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AA size micro power conversion cell for wireless applications

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ABSTRACT

This paper presents the preliminary design and experimental results of a standard AA size vibration-induced micro energy transducer 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 MPG 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 ~1.6V DC when charged for less than 1min. 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 100Hz and amplitudes be approximately 250microns.

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

1. INTRODUCTION

Traditional alkaline battery has being 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. Thus far, we are able to get ~1.1V peak to peak AC from a micro power transducer vibrating at 111Hz which is capable to produce ~27μW when connected with a 100kΩ resistor. We are now targeting to develop a micro power generator integrated with a power-management circuit with total dimension equal to an AA size battery.

Research on micro power generator have been done by various groups throughout the world. Williams and Yates developed an electromagnetic micro generator to produce 0.3μW 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 Cu springs to amplify input mechanical vibrations from the transducer's environment.

2. GENERATOR PRINCIPLE AND DESIGN

The prototype micro power generator is consist 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 laser-micromachined resonating spring 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

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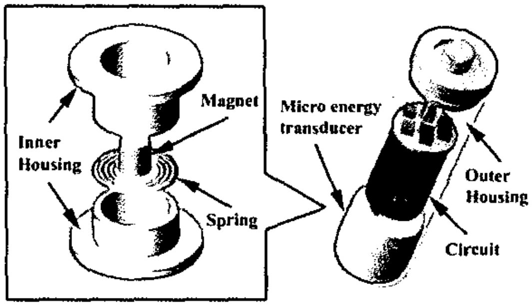
circuit for output voltage step up and energy storing purpose. The resonating spring is attached to the magnet and packed by the inner housing. The orientation of inner housing, magnet and the resonating spring is shown in Figure 1a, and the illustrative drawing of AA size's micro power generator is shown in Figure 1b.



(a) (b)

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]:

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

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:

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

$$V = BlY_0\omega_n / 2\xi \quad \textbf{Eq.3}$$

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 practical, we may need larger current in order to widen our potential applications, experiment has 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.

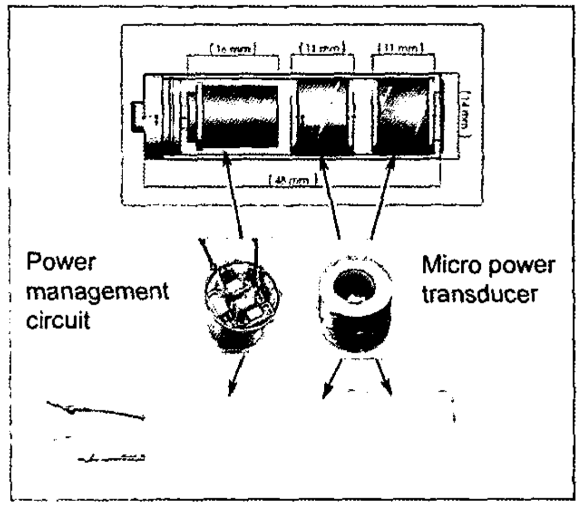


Figure 2. The AA-size micro power generator which consists of two transducers and a power management circuit

3. DESIGN OF RESONATING STRUCTURE

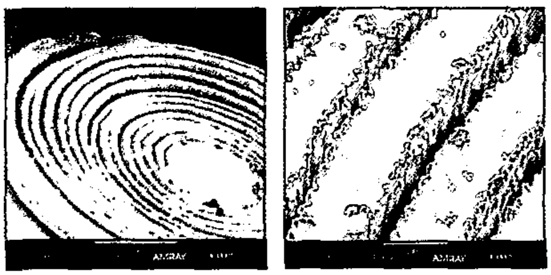
The resonance frequency of the spring-mass system depends on the materials used for the resonating structure, and hence, the choice of spring material will affect the performance of power generator. Copper was chosen to be the material for the resonating structure because of its relatively low Young's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

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)	---	---	---	---

considered, depending on the 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 (1.06μm wavelength) laser to micromachine the spiral resonating spring as shown in Figure3a and b. A copper spring with diameter of 8mm and 0.1mm thickness will be used for the AA size micro power generator.



(a) (b)

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 ~100μm.

Using laser-micromachining to fabricate the copper spring is direct, fast, but the cutting resolution is not ideal (see Figure 3b). We have developed another process which will involve high-aspect-ration electroplating of copper using lithographic techniques. The fabrication process is shown in the following section.

4. SU-8 BASED MEMS RESONATOR

Fabrication Process

The dimensions for the Cu resonator were determined using a dynamic simulation as described in the next section. Then, an SU-8 based electroplating technique (Figure 4) was used to fabricate the springs as presented below. The fabrication process starts with a polymethylmethacrylate (PMMA) substrate. The Cr/Au (500Å/2000Å) seed layers are deposited on a PMMA substrate by E-beam deposition. SU-8, a negative thick photoresist (PR), is deposited on the PMMA by spin-coating (100-150μm thick). The resist is soft baked in an oven at 40°C for 2 days. After that, the resist is exposed with 400nm UV under a mask with the designed spring patterns for 20 minutes. Following the exposure, the resist is developed in SU-8 developer for 10-15 minutes at room temperature with mild agitation and rinsed with isopropyl alcohol. The above processes create the thick SU-8 mold on a PMMA substrate as shown in Figure 4d. Then, the mold is used to electroplate Cu with a current density of 40mA/cm^2 for 1.5 hours. A 100μm thick Cu spring resonator can be fabricated in the SU-8 mold using the above parameters. Finally, the SU-8 resist and PMMA substrate are separated using the MicroChem Remover, resulting in isolated Cu spring resonators as shown in Figure 5.

