SPRINGLESS CUBIC HARVESTER FOR CONVERTING THREE DIMENSIONAL VIBRATION ENERGY

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ABSTRACT

This paper reports the design, fabrication and measurement of a springless cubic energy harvester. Based on the flexible printed circuits, coils are fabricated onto both sides of the polyimide substrate and then folded to a cubic box, meanwhile sealed a free magnet inside the box. As the coils are folded on three different directions, vibration in all dimensions can cause the change of magnetic flux and the energy is effectively harvested. Output performance of the device is both theoretically and experimentally investigated. Benefit from the springless structure, maximum output is achieved at low frequencies with a wide bandwidth. Moreover, the device can be placed on a backpack or wrist to harvest vibration energy from daily life.

INTRODUCTION

With the rapid development of microelectronic technology, devices such as portable electronics, wireless sensors have been applied in various fields. The power consumption of these devices has been lowered to the level of milli or micro watts thanks to the development of CMOS (complementary metal oxide semiconductor) low power consumption technique. Therefore, harvesting vibrational energy from the ambient environment is becoming a promising way to power microelectronic devices [1]. Based on different transduction mechanisms, various electromagnetic [2, 3], piezoelectric [4, 5], electrostatic [6, 7], and hybrid [8, 9] energy harvesters have been fabricated and investigated. Compared with other energy harvesters, electromagnetic energy harvester has been widely studied due to its low resistance and high output current. Moreover, the processing circuit of electromagnetic energy harvesters is relatively simple and efficient, which makes electromagnetic energy harvesters a promising substitute for traditional batteries.

However, previous electromagnetic harvesters have some drawbacks which limit the application field. Firstly, most of the electromagnetic harvesters are based on spring/mass configuration [10]. With this structure, only vibrational energy in a specific direction can be effectively harvested. Besides, fabrication of the spring/mass structure is complex and expensive. Etching process is usually required to fabricate such a structure. Finally, the substrates of previous electromagnetic energy harvesters are basically silicon or steel, which is not flexible and biocompatible.

Therefore, in this work, we fabricate an electromagnetic energy harvester on flexible polyimide substrate. Fabrication process of the device is based on the flexible printed circuits (FPC). To effectively harvest vibrational energy in all direction, we specially designed a cubic structure with a freely located magnet. Theoretical calculation reveals that the total output power of this electromagnetic energy harvester remains unchanged in different vibration directions. Experimental results show that the device can operate at low frequencies with a wide bandwidth. Besides, three dimensional energy harvesting is obtained by this device and applications of harvesting energy in human body movement are demonstrated.

DESIGN OF THE DEVICE

For three-dimensional vibration energy harvesting, this electromagnetic energy harvester is designed to be cubic-shape. Figure 1(a) elucidates the structure of the cubic harvester, which mainly consists of the polyimide substrate, copper coils and a NdFeB permanent magnet. The substrate and copper coils are folded from a planner structure shown in Figure 1(b), thus forming a sealed cube. The permanent magnet is freely located inside the cube without the support of springs. This not only eliminates the sophisticated spring structures but also makes the device able to harvest vibrational energy from all direction, since the magnet is totally free inside the cubic box.

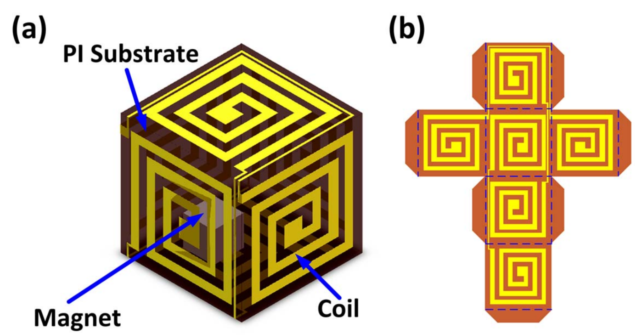

Figure 1: (a) 3D structure and (b) planar layout of the cubic electromagnetic energy harvester.

Compared with previous studies [11], this new device is improved in the following aspects. Firstly, the magnet is freely located rather than attached to a cantilever. Secondly, the planner coils are designed with proper spiral direction. In our design, the top and bottom copper coils have opposite helical direction and are in series connection. The same structure is applied to the left-right coils and front-back coils. In this way, number of the electrodes can be halved while turns of the coil will be doubled, thus enhancing the final output. Finally, copper coils are fabricated on both sides of the substrate, which is also beneficial to the output. Detailed geometry parameters of this electromagnetic energy harvester are listed in Table 1.

