Electromagnetic Energy Harvester with Embedded Ferrofluid In PCB Technology

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Abstract. This paper reports an electromagnetic energy harvester fabricated with Rigid-Flex Printed Circuit Board (PCB) technology by a commercial PCB supplier. Rigid FR-4 boards were used for transduction coil routing and mechanical support; flexible polyimide (PI) films were used to design elastic springs and magnet mounting platforms. Ferrofluid (FF) was injected into the embedded cavities inside the rigid PCB to increase the effective permeability of the medium around the magnet and thus increase the induced electromotive force (emf). Experiments showed up to 70% increase of output emf and 190% increase of output power compared with harvesters without embedded ferrofluid.

1. Introduction
Electromagnetic (EM) energy harvesters are attractive due to their simple structures and ease of operation. Among various fabrication technologies for EM harvesters, PCB technology offers the advantages of low cost, fast turn-around, high reliability, and compatibility with current electronic manufacturing technology [1-4]. In the past, rigid FR-4 PCB [1, 2] had been used to fabricate electromagnetic energy harvesters and flexible PI films [4] had been used to fabricate electret-based electrostatic energy harvesters. FR-4 boards and PI films can be laminated to form compound Rigid-Flex PCB which is also a very mature and common substrate in modern electronic manufacturing industry. In [5], such Rigid-Flex PCB was used to integrate piezoelectric and electromagnetic harvesters. In [6, 7], a wide-band electromagnetic energy harvester based on Rigid-Flex PCB was demonstrated where the nonlinear effect of the PI springs was used to increase the harvesting bandwidth.

PCB technology is well-suited for fabricating electromagnetic harvesters since sub-mm accuracy is good enough for device design and operation. However, the materials used in standard PCB industry, such as fiberglass cloth, epoxy binder, and copper, are non-magnetic. Therefore PCB-based electromagnetic harvesters are less efficient in energy conversion because the equivalent magnetic circuit of the device is not optimized to confine magnetic flux. In this paper, we demonstrate an electromagnetic energy harvester with embedded cavities fabricated by Rigid-Flex PCB technology. To increase the total magnetic flux in the device and guide the flux through the transducing coils to increase the output emf, ferrofluid is injected into the embedded cavities in the rigid PCB stacks. This fabrication process minimizes the number of components and assembly steps. Since no extra ferromagnetic components are used that may increase the volume or weight of the device, the device performance can thus be enhanced while maintaining low fabrication cost.
2. Principle and Design

The proposed device is based on our work presented at PowerMEMS 2015 [6, 7], as shown in Figure 1(a). The device is fabricated with Rigid-Flex PCB technology where flexible PI films are used for suspension springs and rigid FR-4 boards are used for mechanical support and coil routing. Two sets of transduction coils, each with three layers of routing, are designed on the top and bottom surfaces of the device where the magnetic flux has maximum gradient [7], as shown in Figure 1(b). Permanent magnets are attached to the central PI platform after the PCB is manufactured. The motion of the suspended magnets caused by external vibration induces an emf output in the coils in the rigid PCB. In the current device, embedded cavities were milled in the rigid boards during the PCB manufacturing. After the Rigid-Flex PCB device was manufactured, ferrofluid was injected into the cavities, as shown in Figure 1(b).

Magnetic circuit design is important in magnetic actuators such as the voice coil motors (VCM) in optical pickup heads [8]. Proper design of the high-permeability yokes in the magnetic circuits can increase and concentrate magnetic flux and enhance actuation sensitivity. The yoke structure in the current device is implemented by using the ferrofluid in the embedded cavities, as shown in Figure 1(b). Figure 2 shows the simulation of magnetic field distribution in devices without and with embedded ferrofluid. The ferrofluid has a relative permeability $\mu_r$ of 12. It can be seen that the cavity with ferrofluid has higher magnetic B field magnitude compared with that without ferrofluid. Furthermore, ferrofluid causes the magnetic flux lines to bend on the air/ferrofluid interface and results in a higher vertical flux component. These effects increase the total magnetic flux enclosed by the coils and thus the emf output, as shown in Figure 2(c).

![Figure 1](image1.png)

Figure 1. (a) Schematic of harvester fabricated by Rigid-Flex PCB technology, (b) AA’ cross section.

