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A batch-fabricated electromagnetic energy harvester based on flex-rigid structures

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ABSTRACT

In this paper, an electromagnetic energy harvester device is designed and fabricated, based on a rigid-flex structure. The device has a FR4 proof mass carrying a bi-layer copper planar coil, suspended by four soft polyimide springs over a disc permanent magnet. The device is batch-fabricated with a standard production process of rigid-flex Printed Circuit Board (PCB). The assembled energy harvester is excited by sinusoidal accelerations and characterized dynamically. At an acceleration of 2 g peak-to-peak amplitude (±1 g, ±9.8 m/s^2), a maximum output peak-to-peak voltage of 9.85 mV and an output power of 1.24 μW are measured, at the device's resonance frequency of 155 Hz. With an elevated acceleration of 10 g (±5 g), a maximum output peak-to-peak voltage of 22.58 mV and an output power of 7.21 μW are achieved.

1. Introduction

Vibrational energy harvesters are devices that convert vibration kinetic energy into electric power. They have wide applicability due to the abundance of vibration sources in the environment, such as human motions, vehicle movements, and machinery vibrations [1]. Vibrational energy harvesters can be realized by different mechanisms, e.g., piezoelectric, electrostatic, and electromagnetic [2]. Recently, many research activities are focused on the electromagnetic energy harvesters due to their advantages of high output efficiency and relatively easier mechanical design. Commonly, electromagnetic energy harvesters generate power by the relative movement between coils and magnets excited by external vibration. In spite of many different technologies [3–5], two of the most popular approaches to fabricate electromagnetic harvesters are Micro Electromechanical Systems (MEMS) and Printed Circuit Board (PCB) technologies.

Early implementations of MEMS-based energy harvesters started in the mid-1990s. Williams et al. developed a two-wafer MEMS energy harvester based on a samarium-cobalt permanent magnet suspended by a polyimide membrane, outputting a power of 0.3 μW at a frequency of 4 MHz [6]. Later on, cantilever-based MEMS structures gained popularity due to the easy design and fabrication [7,8]. Recently, much attention is paid to the MEMS structures with an inertial mass (proof mass) suspended by multiple springs. This type of device is capable of harvesting energy by different resonant modes. For example, Wang et al. developed a MEMS harvester device with a magnet suspended by four springs over a planar copper coil, generating a peak-to-peak voltage of 42.6 mV at a frequency of 94.5 Hz and an acceleration of 4.94 m/s^2 [9]. Alternatively, the MEMS energy harvester are also implemented by suspending planar coils below magnet, reaching 0.444, 0.242 and 0.125 μW/cm^3 at 3 different vibration modes [10].

Compared to MEMS technologies, PCB technologies are relatively cheaper, easier to fabricate, and capable of generating more energy (by sacrificing the footprint of the devices). Most often, PCB technologies are used to produce planar coils in the PCB-based energy harvesters. The simplest PCB-based energy harvester can be implemented by mounting a planar coil in the vicinity of a permanent magnet [11,12]. Alternatively, the Flame Retardant 4 (FR4) material of PCB board can be used to fabricate the spring for suspending the movable part of the energy harvesters [13,14]. Due to the low Young's modulus of FR4, the movable part of the energy harvester is capable of reaching a higher vibration amplitude (at a given excitation level) and a lower resonance frequency (where most of the ambient vibrations are). In a very recent work, a permanent magnet is glued on a flexible polyimide suspension fixed to rigid FR4 frame, where a maximum output power of 160 nW is achieved at 1 g_{rms} vibration and 250 Hz [15].