Table 1: Geometry parameters of the cubic energy harvester.

Components	Length	Width	Thickness/Height
PI substrate	10 mm	10 mm	0.025 mm
Copper coil	-	0.2 mm	0.018 mm ×2
NdFeB magnet	5 mm	5 mm	5 mm
Total device	**10 mm**	**10 mm**	**10 mm**

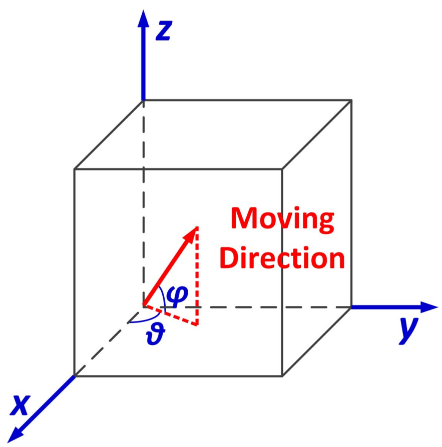

Figure 2: Theoretical calculation demonstrating that the total output power is proportional to the velocity.

To prove the ability of three-dimensional energy harvesting, theoretical calculation is conducted. First, we imagine the magnet moving in an arbitrary direction, with the velocity of v. The angle between the moving direction and XY plane is defined as φ. The angle between moving direction projection in XY plane and X-axis is defined as θ. Then, the velocity components along X-axis, Y-axis, and Z-axis can be expressed as:

$$v_x = v\cos\varphi\cos\theta, \quad (1)$$

$$v_y = v\cos\varphi\sin\theta, \quad (2)$$

$$v_z = v\sin\varphi. \quad (3)$$

The induced voltage in each coil can be obtained from Faraday's law:

$$E_i(t) = -2\times N\frac{d\phi}{dt} = -2\times NA\frac{dB}{dz}v_i(t), \quad (4)$$

where $E_i(t)$ is the induced voltage, N is the turns of each coil, $\frac{dB}{dz}$ is the changing rate of magnetic flux density, $v_i(t)$ ($i = x, y, z$) is the velocity along each axis. The factor 2 is caused by the series connection of two coils. By combining the output together, total output power generated by this cubic energy harvester can be expressed as:

$$P_{total}(t) = \sum_{i=x,y,z}\frac{E_i^2(t)}{R_i}, \quad (5)$$

where R_i ($i = x, y, z$) is the inner resistance of the two series connected coils. Assuming that $\frac{dB}{dx} = \frac{dB}{dy} = \frac{dB}{dz}$ and $R_x = R_y = R_z$, we can obtain that $P_{total}(t) \propto v(t)^2$. The result shows that the total output power of this cubic energy harvester is only related to the magnet moving velocity, regardless of the moving direction.

FABRICATION PROCESS

Fabrication of this electromagnetic energy harvester is carried out using FPC method, which is robust, low-cost and mass-productive [12]. Detailed fabrication process is shown in Figure 2. First of all, a 25 µm polyimide substrate with copper foil on both sides is prepared (Figure 2a). Then, photoresist is patterned on the copper foil as a mask to etch the copper foil (Figure 2b). As the next step, polyimide substrate is etched to form a through-hole (Figure 2c). Later, catalyst activation is performed and copper is electroplated on both sides and the through-hole (Figure 2d). After that, photoresist is patterned on both sides and the electroplated copper is wet etched using $FeCl_3$ solution (Figure 2e). Finally, by removing the photoresist, the polyimide-based double-side copper coils if fabricated (Figure 2f). To make the electromagnetic energy harvester, the polyimide-based double-side copper coils is then folded to form a cube, in which the permanent NdFeB magnet is placed.

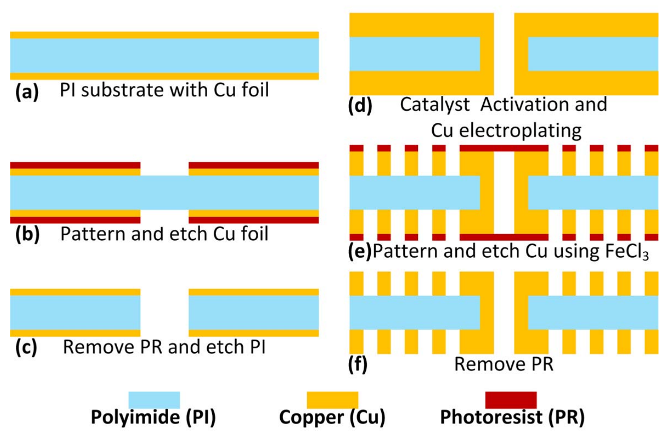

Figure 3: Fabrication process of the polyimide-based double-side copper coils.

