Design and fabrication of a micro electromagnetic vibration energy harvester*

Wang Peng(王鹏)[1,2], Li Wei(李伟)[1], and Che Lufeng(车录锋)[1,†]

[1]State Key Laboratory of Transducer Technology, Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, Shanghai 200050, China
[2]Graduate University of the Chinese Academy of Sciences, Beijing 100049, China

Abstract: This paper presents a new micro electromagnetic energy harvester that can convert transverse vibration energy to electrical power. It mainly consists of folded beams, a permanent magnet and copper planar coils. The calculated value of the natural frequency is 274 Hz and electromagnetic simulation shows that the magnetic flux density will decrease sharply with increasing space between the magnet and coils. A prototype has been fabricated using MEMS micromachining technology. The testing results show that at the resonant frequency of 242 Hz, the prototype can generate 0.55 μW of maximal output power with peak–peak voltage of 28 mV for $0.5g$ ($g = 9.8$ m/s^2) external acceleration.

Key words: electromagnetic energy harvester; MEMS; resonance; permanent magnet
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1. Introduction

Wireless sensor systems are receiving increasing interest since they offer flexibility, ease of implementation and the ability to retrofit systems without the cost and inconvenience of cabling[1]. At present, the majority of wireless sensor nodes are simply battery-powered. But sometimes replacing batteries is not compatible with embedded applications, nor is it feasible for networks with large numbers of nodes. The advances made in lowpower wireless systems present an opportunity for alternative types of power source[2].

Energy harvesting approaches that transform light, heat and kinetic energy that is available in the sensor's environment into electrical energy offer the potential of renewable power sources that can be used to directly replace or augment the battery. Such renewable sources could increase the lifetime and capability of the network and mitigate the environmental impact caused by the disposal of batteries[1−3].

The vibration energy harvester is a kinetic energy generator that converts mechanical energy in the form of vibrations present in the application environment into electrical energy. Kinetic energy is typically converted into electrical energy using electromagnetic, piezoelectric or electrostatic transduction mechanisms[4].

The electrostatic energy harvester has the lowest energy and usually needs an electret layer. Université Paris-Est has made an electret-free silicon electrostatic vibration energy harvester[5], which can generate a maximum power output of 61 nW on a 60 MΩ resistive load, under a vibration level of 0.25 g at 250 Hz. The piezoelectric energy harvester needs very thin material and usually is not compatible with CMOS[6]. The electromagnetic energy harvester needs a permanent magnet and has a large volume，but it also has the highest energy and it can be used in many wireless sensor systems[7]. A silicon electromagnetic microgenerator with a volume of about 10 mm^3 was fabricated by Southampton University[8]. It can generate a maximum power output of 104 nW for 0.4 g input acceleration at 1.615 kHz. A prototype made by Shanghai Jiaotong University can generate induced voltage (peak–peak) of 18 mV and output power of 0.61 μW for 14.9 m/s^2 external acceleration at its resonant frequency of 55 Hz[9].

The new electromagnetic energy harvester can convert transverse vibration energy to electrical power. The transverse stiffness and the damping coefficient of the folded beams are very small, so the energy harvester can convert low frequency and low level transverse vibration energy to electrical power. A prototype has been fabricated using MEMS micromachining technology. It can generate peak–peak voltage of 28 mV and output power of 0.55 μW for 0.5 g external acceleration at its resonant frequency of 242 Hz.

2. Design of the energy harvester

2.1. Design of the structure

The structure of the electromagnetic energy harvester is shown in Fig. 1. The permanent magnet is placed on the spear plate and we can adjust the space between the magnet and coils.