![Figure 2](image2.png)

Figure 2. Magnetic field simulation showing B field magnitude and flux lines, (a) without FF, (b) with FF, (c) total magnetic flux vs. magnet displacement.
3. Device Fabrication and Measurement

The device was fabricated by a commercial PCB process, as shown in Figure 3. First, three kinds of circuit boards were prepared separately by standard processes, including (1) FR-4 boards containing three layers of coil routing, (2) thick dummy boards with milled cavities, and (3) PI films with punched geometry for springs and central platforms, as shown in Figure 3(a). The FR-4 coil routing and the dummy boards were then laminated and central opening were milled. Subsequently all boards were laminated. Via holes were then drilled and electroplated to connect routings on different layers, as shown in Figure 3(b). Next, vent/injection holes were drilled through the PCB stack and ferrofluid was injected into the cavities, as shown in Figure 3(c). To inject ferrofluid, the PCB assembly was immersed in ferrofluid and placed in a closed chamber. When the chamber was pumped and then vented, ferrofluid was pushed into and filled the cavities automatically due to the atmospheric pressure, as shown in Figure 3(c). Finally, two NdFeB magnets were attached to the central PI platform.

Figure 4(a) shows a fabricated and assembled device with two 2-mm-thick NdFeB magnets with 0.3-T surface flux density. The total dimension of the device is $20 \times 20 \times 4 \text{ mm}^3$ and the central opening in the rigid boards is $10 \times 10 \text{ mm}^2$. Both top and bottom coils have a measured internal resistance of about 70 $\Omega$. In Figure 4(b), the top FR-4 PCB layer was removed to reveal the embedded cavities and the vent/injection holes drilled in the sandwiched PI film. Figure 4(c) shows the BB’ cross-sectional view of the embedded cavities and the electroplated through via holes in the FR-4 PCB.

In vibration tests, two kinds of different cylindrical magnets ($\phi 6 \times 3 \text{ mm}$ and $\phi 6 \times 2 \text{ mm}$) were used and the harvesters were tested before and after ferrofluid was injected. The measurement setup is shown in Figure 5 [7]. An Agilent 35670A Dynamic Signal Analyzer (DSA) was used to control the vibration and record data. The vibration amplitude was calibrated and fixed at 1 g$_{\text{rms}}$ by using a commercial accelerometer. Both up-sweep and down-sweep were performed to characterize the frequency response of the harvester. The measured open-circuited output voltage $V_{oc}$ when the top and bottom coils were connected in series is shown in Figure 6. The output voltage is increased by 70%
and 40% and the output power is expected to increase by 190% and 100%, respectively, for the two magnets after ferrofluid is injected. Therefore, ferrofluid can effectively increase the output voltage and power. With ferrofluid, the maximum open-circuit output voltage is 35.9 mV and 26.5 mV, respectively, for the two magnets. For matched load, the expected maximum output power $P_{opt, max}$ is 2.3 $\mu$W and 1.3 $\mu$W, respectively. The performance is summarized in Table 1.

| Magnet     | $V_{oc, max}$ (mV$_{rms}$) | $P_{opt, max}$ (\(\mu\)W$_{rms}$) | Max power density (\(\mu\)W$_{rms}$/cm$^2$) |
|------------|-----------------------------|-------------------------------------|----------------------------------------|
| w/ FF      | w/ FF                        | w/ FF                               | w/ FF                                  |
| $\phi$6x3mm | 20.9                         | 0.78                                | 0.20                                    |
| $\phi$6x3mm w/ FF | 35.9                         | 2.30                                | 0.58                                    |
| $\phi$6x2mm | 18.6                         | 0.62                                | 0.15                                    |
| $\phi$6x2mm w/ FF | 26.5                         | 1.25                                | 0.31                                    |

4. Conclusion

This paper reports an electromagnetic energy harvester fabricated with Rigid-Flex PCB technology. Ferrofluid was injected into the embedded cavities inside the PCB to increase the output emf. Experiments showed up to 70% increase of output emf and 190% increase of output power with embedded ferrofluid. Maximum expected output power at 1 g$_{rms}$ is 2.3 $\mu$W$_{rms}$. The project was supported in part by the Ministry of Science and Technology, Taiwan, ROC (MOST 104-2221-E-009-168-MY2, MOST 106-2221-E-009-091-MY2, MOST 104-2221-E-009-156-MY3, MOST 106-2633-E-009-001). The authors are grateful for the support of the Chip Implementation Center, the National Center for High-performance Computing, the National Nano Device Laboratory, and the National Chiao Tung University Nano Facility Center, Taiwan, R.O.C.

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