From the above FPC-based fabrication process, we can conclude that there is no need to fabricate complex cantilever or spring structure. After fabricating the double-side planar coils, electromagnetic energy harvester can be obtained through folding and packaging. This greatly simplifies the fabrication process, thus improving the production efficiency. Moreover, this fabrication process is compatible with other

FPC fabrication process, which brings hope for further integration with the circuit.

MEASUREMENT AND DISCUSSION

Experimental measurement of the cubic energy harvester is conducted using a vibration system shown in Figure 4a. The dynamic signal analyzer (Agilent 35670A) is used to generate sinusoidal signal with tunable frequency. The signal is then amplified by a power amplifier to drive a vibrator. The cubic energy harvester is fixed on to the vibrator and the induced voltage is sent back to the dynamic signal analyzer.

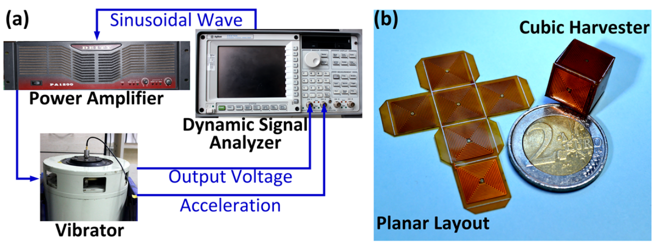

Figure 4: (a) Experimental setup. (b) Photos of the planar layout and the fabricated cubic harvester.

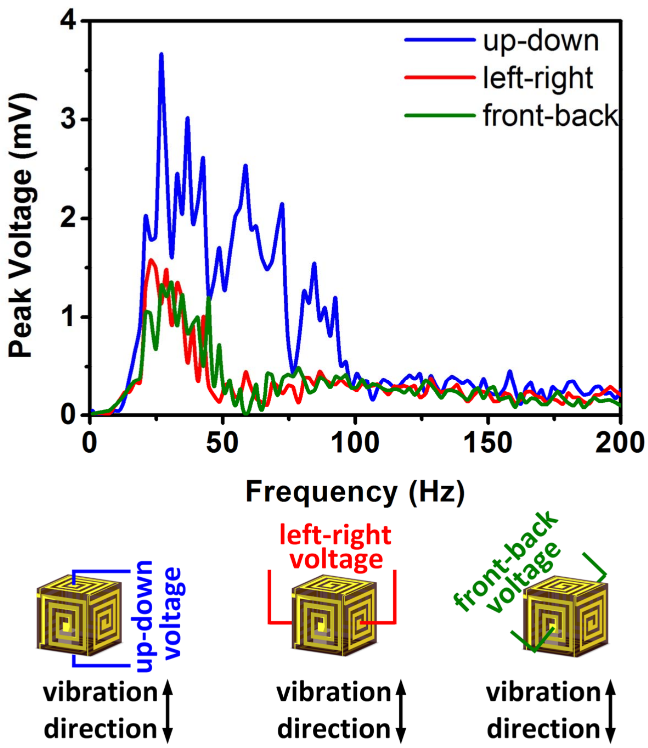

Figure 5: Output peak voltages versus vibration frequency at the acceleration of 0.5 g. Output voltages at three directions are illustrated.

Using the vibration system, output performance of this cubic energy harvester is investigated. First, a vibration is given in up-down direction, and the induced voltage in the up-down coils is recorded, as shown in the blue line in Figure 5. With the acceleration of 0.5 g, the maximum induced voltage in up-down surface reaches 3.82 mV at 26.87 Hz and shows an ultra-wide working bandwidth between 20 and 100 Hz. This wide band behavior is caused by the springless vibration structure. Moreover, the vibration in up-down direction will inevitably make the magnet move in left-right direction and front-back direction, because the magnet is completely free inside the cube. The induced voltage and frequency response of the surfaces perpendicular to the vibration direction are also measured. As shown in the red and green lines in Figure 4, the maximum induced voltage is about 1.5 mV at resonance. Compared with the output voltage in up-down surface, the maximum voltage is lowered and the bandwidth is narrowed. By adjusting the vibration direction, the output voltage at up-down, left-right, and front-back surfaces will change according to the velocity components in each direction. Thus, three-dimensional vibration energy harvesting is achieved.