In most of the works cited above, a common approach to increase the amplitude and reduce resonance frequency of the

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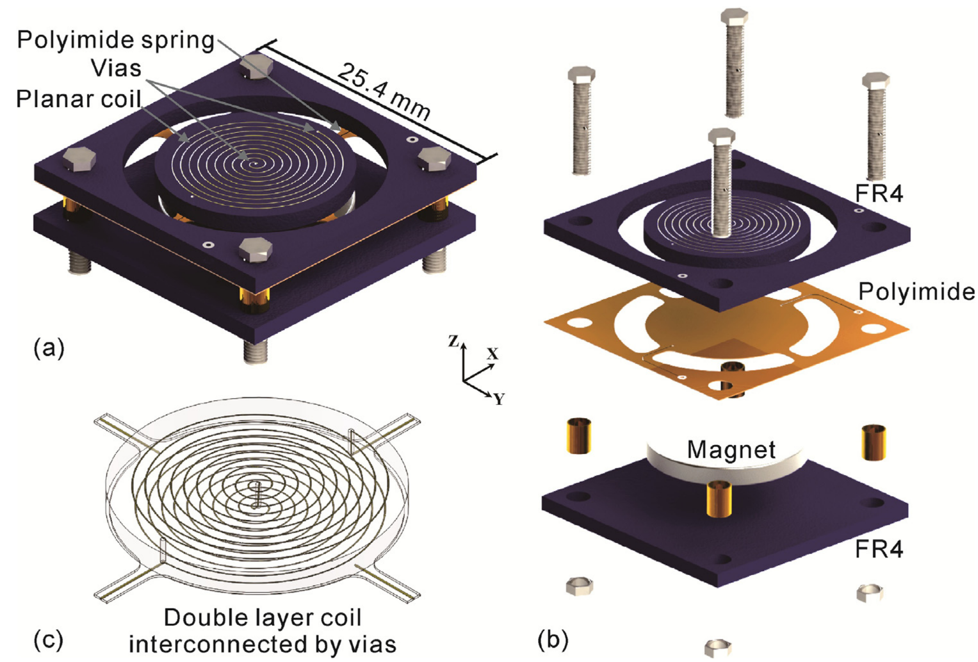

Fig. 1. (a) Schematic illustration of the assembled energy harvester device. (b) Exploded view of the energy harvester device. (c) Schematic illustration of the bi-layer planar copper coil.

energy harvesters is to attach the magnet to the mechanical suspensions, by either gluing or magnetic attraction between magnets. The disadvantages of these processes are the complexity and lack of precision in the manual processes (e.g., gluing). Slight variations in the mechanical properties of the mechanical suspension (e.g., off-centered mass and stress induced by the curing of the glue) of the energy harvester may influence substantially the performance of the device, in terms of vibration amplitude and resonance frequency. Therefore, the reliability, repeatability, and possibility of batch production might still be the major challenges before those devices can be used in the real-world applications. In this paper, we report an electromagnetic energy harvester device based on a rigid-flex structure with a batch-fabricated mechanical vibrating proof mass. The device is composed of a circular FR4 rigid board with a double-layer planar coil suspended by four polyimide springs over a permanent disc magnet. The polyimide springs enable low spring stiffness (and thus high power output) and low resonance frequency of the energy harvester device. The device is produced by a standard rigid-flex PCB manufacturing process. The dynamic behaviour of the energy harvester will be presented and discussed.

2. System design

2.1. Concept of the system

The electromagnetic energy harvester in this work is composed of a circular FR4 plate (the proof mass) and a disc magnet mounted vertically, as shown in Fig. 1(a). An exploded view of the device can be seen in Fig. 1(b). The coil of the device consists of two layers of spiral copper wires electroplated on two sides of the FR4 plate, interconnected by copper vias. The FR4 plate is suspended by four polyimide springs anchored to the outer FR4 frame. The copper wires on the polyimide springs connect electrically the coils and the electrical pads on the FR4 frame through copper vias on the edge of the FR4 plate. The magnet is glued in the center of another FR4 PCB mounted below the coil with four M2 screws. Spacers with different length can be used to adjust the distance between the coil and the magnet. When excited by external vibration, the circular FR4 plate vibrates in the magnetic field of the permanent magnet and generates electrical power. