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Nonlinear electromagnetic energy harvesters fabricated by rigid-flex printed circuit board technology

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Abstract. In this paper, a wideband electromagnetic energy harvester designed and fabricated by commercial rigid-flex PCB technology is demonstrated. The rigid FR-4 boards are used for mechanical frames and coil winding whereas the flexible polyimide film is used for mechanical springs and mass platforms. The total dimension of the device is 20 × 20 × 2 mm^3. The internal coil resistance is 15 Ω. In vibration tests, nonlinearity can be observed even at 0.1 g vibration level due to the spring hardening effect. The peak frequency was increased as the vibration level increased. The effective bandwidth was increased from 6 Hz at 0.1 g to 21 Hz at 0.5 g and 27 Hz at 1 g, respectivel, due to the hysteresis effect. For a matched load and 1 g vibration at 240 Hz, the maximum output power is 24.5 nW, corresponding to a power density of 31 nW/cm^3.

1. Introduction

Energy harvesters are typically cm-scale devices fabricated by micromachining technology [1] or by assembling components with cm to sub-mm dimensions [2, 3]. The fabrication or assembly cost can be high and impede wide application of the emerging technology. In comparison, printed circuit boards (PCB) is a mature and lost-cost fabrication technology suitable for cm-scale devices. Its design rules are typically 100 μm and can be used for most harvesting devices. Among different types of energy harvesters, electromagnetic harvesters have the advantage of simple structures, simple material requirement, and low output impedance. PCB technology is particularly attractive for fabricating electromagnetic harvesters since fine structures and gaps are seldom used in these devices. Furthermore, PCB can be used for coils winding and as mounting platforms for permanent magnets. Both rigid PCB [4, 5] and flexible PCB [3] have been used to fabricate energy harvesters. In [4], springs, magnet platforms, and support frames were fabricated in standard FR-4 PCB by CNC machining. A copper wire wound coil was bonded to a glass substrate to pick up the flux change and generate power during vibration. In [2, 6-8], various polymer films such as PE, PI/Kapton, and PDMS, were used as suspension membranes for the permanent magnet to achieve low resonance frequency. However, these films had to be attached to another rigid frame during device assembly. This extra assembly process can increase fabrication cost and reduces device reliability. Both flexible polyimide (PI) films and rigid FR-4 boards used in the literature are common and well known substrates in the PCB industry. They can be laminated together to form rigid-flex PCB. In [9], rigid-flex PCB were used to fabricate an integrated piezoelectric/electromagnetic harvester. However, the flexible layer in

[9] was used mainly to support the PZT bimorph only. In this paper, an electromagnetic energy harvester fabricated by the rigid-flex PCB technology is demonstrated. The rigid boards are used for mechanical frames and coil winding whereas the flexible polyimide is used for mechanical springs and mass platform. The device is designed and fabricated by using commercial PCB technology, thus low cost and good reliability can be ensured.

2. Device principle and design

The schematic of the proposed harvester is shown in Figure 1. The 50-μm thick flexible polyimide layer is sandwiched between top and bottom rigid FR-4 boards. Springs (1×2.5 mm^2) and central platforms (ϕ 5 mm) are fabricated in the flexible PI layer. After the rigid-flex structures are fabricated, two cylindrical permanent magnets are attached to the central platform. When subject to external vibration, the magnets move in the vertical *z* direction and an electromotive force (emf) *V* is induced in the coil fabricated in the rigid boards. The PCB layout is shown in Figure 2. Both the top and bottom rigid boards have 3 layers of coil windings designed with 5-mil line/space design rules. Each layer has 11 turns. The two sets of coils can be connected externally in parallel to increase the output current or in series to increase the output voltage.

The output voltage *V* is determined by Faraday's law of electromagnetic induction,

$$V = -n\frac{\mathrm{d}\Phi}{\mathrm{d}t} = -n\frac{\mathrm{d}\Phi}{\mathrm{d}z}\dot{z},$$

where Φ is the total magnetic flux enclosed by the coils and *z* is the position of the magnets with respect to the coils. To maximize the output voltage, the spatial derivative of the total flux Φ should be maximized. In finite element simulation, it was found that $\mathrm{d}\Phi/\mathrm{d}z$ reached maximum when the coils were placed at the same plane as the top surface of the magnets. Therefore the rigid FR-4 boards are designed so that the coil routing are laminated in boards with minimum thickness (0.1 mm) and a thick dummy board is used to adjust the position of coils to align with the magnet surfaces, as shown in Figure 3(c).