Output performance of this cubic energy harvester under different external load resistance is also investigated. As shown in Figure 6a, with the load resistance varying from 0 to 10 Ω, the induced voltage raises monotonously and tends to saturate. On the contrary, the current in the coil reduces as the load resistance increases. For the output power, maximum value of 0.75 μW is achieved with a 2.5 Ω optimal resistance, as shown in Figure 6b.

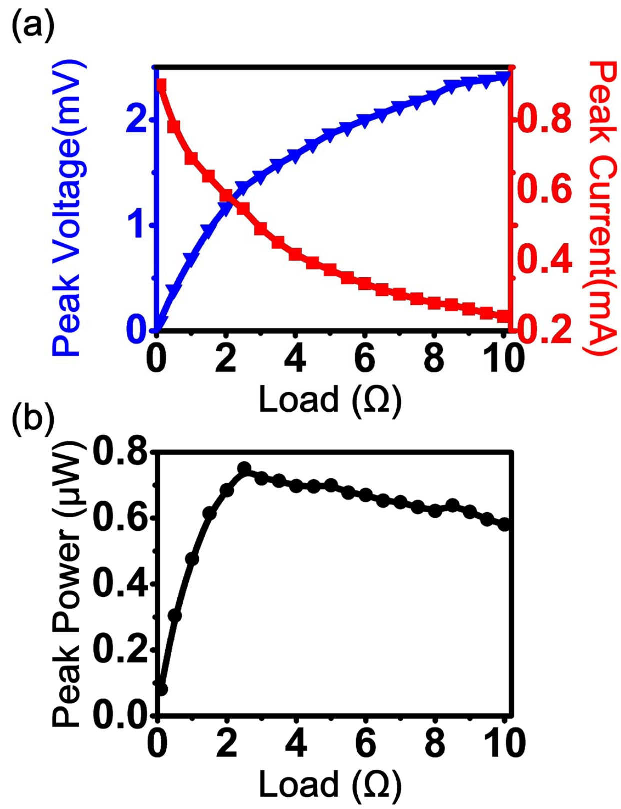

Figure 6: (a) Peak output voltage (left axis) and current (right axis) as a function of the external load resistance. (b) Peak output power as a function of the external load resistance.

Benefit from its cubic structure, this energy harvester offers great opportunity to harvest vibration energy from ambient environment. As an example, the device can be placed on a backpack to harvest the vibration energy from daily walking. As shown in Figure 7a, a gentle jump can generate voltage as high as 13.97 mV. Moreover, by fixing the device on the wrist, energy can be harvested in the writing process, as illustrated in Figure 7b.

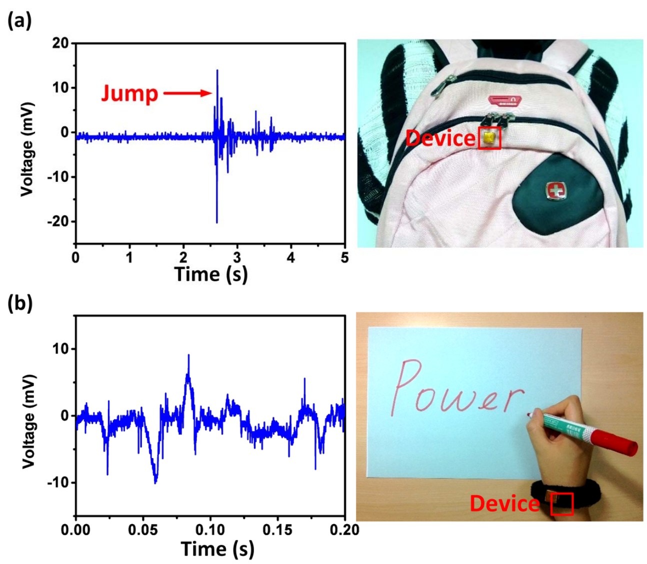

Figure 7: (a) Output voltage of the harvester placing at the backpack. (b) Output voltage of the harvester in the writing process.

CONCLUSION

In summary, we innovatively design a cubic energy harvester that can convert three-dimensional vibration energy into electricity. With a magnet freely located inside a cubic box, a springless structure is proposed. Trough, theoretical calculation, we obtain that the total output power of this cubic energy harvester is only related to the magnitude of the magnet's velocity, regardless of the moving direction. Fabrication of the device is based on FPC process, which is simple, reliable, and mass-productive. Experimental results indicate that this device can effective harvest vibration energy from all directions, with a relatively low resonant frequency and wide bandwidth. Additionally, by fixing this device onto a backpack and human wrist, vibrational energy harvesting from daily life is demonstrated.

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