The operation principle of the electromagnetic vibration energy harvester is Faraday's law of electromagnetic induction, which is expressed as [9]

$$U = -n\frac{\partial \Phi}{\partial t} = -n\frac{\partial (\boldsymbol{B} \cdot \boldsymbol{S})}{\partial t}, \tag{1}$$

where n is the number of turns of the closed circuit, $\boldsymbol{B}$ is the magnetic flux in every turn, and $\boldsymbol{S}$ is the area vector of the closed circuit. The change rate of the magnetic flux through the coils should be as large as possible. The vibration frequency of the system is known and unchanged for a given vibration energy harvester. Therefore, only magnetic field density can be increased in order to increase the change rate of the magnetic

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† Corresponding author. Email: lfche@mail.sim.ac.cn
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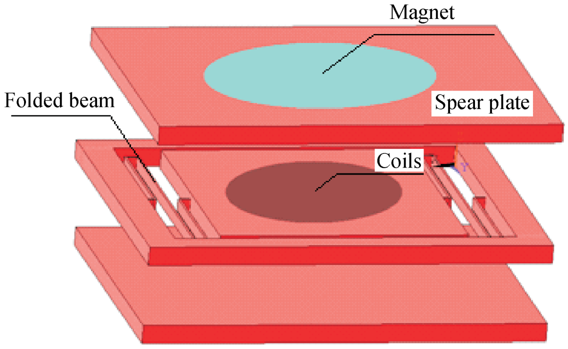


Fig. 1. Schematic structure of the electromagnetic energy harvester.

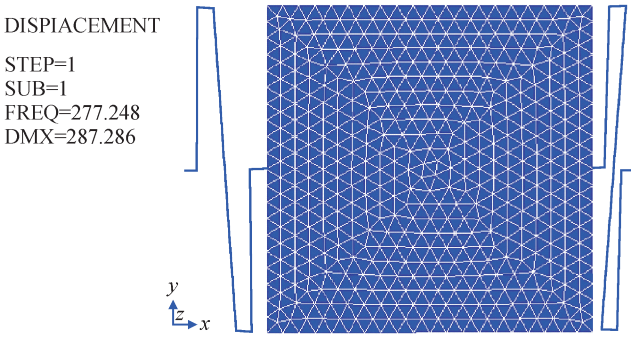


Fig. 2. First modal shape of the vibration.

flux. So a kind of magnet with high magnetic energy product should be selected. We choose NdFeB N35 permanent magnet material.

2.2. Design of the spring

Because the energy harvest works at its resonant frequency, at this time the maximum of the average power transferred to the system is[10]

$$\bar{P}(t)=\frac{mY^2\omega_{\mathrm{n}}^3}{4\zeta}=\frac{Y^2\omega_{\mathrm{n}}^3 m^{3/2}k^{1/2}}{2c}. \qquad (2)$$

If the frequency and the amplitude of the input vibration are given, the mass should be as large as possible and the damping coefficient should be made as small as possible.

We choose the folded beams, as in Fig. 2.

The mass block is 4000 × 4000 × 420 $\mu\mathrm{m}^3$. The mass of the block is $M=\rho V=15.7\,\mathrm{mg}$.

The linewidth and thickness of the spring is h and d.

The space of the spring is 160 μm.

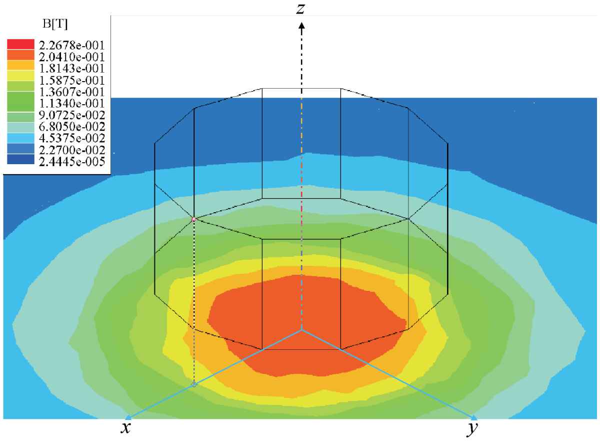
For a folded beam, the transverse stiffness, K_{X}, is

$$K_{\mathrm{X}}=192EI_{\mathrm{Z}}X, \quad I_{\mathrm{Z}}=\frac{dh^3}{12}, \qquad (3)$$

