

# A Laser-micromachined Multi-Modal Resonating Power Transducer for Wireless Sensing Systems

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## ABSTRACT

This paper presents the development of a vibration-induced power generator with total volume of  $\sim 1\text{cm}^3$  which uses laser-micromachined springs to convert mechanical energy into useful electrical power by Faraday's Law of Induction. The goal of this project is to create a minimally sized electric power generator capable of producing enough voltage to drive low-power ICs and/or micro sensors for applications where ambient mechanical vibrations are present. Thus far, we have fabricated generators with total volume of  $1\text{cm}^3$  that are capable of producing up to 4.4V peak-to-peak, which have a maximum rms power of  $\sim 830\mu\text{W}$  with loading resistance of  $1000\Omega$ . The mechanical vibration required to generate this electrical energy has frequencies ranging from 60 to 110Hz with  $\sim 200\mu\text{m}$  amplitude. The generator was shown to generate sufficient power at different resonating modes. We have demonstrated that this generator can drive an IR transmitter to send 140ms pulse trains every minute, and also a 914.8MHz FM wireless temperature sensing system.

**Keywords:** micro power generator, micro power supply, micro power transducer, wireless sensing.

## INTRODUCTION

One of the projected goals for MEMS technology is to develop low-cost and high-performance distributed sensor systems for medical, automotive, manufacturing, robotics, and household applications. Ideally, these distributed systems will have their own integrated power supplies to reduce potential problems such as interconnection, electronic noise and control system complexity. Efforts are underway to develop integrated chemically based power supplies with MEMS devices [1]. However, where shelf life or replacement accessibility is a limiting factor, chemical power supplies may not be the optimal choice. We report here our development of a mechanically based integrated MEMS power generator that converts vibrational kinetic energy transferred from the immediate environment to electrical energy usable by low-power ICs or integrated micro sensors.

Some pioneering work related to vibration-based power generators were done by researchers at the University of Sheffield [2] and Chandrakasan's group at MIT [3]. Nevertheless, to the best of our knowledge, no one has demonstrated a micromachined generator with enough power to drive an off-the-shelf circuit. For this work, micromachining techniques are used to build the vibration-induced power generator because they offer two distinct advantages: 1) precise control of the mechanical resonance which is necessary to produce an efficient generator, and 2) batch fabricability which will allow low-cost mass production of commercially viable generators. The design analysis and experimental results of our first generation micro generators are presented in this paper.

## GENERATOR CONCEPT AND DESIGN

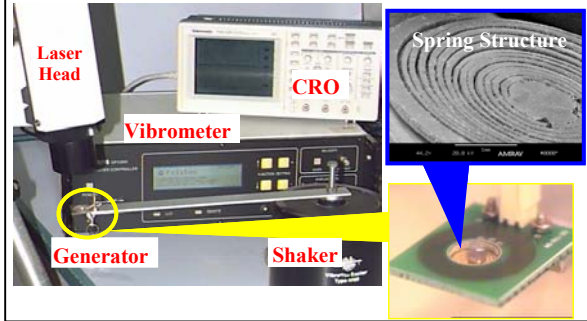
Photographs of the micro electromagnetic generator and the measurement setup are shown in Fig. 1. The generator consists of a rare-earth Nd-Fe-B magnet of mass  $m$  with magnetic field strength  $B$ , springs with total spring constant  $k$ , and coil of length  $l$ . The spring is attached to the magnet and a solid frame, forming a mass-spring resonator structure. The electrical coil is fixed on the rigid housing of the device. When the rigid housing is vibrated, the magnet will move relatively to the housing and the coil. This relative movement of the magnet to the coil

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results in varying amount of magnetic flux passing through the coil. According to Faraday's Law of induction, a voltage is induced on the coil. Optimization of the power transducer design based on electro-magneto-mechanical considerations was given in [4].



**Fig. 1.** Experimental setup for generator output and mass displacement measurement, and pictures of a "spiral" Cu spring structure and a generator.

