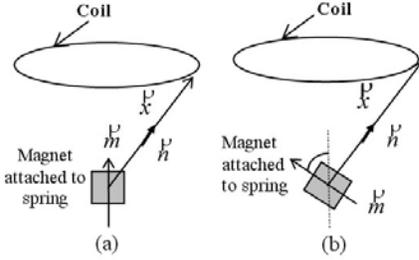


Figure 8. Motion of the mass-spring resonator structure through the coil : (a) Translational motion; (b) rotational motion.

The induced emf in the coil is given by Faraday's Law as:

$$V = -N \frac{d\phi}{dt} \quad \text{Eq.4}$$

where N is the number of turns of coil and ϕ is the flux. The flux ϕ is defined by:

$$\phi = \vec{B}(\vec{x}) \cdot \vec{A} \quad \text{Eq.5}$$

where \vec{A} is the vector area of the loop of coil, and $\vec{B}(\vec{x})$ is the magnetic field at the coil at a distance x from the magnetic dipole, which is given by:

$$\vec{B}(\vec{x}) = \frac{\mu_0}{4\pi} \frac{(3\vec{n}(\vec{n} \cdot \vec{m}) - \vec{m})}{|\vec{x}|^3} \quad \text{Eq.6}$$

Here, \vec{m} represents the magnetic dipole moment of the magnet, \vec{n} is the unit vector in the \vec{x} -direction, and μ_0 is the permeability constant. Based on the above expressions, an electro-mechanical model was implemented in MATLAB such that different magnitudes of induced emf could be obtained by varying the orientations and movements of the

magnetic dipole moment. Results of different configurations can also be analysed. Thus, the model serves as the basis for system level optimization. As an example, an SU-8 fabricated spring with parameters given in Figure 9 was experimentally tested and compared with the modeled results using the model. As indicated in Figure 9, the experimental and modeled results matched well in terms of output voltage amplitude. However, the predicted output frequency has slight variation from the experimental results (i.e., 167.8Hz for experimental and 176Hz from modeling). We conjecture that this is mainly due to the location of the magnet on the copper resonator, which is not well-controlled in our current packaging process

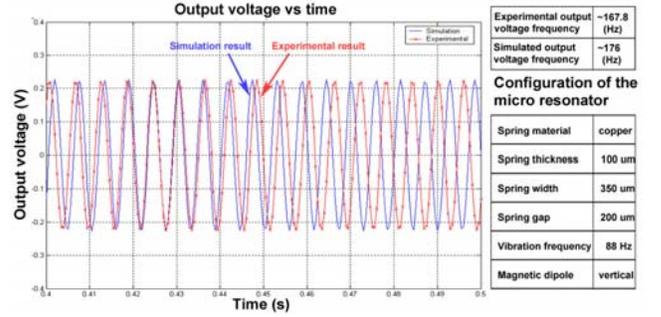


Figure 9. Comparison of experimental and modeled results at 1st mode resonance. Note that the transducer mechanical resonance is ~ 88 Hz, but the voltage output is 2 times this frequency due to the up and down motion of the mass-spring

VII. POWER – MANAGEMENT CIRCUIT DESIGN

A tripler circuit was integrated with the micro power generator to step up and rectify the AC output to DC voltage. The schematic diagram of the tripler, complete power-management circuit and the rectifying performance for quadrupler compared with tripler and doubler is shown in Figure 10. A capacitor of 1000 μ F is connected with the tripler, it acts as a reservoir to store the electrical energy generated by the micro power generator.

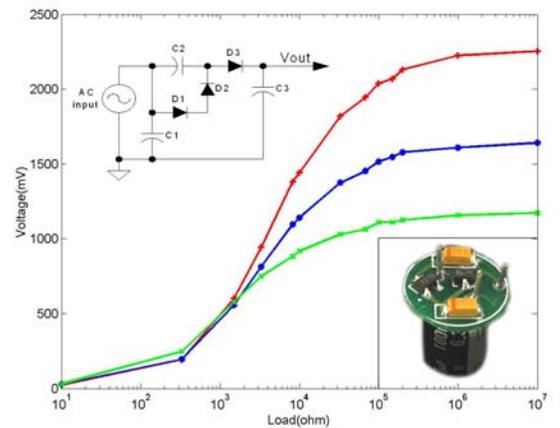


Figure 10. Schematic diagram, picture of tripler and comparison on performance for quadrupler, tripler and doubler.