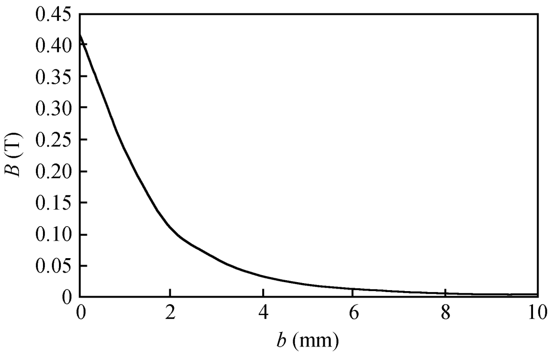
where E is the Youngs modulus of the material[11], the crystallographic direction <100>, $E=1.3\times10^{11}$ Pa.

X is a modulus for the folded beam,

$$X=\frac{64a+12b}{2b^2\left[12a^2\times58+30b^2+4ab\times82\right]},$$
$$a=0.11\times10^{-3}\,\mathrm{m}, \quad b=4.97\times10^{-3}\,\mathrm{m}. \qquad (4)$$



(a) Flux density distribution on *xy* surface simulated by Maxwell



(b) Calculated magnetic flux density versus the space

Fig. 3. NdFeB N35 permanent magnet material.

We choose $h=35$ μm, $d=180$ μm, the two folded beams,

$$K_{\mathrm{X}}^*=2K_{\mathrm{X}}=46.65\,\frac{\mathrm{kg}}{\mathrm{s}^2}, \quad f_{\mathrm{X}}=\frac{1}{2\pi}\sqrt{\frac{K_{\mathrm{X}}^*}{M}}\approx274\,\mathrm{Hz}. \qquad (5)$$

By mechanical simulation, the first modal shape of the vibration is shown in Fig. 2 and the value of the natural frequency is 277 Hz, similar to the calculated value. The vibration of the mass of the block is transverse vibration, as in our design.

2.3. Electromagnetic simulation

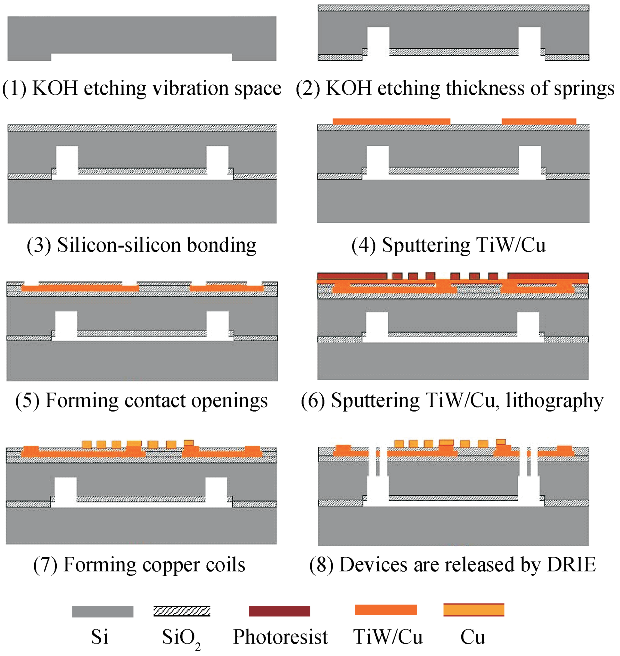
We choose NdFeB N35 permanent magnet material, and $B_{\mathrm{r}}=1.2\ T$, $R=2$ mm, $T=2$ mm. The simulation result of the flux densities on the transverse surface using the software of Maxwell 3D is shown in Fig. 3(a).

For a given cylinder magnet, the magnetic flux density B is given by equation[10],

$$B=\frac{B_{\mathrm{r}}}{2}\left[\frac{d+T}{\left[R^2+(d+T)^2\right]^{1/2}}-\frac{d}{\left(R^2+d^2\right)^{1/2}}\right], \qquad (6)$$

where d is the distance from the coil to the magnet, B_{r} is the residual magnetic flux density, and R and T are the radius and thickness of the magnet, respectively.