## SPRING FABRICATION AND TESTING

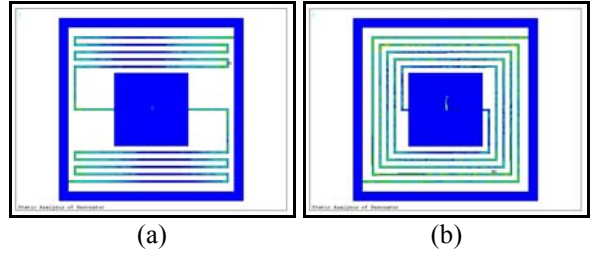
A comprehensive study concluded that copper is much better than silicon in terms of reliability and power generation for the spring structure [4]. The material properties of some common metals found in micromachining processes are compared in Table 1. It should be noted that although copper is better than Si, it is not the best material in terms of yield stress and fatigue limit. For instance, if extremely large displacement of the spring is needed, titanium should be used, as it is able to withstand a much higher stress. If the generator is required to work at low frequency range, 55-Ni-45-Ti should be used, as its Young's modulus is lower than copper. Our ongoing work is to explore 55-Ni-45-Ti as a low-frequency power generator. We employed copper and brass to fabricate the prototypes only because they are much more economical compared to titanium and 55-Ni-45-Ti. Calculations showed a low resonant frequency of about 10Hz can be achieved by using copper and brass spiral spring [5].

**Table 1:** Material data for the spring structure [6].

	Young's modulus (GPa)	Yield Stress (Mpa)	Ultimate Stress (MPa)	Fatigue Limits (Mpa)	Fatigue Ratio
Brass	96 – 110	70 – 550	200 – 620	98 - 147	0.31
Copper	130	55 – 760	230 – 830	63	0.29
Titanium	120	760-1000	900-1200	364	0.59
55-Ni-45-Ti	83	195-690	895	---	---

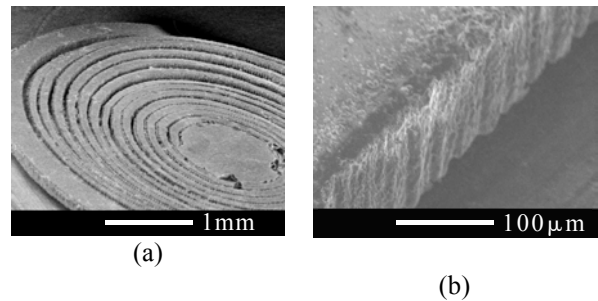
Different patterns of springs were modeled to optimize the resonating spring design, i.e., "zig-zag" and spiral structures (Fig. 2). ANSYS simulation results showed that the spiral springs have lower spring constant and lower stress concentration, thus a larger displacement

can be obtained. Moreover, if circular spiral shape is used, the stress can be further reduced [5].



**Fig. 2.** ANSYS modelling for different spring patterns: (a) "zig-zag" spring; (b) spiral spring

Based on ANSYS modelling results we have used a Q-switch Nd:YAG (1.06 $\mu$ m wavelength) laser to micromachine copper spiral spring structures as shown in Fig. 3. The ElectroX Scriba II D40 laser, which has 40 W of maximum power, was used in our work. The frequency of the laser pulse was set at 2 kHz and the pulse width of the laser was 100-300 nanoseconds. The laser beam was focused by a scanning lens (f- $\theta$  lens) with a focal length of 100mm onto the sample surface. The Gaussian spot size of the beam was determined to be around 400  $\mu$ m<sup>2</sup> at 1064 nm (diameter  $d_b$  of  $\sim$  22.6  $\mu$ m at  $1/e^2$  intensity). A laser system was used to micromachine the resonating springs because it offers direct and fast fabrication of copper springs with reasonable resolution. Our final system will involve high-aspect-ratio electroplating of copper using lithographic techniques.

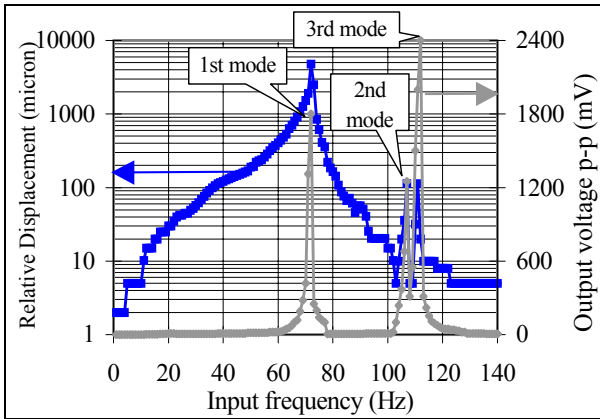


**Fig. 3.** Laser-micromachined copper springs. (a) A planar copper spring with total diameter of 4mm; (b) close-up of the spring shown in (a).

