PCB INTEGRATED MICRO-GENERATOR FOR WIRELESS SYSTEMS

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ABSTRACT

This paper presents the development of a printed circuit board (PCB) integrated vibration-induced power generator with total volume of ~1cm^3 that uses laser-micromachined springs as resonating structures. The goal of our research is to create a minimally sized, economical, and circuit integrated electric power generator capable of producing enough voltage to drive low-power IC circuit or wireless micro sensors where mechanical vibrations are present. Potential applications for the generator may also include mobile phone and heart-pacers where human motions can be used as a source of mechanical energy. Thus far, we have produced a PCB-integrated generator capable of producing 245mV peak-to-peak voltage with 104Hz input frequency and 240μm input vibration amplitude.

KEYWORDS: *integrated power generator, micro power generator, micro battery, micro energy converter*

1. INTRODUCTION

One of the projected goals for Micro Electro Mechanical Systems (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 supply with MEMS devices. However, where shelf life or replacement accessibility is a limiting factor, chemical power supplies may not be the optimal choice. We propose to build a mechanically based integrated MEMS power generator which will convert vibrational kinetic energy transferred from the immediate environment to electrical energy usable by a low-power CMOS circuit chip and integrated microsensors. Micromachining techniques are used to build the vibration electric 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 fabrication which will allow low-cost mass production of commercially viable generators. The current trend in very large scale integration (VLSI) circuits design is in minimization of power consumption to extend battery life in portable systems and heat removal in larger systems. Coupling with the recent advent in low-power MEMS sensors, a MEMS integrated mechanical power generator with life span far greater than its chemically based counterparts will be imperative in diverse sensor and circuit applications in the near future.

Various integrated micro power supplies have been proposed recently. Matsuki et al. used an energy coupling method to remotely induce voltages on-chip by magnetic field in 1988 [1]. Bates et at. developed rechargeable lithium micro batteries which were used as self-contained on-board power supply in 1993 [2]. Lee et al. built a miniaturized high-voltage solar cell array which was effective in driving electrostatic silicon mirrors in 1995 [3]. A comprehensive study on the feasibility of micro power supplies for MEMS was presented by Koeneman et al. in 1997 [4], who concluded that the most practical forms of micro energy storage media are chemical batteries, elastic strain energy, electric fields, and magnetic fields. However, there are many applications where light, thermal, electrical, or magnetic energies are not practical or available, therefore, we propose a new power supply which is integrable with MEMS and IC devices, and which generates electricity from ambient mechanical vibrations.

Shearwood & Yates [5] and Williams and Yates [6] developed an electromagnetic micro generator that attached a magnet to a flexible polyimide membrane to produce 0.3μW on a planar pick-up coil in 1997. No structural optimization or integration of their generator to a circuit system was reported. Amirtharajah & Chandrakasan [7] have successfully used a *macro* (500mg mass, with conventional springs) vibration-based power generator to drive a signal processing circuitry in 1998. To the best our knowledge, no one has published a work combining a MEMS resonating system and a low-power circuit system with optimized mechanical structures for specific applications. For this project, we propose to develop an integrated, efficient, and robust vibration-based power generator suitable for low-power sensor and circuit systems.

2. POWER GENERATION FROM MECHANICAL EXCITATION

A simple power-generation model analysis using frequency domain approach is presented below for the sake of understanding the importance of the governing physical parameters of the system. A schematic illustration of the system is shown in Figure 1(a) and an illustration of an integrated spring-mass power generation system is shown in Figure 2. The voltage generated on the wire coil is modeled by a first order LR circuit which takes the magnet motion z as input. The governing physical parameters are the mass of magnet m, magnetic flux B, spring constant k, inductance of the coil L, and resistance of the coil R_c, and the load resistance R. In addition, the housing vibration amplitude $y(t)$ and frequency ω will affect the relative magnet vibration amplitude $z(t)$, which consequently affects the power output of the system.