Experimental Results

To test the power-conversion cell, a 100kΩ resistor was connected to the AA size micro power generator's output, and the potential difference across the resistor was measured. At 3rd mode vibration, it takes about one and a half minutes for the capacitor to charged to ~2.5V DC. The power output for the transducer when loaded with a 100kΩ resistor is ~40μW. Without the power management circuit, the micro power transducer produced a voltage output of 2.2Vpp AC at 71 Hz (3rd mode). The results given above were obtained using two transducers connected in series for the cell. The transducers can also be connected in parallel in the case that larger current is desired.

VIII. MEASUREMENTS

Two experiments were further set up to measure the characteristics of the AA size micro power generator as shown on Figure 11 and the results are shown in Figure 12. From Figure 12a, the output power of two transducers in series was estimated to be 20 to 100μW for 1kΩ to 30kΩ loads respectively. For simplicity, the two transducers were modeled as an AC source with an internal resistance R_{int} , whose value was measured as 1030Ω. The relationship between power input/output and the load voltage of the tripler are shown in Figure 12c to d.

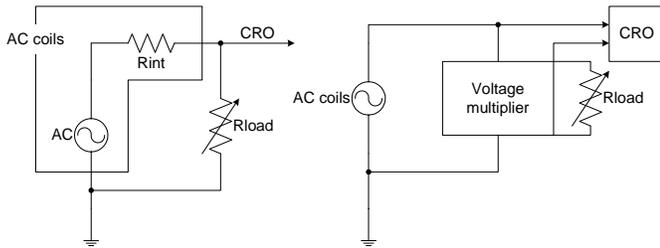


Figure 11. The experiment apparatus for measuring micro power generator characteristics

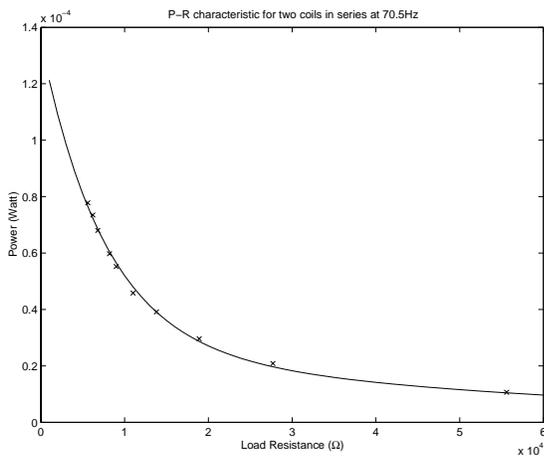


Figure 12(a). Output power versus load resistance for two transducers in series vibrated at 70.5Hz

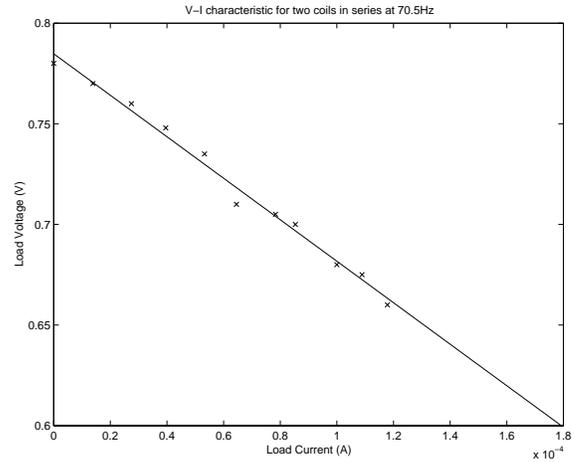


Figure 12(b). Load voltage versus load current for two transducers in series vibrated at 70.5Hz