Using the setup as shown in Fig. 1, the mechanical input vibration and frequency, the transducer spring-mass motion, and the electrical output of the transducer were measured. Conventional model (as given in [4]) predicts that the power output should be proportional to the square of the vertical mass amplitude. However, we have observed experimentally that if springs were designed to have non-vertical resonance vibrations, voltage generated can be significantly higher. As shown in Fig. 4, for a "spiral" spring, the generator gave relatively high

voltage at higher frequencies even though the vibration amplitude was almost negligible in the vertical direction.

The motion of the mass-spring with 3 different modes of resonant vibration were captured digitally and analyzed. Using a strobe light to synchronize the vibration motion of the mass, the mass was observed to have a 2nd and 3rd mode resonance (Fig. 5b and c). The mass appeared to cyclically rotate about an axis parallel to the plane of the coil. Furthermore, it was observed that the amplitude of the rotation was very small compared to the vertical vibration at the 1st mode resonance (Fig. 5a). We therefore conjecture that if the a spring can be designed to vibrate in a horizontal plane with rotation, rather than a vertical plane relative to a coil, even under a force in the vertical direction, the voltage output can be increased and the stress on the spring can be reduced.



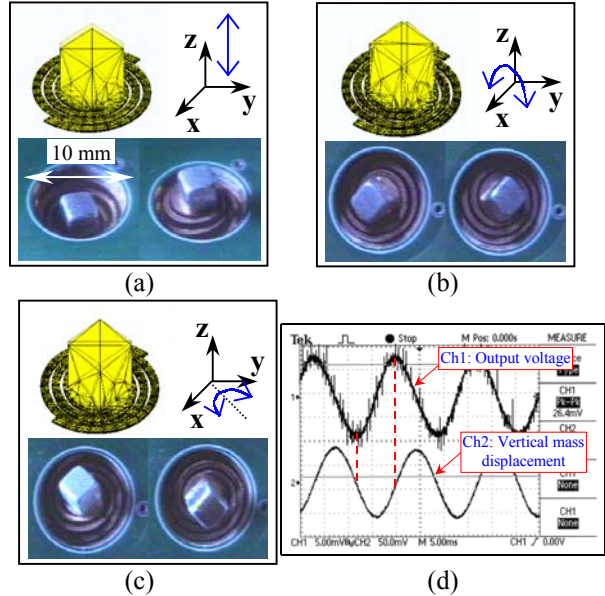
**Fig. 4:** Vibrational amplitude of the mass and the resulting voltage generated for a 2DOF spring structure.

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 translation and rotation of the mass, the greater current induction. As shown in Fig. 5d, at 3rd mode resonant vibration, the faster the rate of change of vertical displacement (i.e. slope of Ch2, it represents the “angular velocity” of the magnet), greater is the voltage induced.

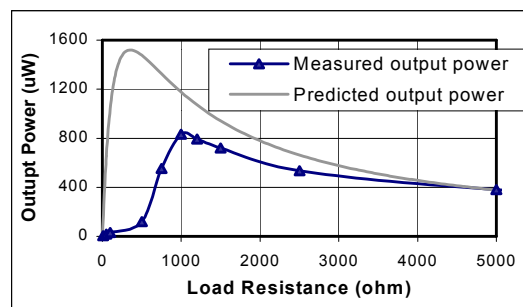
We have also performed ANSYS dynamic modelling for the spring design shown in Fig. 5, which matched the motion observed experimentally. Some discrepancies exist between the experimentally observed and the ANSYS-modelled modal resonant frequencies, which are most likely due to the imprecise packaging technique that we currently use, i.e., the magnetic mass is attached to the spring by epoxy without accurate alignment procedures, which will cause a shift of resonant frequency. We are currently developing a better packaging technique to overcome this problem.