The block diagram for this system is shown in Figure 1(b) and the system transfer function can be rewritten as [8]:

$$V(s)/F(s) = Bls/\left[(ms^2 + ds + k) + s(Bl)^2/R\right] \qquad \textbf{Eq. 1}$$

From the above equation, at resonance, the average power and the voltage output are maximized:

$$P_{\max} = m\xi_e Y_0^2 \omega_n^3/(4\xi) \qquad \textbf{Eq. 2}$$

and

$$V_{\max} = \sqrt{2P_{\max}R} = BlY_0\omega_n/2\xi \qquad \textbf{Eq. 3}$$

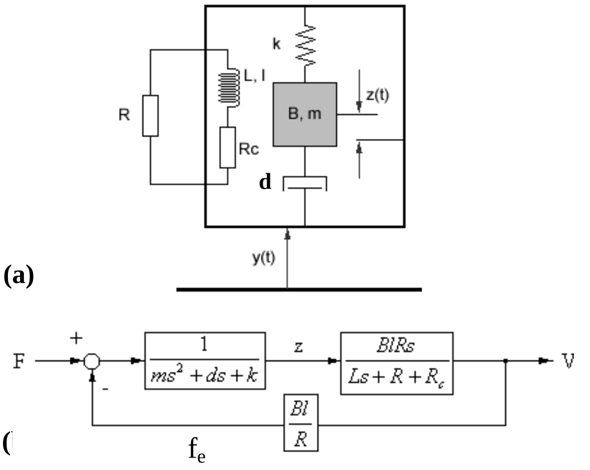


Figure 1. Schematic illustration and transfer function block diagram for the micro power generator.

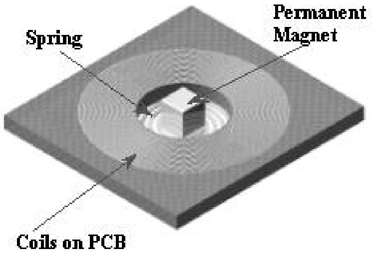


Figure 2. Illustration of a PCB integrated generator.

Design Objective

Since the applications for micro power generators abound we will only constrain the current analysis to the design of a generator which is small and able to generate usable electrical power under typical human activities. So, the question which needs to be answered is: what is the smallest generator possible which can generate 1V for a system consuming 30µW power at input frequencies ranging from 2 to 10 Hz (i.e., human walking or running) using conventional MEMS technology? Our goal is to create an integrated system which contains the resonating spring, the PCB-planer coil, and the IC or micro sensor chip (as shown in Figure 3).

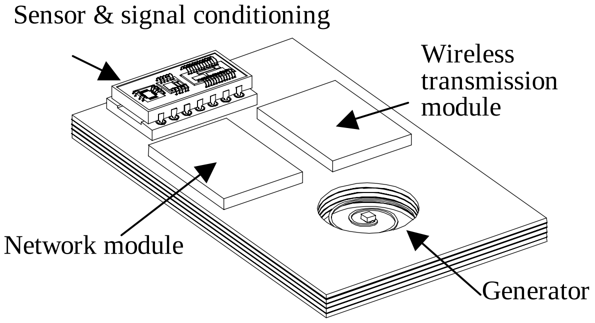


Figure 3. Conceptual drawing of an application example for PCB integrated generator for wireless systems.

Silicon Springs for Low Vibration Systems?

If the mass of magnet is known (governed by state-of-the-art technology for small volume and high field strength material) and assuming all mechanical power can be converted into electrical power (assume 30µW is needed to run a given IC system), then Equation 2 can be used to find the resonant amplitude of the spring at a given input vibrational frequency (Figure 4). So, a spring must, minimally, be able to withstand deflection at this amplitude if it needs to generate the required power. Now, the spring constant k and the mass m have the relationship $\sqrt{k/m}$ at resonant angular frequency ω_n, hence, if the input frequency is given, a spring can be designed to have resonance at that frequency. Then, if the length and width of the spring are given, the thickness of the spring can be designed to achieve a given k. Moreover, if the yield stress of a structural material is known, the maximum deflection allowed for a given spring design can also be found. We have assumed the length of the spring is fixed at 5000µm (allowing the magnet to be centered on a spring of 1cm diameter as shown in Figure 2) and the width is 100µm (conservative estimate for Si bulk-micromachining technology), then the allowable deflection of a spring and its thickness can be found as a function of input frequency. This analysis is shown in Figure 4 for silicon and copper. Clearly, for a 1cmx1cm system with 30µW power output, a Si cantilevered beam can not achieve the <10Hz requirement, because it can not achieve the required amplitude without structural damage. On the other hand, copper is a very good material, because it is non-magnetic, has low spring-constant, and high yield stress, for low frequency resonance power generation. As shown in Figure 4, the allowable deflection exceeds the required deflection even a 2Hz vibration. Also, the required thickness of copper for this deflection is ~10µm, which is readily available commercially.