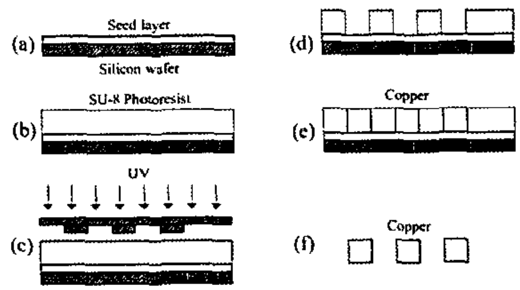


Figure 4. SU-8 based Cu resonator fabrication process. (a) Sputter Cr/Au seed layers on PMMA substrate; (b) coat thick SU-8 negative PR and soft bake; (c) expose SU-8 PR with spring pattern mask using UV light source; (d) develop in SU-8 developer; (f) electroplate copper into the SU-8 mold; (g) strip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

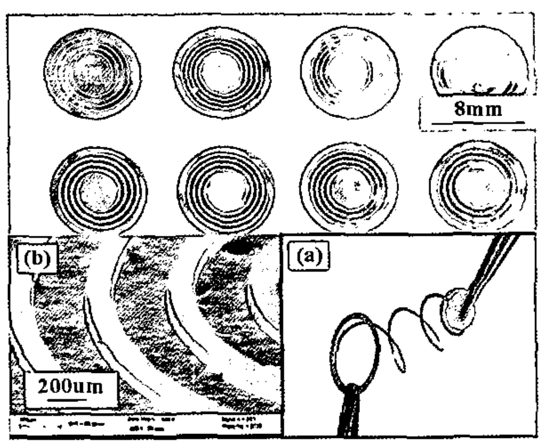


Figure 5. Batch fabricated Cu resonators. Inset (a) shows a spring being stretched. Inset (b) shows an SEM picture of a SU8-fabricated resonator.

5. 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 1^{st} mode is a vertical resonance. For the 2^{nd} and 3^{rd} modes, the mass appeared to cyclically rotate about an axis parallel to the plane of the coil. Most interestingly, the voltage output at the 2^{nd} and 3^{rd} modes of resonance for the generator is higher than the 1^{st} 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 1^{st} 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.

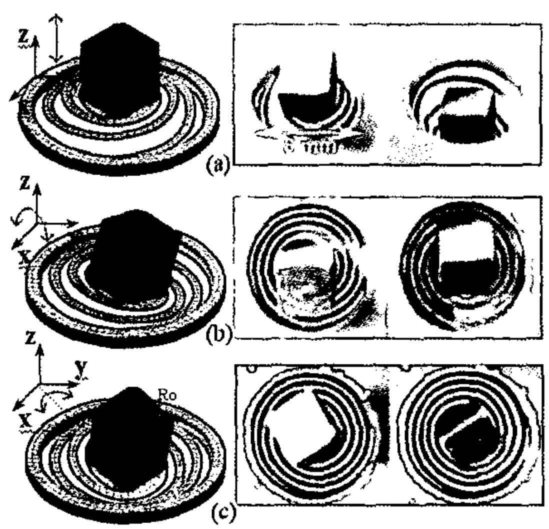


Figure 6. Simulation and experimental results for 3 different resonance vibration modes are matched: (a) 1st mode vibration (vertical); (b) 2nd mode vibration (horizontally along x axis); (c) 3rd mode vibration (horizontally along an axis between x and y axis);

6. 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 6c).

MPG System Modeling

To model different behaviors of the MPG 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.

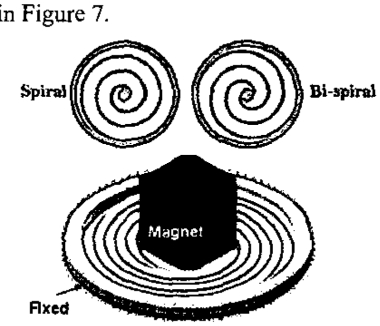


Figure 7. Finite element model of the micro resonating spring.

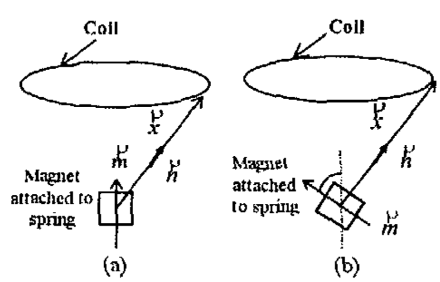


Figure 8. Motion of the mass-spring resonator structure through the coil :(a) Translational motion; (b) Rotational motion.