The experimental generator output was also compared to the theoretical output. Ideally, the generator output with a loading resistance  $R$  can be predicted by (1) if the maximum output voltage  $V_{max}$  and internal resistance  $r$  are given. However, an experimental measurement shows a discrepancy (Fig. 6). The reason is mainly attributed to the existence of back e.m.f. when current passes through the coils. The effect is significant when the load resistance is small because smaller the resistance, larger the current will pass through the coils.

$$Output\ Power = I^2 R = V_{max}^2 R / (r + R)^2 \quad (1)$$



**Fig. 5.** FEA simulation and experimental results both found 3 different resonant vibration modes: (a) 1st mode vibration (vertical); (b) 2nd mode vibration (horizontal); (c) 3rd mode vibration (horizontal); (d) The phase difference between the output voltage of the generator and vertical displacement of the magnet at the 3rd mode vibration.



**Fig. 6.** RMS output power vs. load resistance.

## APPLICATIONS FOR WIRELESS TRANSMISSION

### Infrared Transmission

A standard quadrupler circuit (Fig. 7a) was used to step up the AC output from the generator to DC voltage (Fig. 7b). A prototype of this circuit was built using  $10\mu\text{F}$ ,  $25\text{V}$  electrolytic capacitors and Motorola Inc 1N5817RL Schottky diodes which have a forward voltage of  $0.32\text{V}$ . The output of the generator dropped to  $1.3\text{V}$  when loaded and to  $0.448\text{V}$  when the quadrupler was incorporated. However, the multiplied output DC voltage of  $2.3\text{V}$  is sufficient to drive most low voltage circuits. The measured average current was  $40\mu\text{A}$ , and hence the power output for this system is  $\sim 100\mu\text{W}$ .

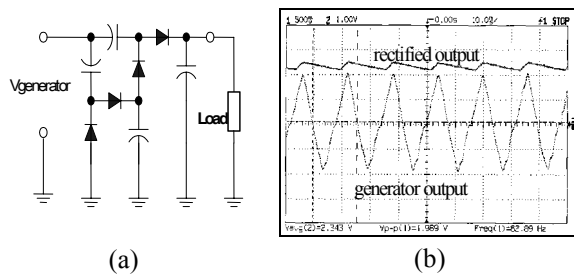


Fig. 7. (a) The quadrupler rectifying circuit; (b) Rectified output and generator output without load.

An Infrared (IR) transmitter was built using a commercial *SM5021* encoder chip. We have experimentally determined that this circuit could operate properly with a power supply as low as  $1.8\text{V}$ . Since the output current from the micro generator system (generator plus the rectifier) was too small ( $40\mu\text{A}$ ) to directly power the chip, the system was first used to charge up a large capacitor, which in turn was used to power the IR transmitter. An IR signal could be sent to a receiver every time a key was pressed. The signal was a  $140.8\text{ms}$  long IR pulse train. For a  $2.0\text{V}$  power supply, the current drawn during a key press was measured to be  $1.5\text{mA}$  and, in standby mode,  $2.4\mu\text{A}$ .

A capacitor of  $1.16\text{mF}$  was used as the power reservoir in the experiment. It was first charged up to  $2.0\text{V}$  and used to power the transmitter. It took 58 seconds to charge the capacitor from  $0\text{V}$  to  $2.0\text{V}$  and the charge stored is enough for 2 key presses whereupon the output voltage drops to  $1.56\text{V}$ . It would take another 30 seconds to charge it back to  $2.0\text{V}$ .

### RF Transmission

Again, since the generator could not produce enough instantaneous power and voltage to for this system, its output voltage was rectified and multiplied with a

standard tripler circuit and stored in capacitor  $C_1$ , which acts as a power reservoir (Fig. 8). The output of the tripler is  $3.5\text{V DC}$  at  $70\mu\text{A}$ . When the generator starts operating, it will charge up another capacitor  $C_2$  at the same time with a slower rate than  $C_1$  due to presence of the  $250\text{k}\Omega$  resistor. The resistance and capacitances were chosen such that the logic gate *MC14001*, will only switch on after  $C_1$  has been charged to  $3.5\text{V}$ . By doing so, the system will not consume any power before enough energy has been stored in  $C_1$ . This will ensure that there is enough energy for the first operation.

There are 3 main power-consuming components in the system: microcontroller (*SX-28*), temperature sensor (*DS1620*) and UHF-FM data transmitter (*TX3*). The controller is used to control the operations of the whole system, and process data. It instructs the temperature sensor to convert the ambient temperature to digital format and read the converted temperature through 3-wire communication protocol. The controller then sends the data serially to the *TXD* pin of the transmitter (Fig. 9c), which will modulate the digital temperature data into FM signal at  $914.5\text{MHz}$  to be received by the receiver module at a distance of  $25\text{m}$ . The microcontroller then disables all components and enter sleep mode. This allows the reservoir capacitors to be charged up again. After  $30\text{s}$ , the system will be waken up by the *Wakeup* signal from the multivibrator (Fig. 9b) and starts another conversion cycle.