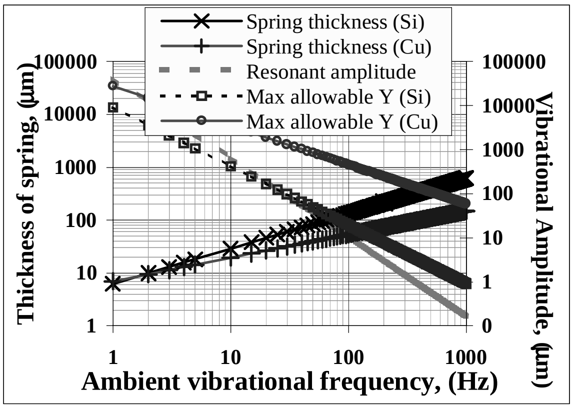


Figure 4. Analysis of spring thickness requirement and the maximum allowable deflection as functions of ambient and coil length

In addition, as implied by Figure 1, many parameters govern the optimization of a generator even if the size of the generator is known a priori. These parameters are listed in Table 1. As an example, the dependence on voltage output versus coil length and input vibration frequency is shown in Figure 5. In general, even though voltage output can be maximized by increasing input frequency, precise coil length is critical in optimizing the voltage output, especially for higher frequency vibrations.

z	Mass displacement relative to coil	R	Load resistance
V	Voltage output at load resistor	L	Coil inductance
ω_v	Spring natural frequency	R_c	Coil resistance
d	Mechanical damping coefficient	M	Mass of magnet
B	Magnetic field strength of magnet	F	Input force
k	Spring constant of springs	l	Coil length
y	Input displacement	f_e	Feedback e.m.f.

Table 1. List of variables critical to the performance of the power generator

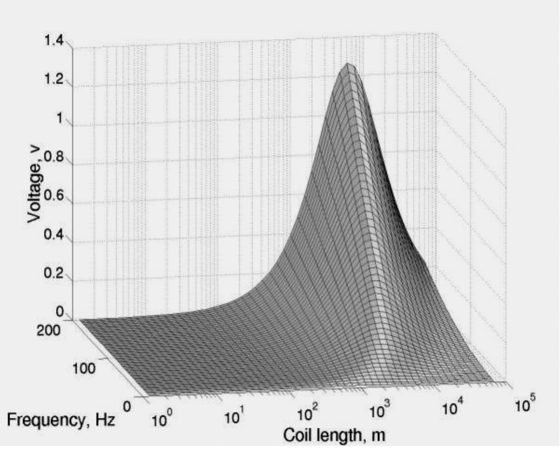


Figure 5. Voltage output versus vibration frequency.

3. FABRICATION OF THE POWER GENERATOR SYSTEM

Illustrations of the single- and multi-layer PCB power generators are shown in 6(a) & (b), respectively. The current generator system is composed of 3 parts: the laser-micromachined spring, PCB coils and rare earth (sintered neodymium) permanent magnet.

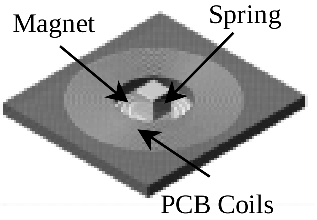


Figure 6(a) Integrated power generator system with single-layer PCB coil.

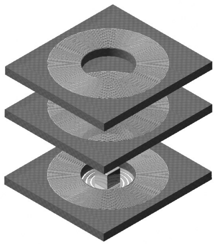


Figure 6(b) Integrated power generator system with multi-layer PCB coil.