Figure 3(b) shows the relationship between the magnetic flux density and the space of magnet and coils based on the

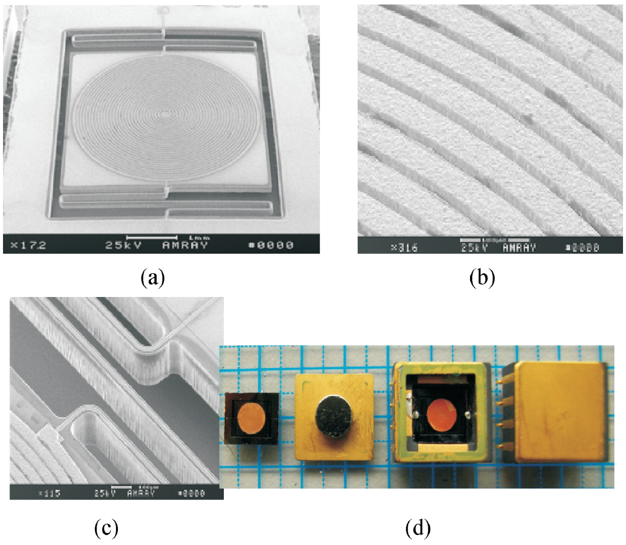

(1) KOH etching vibration space (2) KOH etching thickness of springs

(3) Silicon-silicon bonding (4) Sputtering TiW/Cu

(5) Forming contact openings (6) Sputtering TiW/Cu, lithography

(7) Forming copper coils (8) Devices are released by DRIE

Fig. 4. Fabrication process of the prototype.


(a) (b)

(c) (d)

Fig. 5. The fabricated energy harvester. (a) SEM picture of the structure. (b) SEM picture of the copper coils. (c) SEM picture of folding beam and conducting wire. (d) Photo of the prototype, magnet and package of the energy harvester.

equation. It is clear that the flux density will decrease sharply with increasing space between the magnet and coils.

A smaller space between the magnet and coils is attributed to a higher output performance.

3. Fabrication process

The prototype that has the same structure as the modified model shown in Fig. 1 has been fabricated by MEMS technology. The fabrication process of the prototype is shown in Fig. 4.

(1) First, an oxide layer is formed on the silicon substrate, lithography on the backside, using KOH etching the place for vibration, get rid of SiO_2. (2) An oxide layer is formed again, lithography on the backside, using KOH etching the thickness of the spring, the rest SiO_2 is used for isolation. (3) Silicon–silicon bonding. (4) Form the copper conducting wire by sputtering TiW/Cu. (5) An oxide layer is formed on the silicon substrate by PECVD, used for isolation. Lithography, etch and form the contact openings of the two pads and the two copper conducting wires. (6) Sputter TiW/Cu and pattern the first metal, lithography of the thick film. (7) Copper coils are formed by electroplating. Remove the superfluous TiW/Cu by ionbeam. (8) The silicon is etched by DRIE and the devices are released.

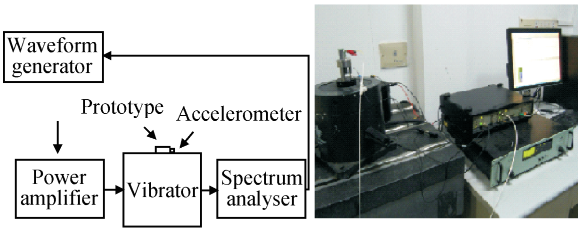


Fig. 6. Schematic of the testing setup.

Figures 5(a)–5(c) show the SEM pictures of the structure, the copper coils and the folded beam, respectively. The width and the gap of the coils are 60 μm and 20 μm, the height is 16 μm and the number of turns is 26. Figure 5(d) shows a photo of the package of the energy harvester. First, the permanent magnet is fixed on the spear plate. Second, the prototype is placed on the purpose made ceramic tube ($12 \times 11 \times 5$ mm^3), then fabricates the electrode leaders. Finally, the spear plate is fixed in the ceramic tube. The space of the magnet and coils is 0.8 mm.