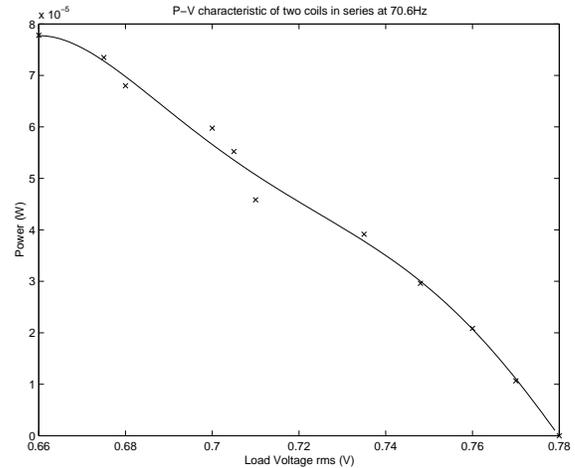


Figure 12(c). Output power versus load voltage of two transducers in series vibrated at 70.6Hz

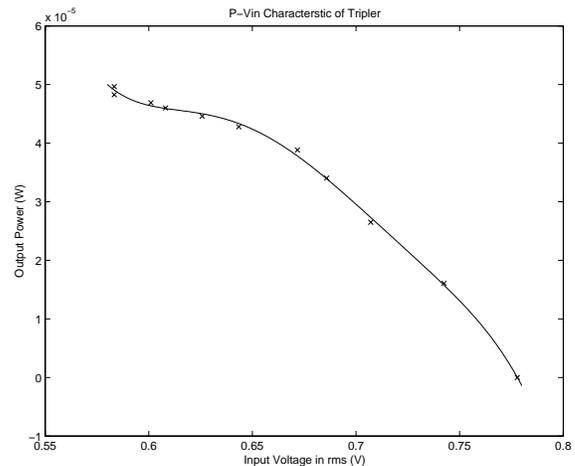


Figure 12(d). Output power versus input voltage of the tripler

IX. APPLICATION

RF Wireless Thermometer

We have already shown that a 1cm^3 micro power generator is capable of driving IR [3] and RF [4] wireless transmission circuit. A wireless thermometer system was implemented to demonstrate an application of the micro power generator. Figure 13 shows the system block diagram. The system has three main components: the micro power generator, startup circuit and application circuit. The micro power generator contains a voltage multiplier, i.e., tripler, which is used to step up the input voltage to $>0.9\text{V}$ DC. The tripler is a passive circuit which can operate at voltages lower than a normal MOS transistor's threshold voltage. It charges up the reservoir capacitor C_{res} . The startup circuit only applies power to the application circuit when the voltage at the output of the tripler exceeds a fixed threshold, $V_{\text{th}}(\text{H})$. It will bridge off the system ground rail from power ground when voltage at the output of the tripler drops below a low threshold, $V_{\text{th}}(\text{L})$. A charge pump regulator further steps up the output of tripler to 3.0V . To save power, the microprocessor controls the power supplies for peripheral chips and only applies power via its programmable I/O pins when required. Host-received data latency was designed and verified as ~ 1.4 seconds. The system took ~ 80 seconds for first activation and consecutive measurements were made with a period of ~ 25 seconds.

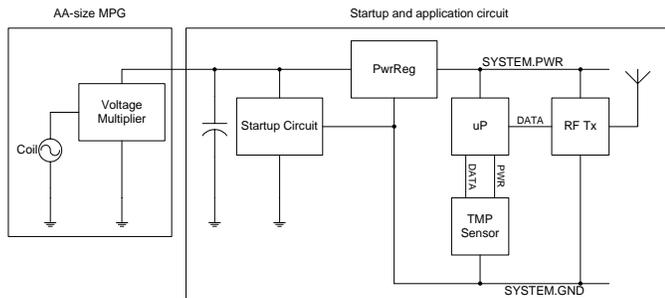


Figure 13. System block diagram for RF wireless thermometer

X. SUMMARY

Thus far, we have shown at a 1cm^3 magnetic-induction based micro power transducer is capable of converting mechanical vibrations into electrical power sufficient to drive both IR and RF wireless circuit. Typical input mechanical amplitude needed is $\sim 250\mu\text{m}$ at 80Hz to allow the transducer to generate enough power for wireless data transmission over $\sim 15\text{m}$. We have also successfully developed a vibration-induced power generator which can be housed in an AA size battery container. Efforts are underway to find specialized wireless applications for this AA size power conversion cell. The main component of this power cell is an energy transducer made using MEMS compatible high-aspect-ratio SU-8 process.

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