Laser-micromachining for the single- and five-layer PCB coils

Two prototype PCB coils were made by using a Nd:YAG (Neodymium: Yttrium Aluminum Garnet) laser machine (Electrox: Scriba D40) to pattern the planar coils on the PCBs. The details of the single- and five-layer prototypes are shown in Table 2. The single-layer PCB generator was fabricated with a single-layer PCB by the laser-mircomachining, and the 30mV maximum peak-to-peak output voltage and output power of 1.5μW were obtained. However, the prototype of the 5-layer PCB coil consists of two double-sided PCBs and one single-sided PCB. Copper wires were used to inter-connect every layer to multiply the turns of coil and protective lacquer (CRC Plasticote 70) was sprayed to insulate the unwanted contact. Maximum peak-to-peak output voltage of 245mV and 5μW output power were recorded for the 5-layer PCB generator. The results revealed that higher density of the coil on board and more layers can increase the output voltage the generator significantly when the same spring structure is used.

Laser-micromachining is only used to get higher coil density (trace/space: 25/25μm) for the PCB coils because the available commercial PCB process gives only 100/100μm in Hong Kong.

Multi-layer PCB fabrication technique for the 6-layer PCB generator

After fabricating the prototypes of the single-layer and 5-layer PCB coil, we proved that by using multi-layer PCB coil output power of the generator can be multiplied. However, in using laser-micromachining to fabricate the PCB coil, we found the problems of inconsistency and "over cut" are common in the prototype fabrication process. Base on these facts, the 6-layer PCB planar coils were designed to be patterned by conventional process. PCB boards will be etched on every layer to result in multi-turn windings. Plated via holes are used to interconnect every layer to increase total number of coil turns. The layout of the 6-layer PCB coil was drawn using an EDA (electronic design automation) software (Protel 99) (as shown in Figure 9(a)). Design of arrays of generators are proposed in this new prototype (Figure 9(b)) and the output voltage will be expected to multiply by connecting two or more generators in series. By using the layout files (Gerber format), prototypes of 6-layer PCB coils can be fabricated with automated equipment in a local factory. The resolution of the trace/space will be about 100/100µm. Experiments of the prototype will be done after fabricating the prototypes.

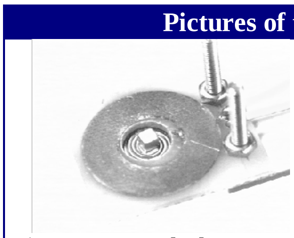
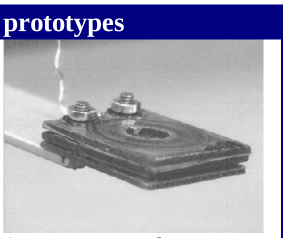
<table>
<tr><th colspan="2">Pictures of the prototypes</th></tr>
<tr><td>
Figure 7. Single-layer prototype.</td><td>
Figure 8. Five-layer prototype.</td></tr>
<tr><th colspan="2">Main specs. of the PCB coils</th></tr>
<tr><td>Outer diameter: 24mm
Inner diameter: 12.4mm
Number of turns: 48
Pitch of coil: 120µm
Coil length: 2744mm
PCB thickness: 1.6mm</td><td>Outer diameter: 25mm
Inner diameter: 12.4mm
Total no. of turns: 580
Coil pitch: 54µm
Coil length: 32984mm
PCB thickness: 4.8mm</td></tr>
<tr><th colspan="2">Experimental results</th></tr>
<tr><td>Output
max. peak-to-peak
output voltage: 30mV
output power: 1.5µW
Input
frequency: 107Hz
amplitude: 210µm</td><td>Output
max. peak-to-peak
output voltage: 245mV
output power: 5 µW
Input
frequency: 104Hz
amplitude: 190µm</td></tr>
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Table 2. Details and comparisons between single and five-layer PCB generator.