The transmitted data is readily available in digital form from *RXD* pin of the receiver (Fig. 9d). The *RSSI* pin will indicate the receiving of new data when voltage goes high and the temperature data can be read after the indication of the *RSSI* pin.

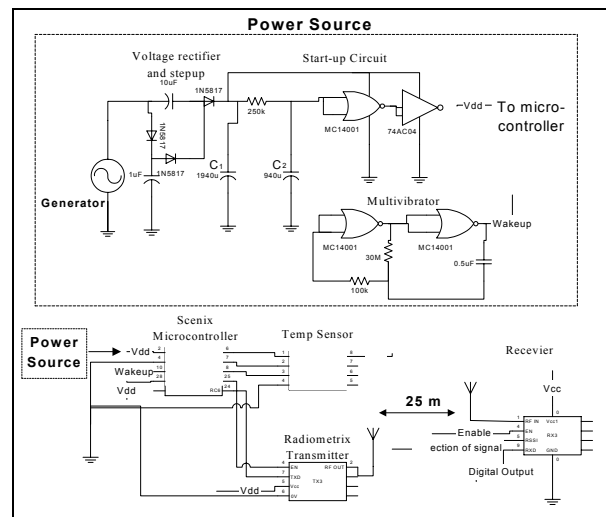


Fig. 8. Schematic diagram of the wireless temperature sensing system.

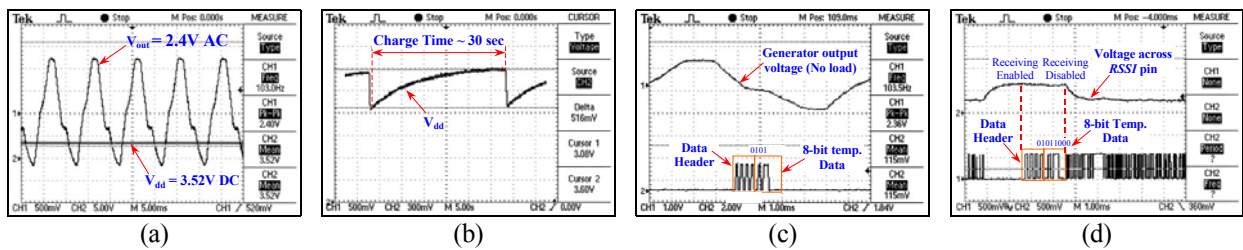
## CONCLUSION

We have demonstrated a magnet-based micro power generator that converts ambient vibration energy into electrical power using Faraday's Law of Induction. The generator is capable of powering a commercial IR remote control system and a custom built wireless temperature sensing circuit. We have found that, by innovative spring designs, the mass can be made to vibrate horizontally while the input vibration is applied vertically, and that this horizontal vibration gives significantly higher output voltage for the generator. Currently, for a generator with total volume of  $1\text{cm}^3$  or less, AC peak-to-peak output of 2 to 4.4V with maximum rms output power of  $200\mu\text{W}$  to  $830\mu\text{W}$  is possible between input frequencies of 60 to 110Hz with no more than  $200\mu\text{m}$  input vibration amplitude. Future work for this project include 1) design and development of low

frequency resonating springs with the aid of ANSYS modelling, 2) fabrication of the spring-mass and coil with an integrated process using optimized coil length, and 3) integration of the generator with low-power ICs and MEMS sensors. We believe that with the current trend in VLSI circuit design to minimize power consumption to extend battery life in portable systems, our micro generator can be incorporated in many applications, especially in distributed sensing systems.

## ACKNOWLEDGMENT

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**Fig. 9.** Readings from CRO: (a) The output voltage of the generator; (b)  $V_{dd}$  versus time (charge time is about 30 sec); (c) data read at TXD pin of the transmitter represents the room temperature is  $26^\circ\text{C}$  ("01011000", counted from right to left); (d) data read at RXD pin of the receiver is also  $26^\circ\text{C}$ .

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