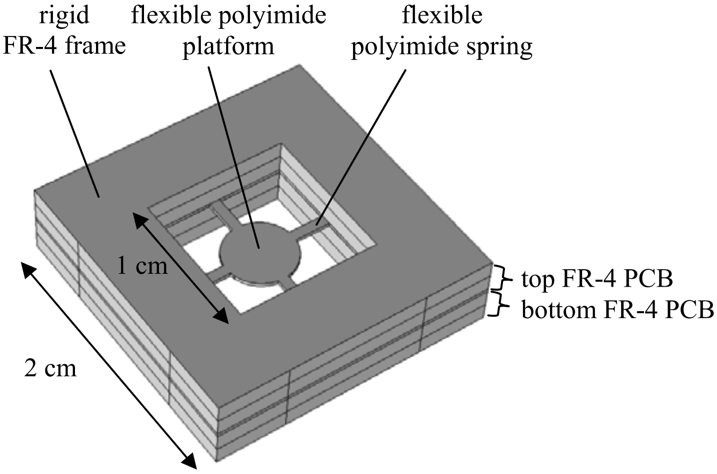

Figure 1. Schematic of harvester fabricated by rigid-flex PCB technology.

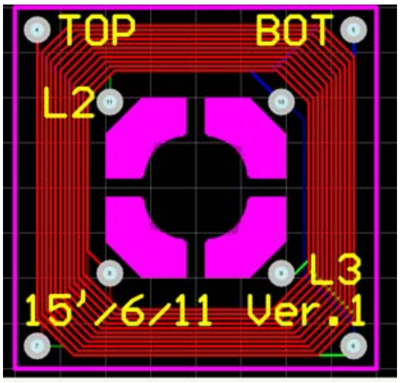

Figure 2. PCB layout.

3. Fabrication and measurement

The device was fabricated by a commercial PCB manufacturer, as shown in Figure 3. First, the rigid and flex boards were prepared by standard PCB processes (Figure 3(a)). The copper thickness of the inner and outer coils were 17.5 μm and 35 μm, respectively. Then the center hole was drilled in the rigid boards and the spring/platform shapes were punched in the flexible boards (Figure 3(b)). Next, the three boards were laminated (Figure 3(c)) and through holes were drilled and plated to connect coil windings in different layers (Figure 3(d)). Figure 4 shows a fabricated device with two 2-mm thick NdFeB magnets with 0.3-T surface flux density attached to the central platform. The total dimension of the device is $20 \times 20 \times 2$ mm^3 and the center hole in the rigid boards are 10×10 mm^2. The measured internal coil resistance is 15 Ω.

In vibration tests, the harvester was excited by a shaker and a commercial accelerometer was used to monitor the vibration level. The harvester output was connected to an oscilloscope and a dynamic signal analyzer; the total input impedance of the instruments was 500 kΩ. Figure 5 shows the output voltage vs. driving frequency for various vibration levels. Due to the spring hardening effect [1, 2, 4] of the miniaturized springs, nonlinearity and hysteresis was observed even at 0.1 g vibration. The effective bandwidth was increased from 6 Hz at 0.1 g to 21 Hz at 0.5 g and 27 Hz at 1 g, respectively. Thus the bandwidth can be increased by 3 to 4 times at high vibration levels. The peak output frequency was also shifted as the vibration level increased, as shown in Figure 6. A load resistor was connected to the harvester and the output power at 240 Hz and 1 g vibration is shown in Figure 7. For

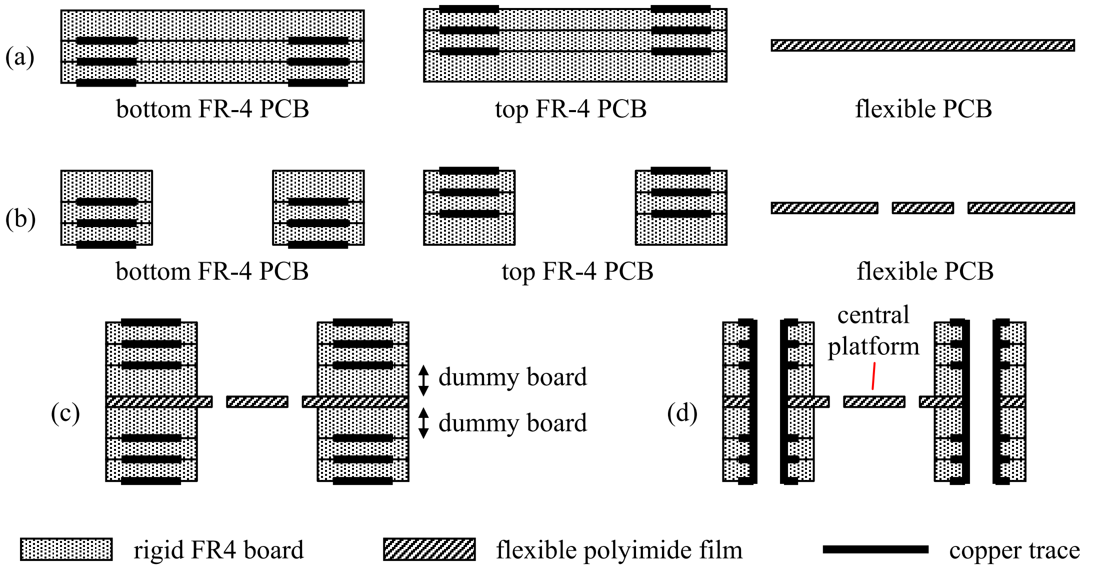

Figure 3. Fabrication processes, (a) preparation of rigid PCB and flexible polyimide films, (b) drilling of rigid boards and punching of flexible boards, (c) lamination, (d) through hole drilling and plating