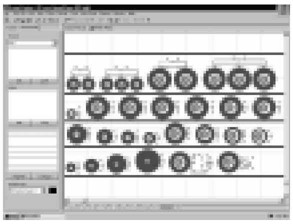


Figure 9(a). Layout of different designs of the 6-layer PCB generator in one board.

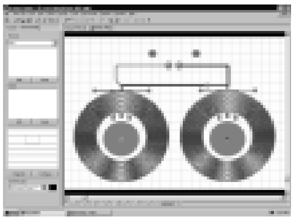


Figure 9(b). Array of the generators design.

Fabrication of the Spring Structures

We use laser-micromachining to fabricate the spring structures. A laser-micromachined spring structure is shown in Figure 10(a). Since copper springs are more suitable for low-frequency energy conversion we use the YAG laser machine to micromachine copper spring structures. A 5mm diameter resonating structure is shown in Figure 10(a). As indicated by Figure 10(b), the laser gives rough vertical surfaces if the power, pulse rate, and scan speed are not optimized. We are now working on optimizing these parameters to obtain smooth vertical side walls for the copper resonating structures as rough walls may affect the designed resonant frequency of the structures.

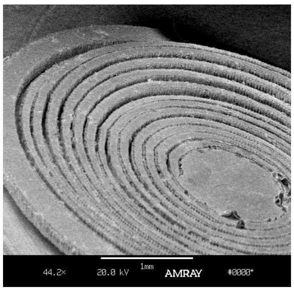


Figure 10(a) A laser-micromachined Cu spring structure. The diameter of the entire structure is 5mm.

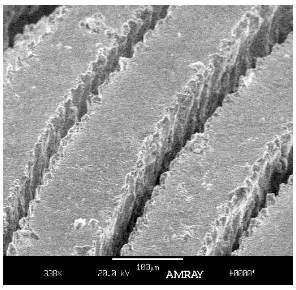


Figure 10(b) Close-up view of the structure in (a). The width of the spiral-structure is about 100µm.

4. EXPERIMENT AND SIMULATION RESULTSMass vibration motions and Power Output

The measurement setup for vibration amplitude and power output is indicated by Figure 11. The vibrometer and laser head are used to measure the vibration amplitude of the mass. The CRO can show the readings from the vibrometer and the power output of the generator. Figure 12 indicates the vibration amplitude at the tip of the cantilever produced by the vibration drum.

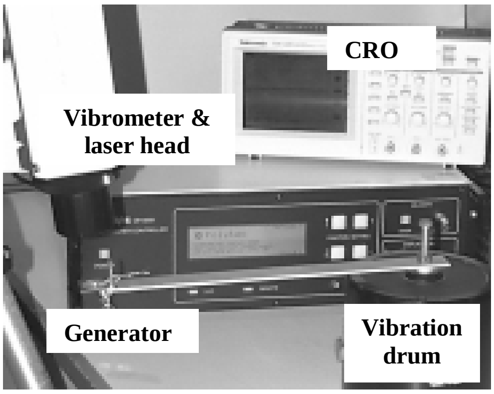


Figure 11. Measurement setup to measure vibration amplitude.

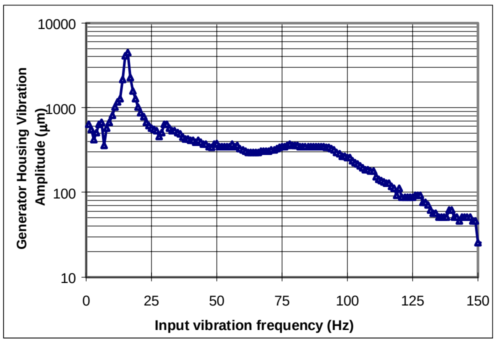
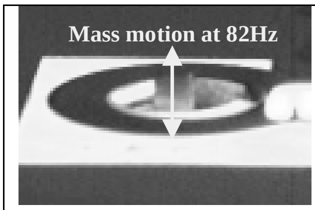
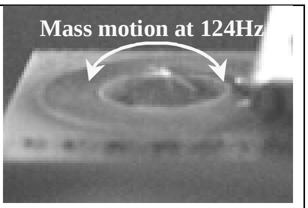
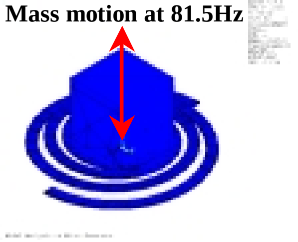
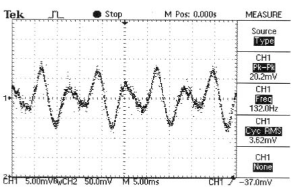
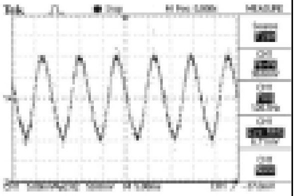