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

$$V = -N\frac{d\phi}{dt} \qquad \textbf{Eq.4}$$

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

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

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:

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

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 analyzed. 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 Cu resonator, which is not well-controlled in our current packaging process

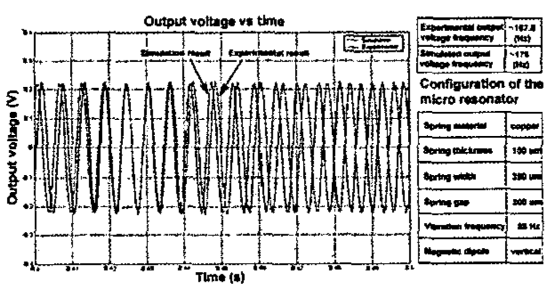


Figure 9. Comparison of experimental and modeled results at 1st mode resonance. Note that the transducer mechanical resonance is ~88Hz, but the voltage output if 2 times this frequency due to the up and down motion of the mass-spring

7. POWER-MANAGEMENT CIRCUIT DESIGN

A quadrupler circuit was integrated with the micro power generator to step up and rectify the AC output to DC voltage. The schematic diagram of quadrupler, complete power-management circuit and the rectifying performance for quadrupler compared with tripler and doubler is shown in Figure 10. A capacitor of 1mF is connected with the quadrupler and act as a reservoir to store the electrical energy generated by the micro power generator.

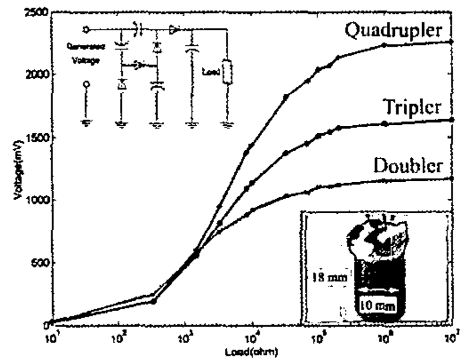


Figure 10. Schematic diagram, picture of quadrupler and comparison on performance for quadrupler, tripler and doubler.

Experimental Results

To test the power-conversion cell, a 100kΩ resistor was connected to the capacitor of the power management circuit, and the potential difference across the resistor was measured. The capacitor was charged to about 1.55V at 1st mode and 1.65V at 3rd mode (within ~1min). Using these values, we calculated the power output for the transducer when loaded with a 100kΩ resistor is ~24μW at 1st mode and ~27μW at 3rd mode, respectively. Without the power management circuit, the micro power transducer produced a voltage output of 1.34Vpp AC at 85 Hz (1st mode), and a voltage output of 1.44Vpp AC at 111 Hz (3rd mode). The results given above were obtained using only 1 transducer for the cell. A maximum of 2 transducers can be packaged in a power-conversion cell with our current design.

8. APPLICATIONS

RF Wireless Circuits for ID Tagging

We have already shown that a 1cm^3 MPG is capable of driving IR [3] and RF [4] wireless transmission circuit. Currently, we are developing a circuit system for RF wireless transmission applicable for ID tagging using the AA-size MPG. This new circuit system consists of 1) a voltage rectifier, charge pump regulator and 3V comparator, 2) uP, 3) NVRAM, RTC, Temperature and iMems accelerometer, and 4) RF Transmitter. A voltage tripler is used to step up the input voltage to >0.9V DC. This is a passive circuit which can operate at voltages lower than a normal MOS transistor's threshold voltage. A charge pump regulator further steps up the output of multiplier to 3.3V and charges up the reservoir capacitor Cres. To save power, the microprocessor controls the power supplies for peripheral chips and only applies power via an analog switch when required. The microprocessor is in sleep mode until the voltage level of Cres rises to 3.3V when it will be awaked by the 3V comparator.

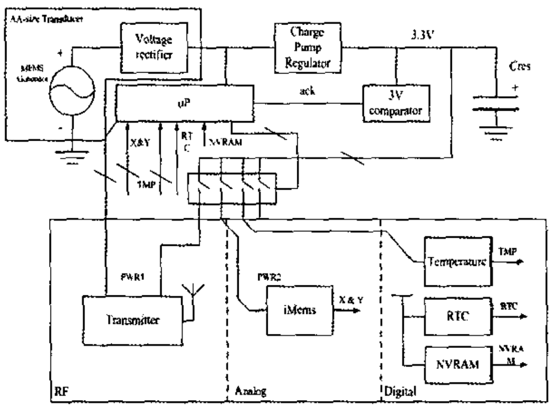


Figure 11. Circuit schematic for the proposed RF ID tagging wireless transmission system.

9. SUMMARY

Thus far, we have shown at a $1cm^3$ magnetic-induction based micro power transducer is capable of converting mechanical vibrations in to electrical power sufficient to drive both IR and RF wireless circuit. Typical input mechanical amplitude needed is ~200um at 100Hz to allow the transducer to generate enough power for wireless data transmission over 5m. 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 a energy transducer made using MEMS compatible high-aspect-ratio SU-8 process.

10. ACKNOWLEDGMENT

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