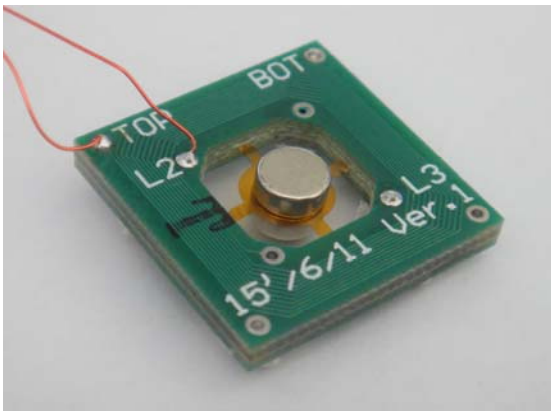

Figure 4. Fabricated device with magnets attached.

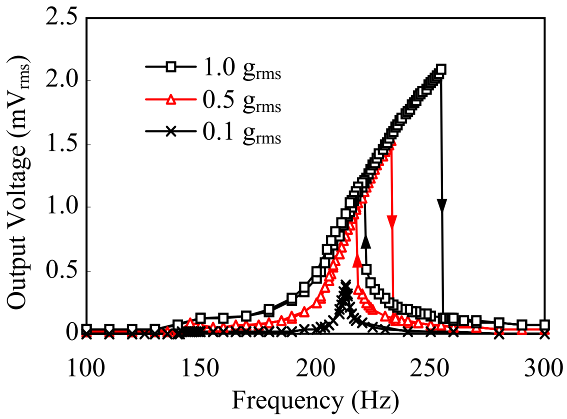

Figure 5. Output voltage vs. frequency for various vibration levels.

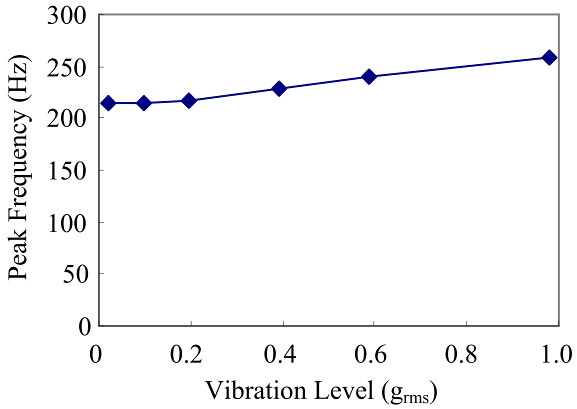

Figure 6. Peak frequency shift.

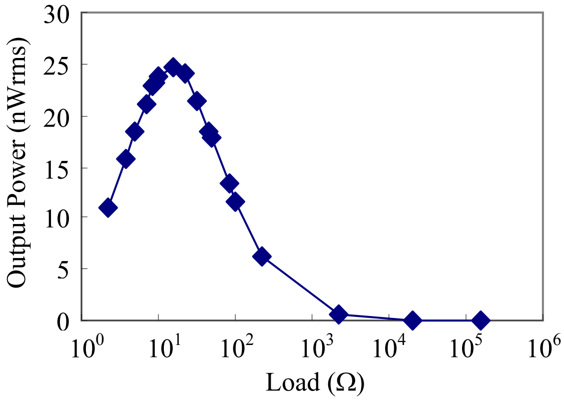

Figure 7. Output power vs. load at 240 Hz and 1 g vibration.

the matched load of 15 Ω, the maximum power was 24.5 nW, corresponding to a power density of 31 nW/cm^3, which was comparable to the reported value in literature [1].

4. Conclusion

This paper demonstrates an electromagnetic energy harvester designed and fabricated by the commercial rigid-flex PCB technology. The simple device structure design and mature manufacturing technology reduce production cost. Due to the nonlinear spring effect, the bandwidth was increased by 3 to 4 times at high vibration levels. Therefore the proposed device can be employed in wideband applications. For a matched load, a maximum output power of 24.5 nW, corresponding to a power density of 31 nW/cm^3, was achieved at 240 Hz and 1 g vibration.

Acknowledgments

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