Figure 12. Cantilever tip vibration amplitude versus input frequency.

With a special design of spring, two different modes of resonance are observed and analyzed. The first mode occurs at the frequency range of 65-80Hz and the mass motion is mainly vertical (as shown in Figure 13 (a)&(c)). The frequency of mass vibration is exactly same as the input frequency. With higher input frequency (~100-130Hz), the second mode of the resonance dominated the mass vibration motion which is front-and-back motion (as shown in Figure 13 (b) & (d)). Experiments showed that the second mode resonant vibration could generate higher output voltage (as shown in Figure 13 & 14) because magnetic flux lines will change more with this oscillating movement. On the other hand, the vibration amplitude in z-axis of the second mode vibration is much less than the first mode so the spring structure will be more reliable.

 **Figure 13(a).** *Experimental result*: mass motion at the first mode resonance.	 **Figure 13(b).** *Experimental result*: mass motion at the second mode resonance.
 **Figure 13(c).** *Simulation result*: mass motion is same as the experimental result at 81.5Hz.	 **Figure 13(d).** *Simulation result*: mass motion is same as the experimental result at 135.5Hz.
 **Figure 13(e).** *Experimental result*: The peak-to-peak output voltage of 20mV at the 1st mode resonant vibration at 82Hz.	 **Figure 13(f).** *Experimental result*: The peak-to-peak output voltage of 30mV at the 2nd mode resonant vibration at 124Hz.

5. CONCLUSION

This paper presented the development of a PCB integrated power generator with laser micromachined spring structures that converts mechanical vibrations into electrical power. The prototype generator is able to generate 5µW power at peak-to-peak voltage, 245mV AC with an input excitation frequency of 104Hz and amplitude of 190µm. Some mechanical structures have been studied to optimize the spring constant for different environmental excitation. Future work for this project include 1) improvement of the micro generator by optimizing the damping factor of the system and PCB planar coil, 2) reduce resonant frequency of the spring structure, and 3) integrate the generator for a wireless systems.

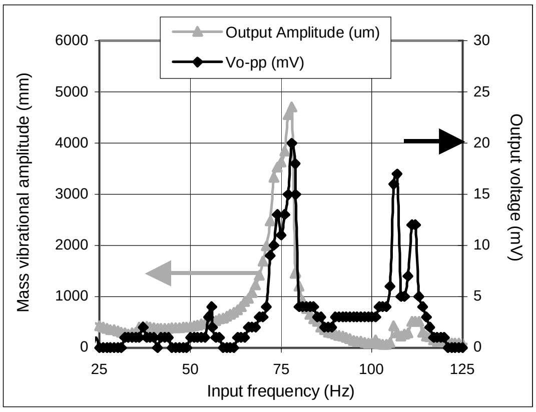


Figure 14. Experimental result of the single layer prototype.

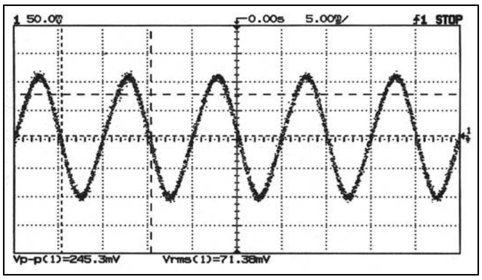


Figure 15. The peak-to-peak output voltage of 245mV produced from the 5-layer PCB prototype with input frequency of 104Hz and input amplitude of 190µm.

ACKNOWLEDGEMENT

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