4. Experimental results and discussion

In addition to the induced voltage in the coils, the output power is another important evaluation parameter for the vibration energy harvester. The power generated on the outer circuit is

$$P = \left(\frac{U}{R_{\rm H} + R_{\rm L}}\right)^2 R_{\rm L}, \tag{7}$$

where $R_{\rm H}$ and $R_{\rm L}$ are the inner resistance of the harvester and that of the outer circuit, respectively. When $R_{\rm L} = R_{\rm H}$, the maximum output power can be determined from $P_{\rm M} = U^2/4R_{\rm H}$. So the maximum output power is inversely proportional to the inner resistance of the harvester. The calculated value of the $R_{\rm H}$ is

$$R_{\rm H} = R_{\rm wire} + R_{\rm coils} = \frac{\rho l_1}{S_1} + \frac{\rho l_2}{S_2} = 37\,\Omega. \tag{8}$$

The testing value of the fabricated prototype is 89 Ω. This is because the contact resistance between the coils and the copper conducting wire, the electrodes and the fabricated electrode leaders is very large.

The output performance of the prototype is measured using the experimental setup shown in Fig. 6. A B&K vibrator is used to supply mechanical vibration for the prototype. A B&K power amplifier incorporated with a waveform generator

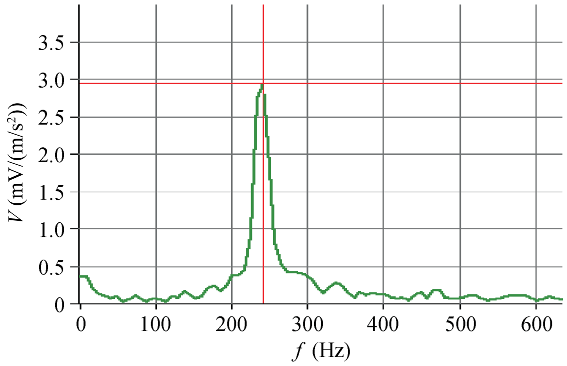


Fig. 7. Resonant frequency of the energy harvester.

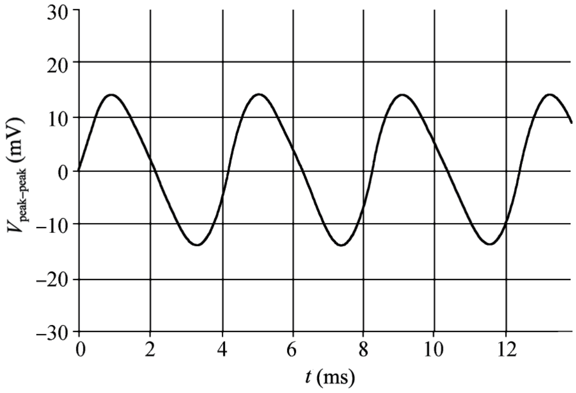


Fig. 8. At the resonant frequency of 242 Hz, the peak–peak voltage for 0.5g external acceleration.

is used to drive the vibrator and regulate its vibration strength. The prototype is glued on the top of the vibration generator.

Figure 7 shows that the resonant frequency of the energy harvester is 242 Hz.

Figure 8 shows that voltage (peak–peak) is 28 mV for 0.5g external acceleration at its resonant frequency of 242 Hz. So the maximum output power is 0.55 μW.

5. Conclusion

The subject of this paper is a new micro electromagnetic energy harvester. It mainly consists of folded beams, a permanent magnet and copper planar coils. The transverse stiffness of the spring is very small, so the energy harvester can convert low frequency transverse vibration energy to electrical power. A prototype has been fabricated using MEMS micromachining technology. It can generate peak–peak voltage of 28 mV and output power of 0.55 μW for 0.5g external acceleration at its resonant frequency of 242 Hz.

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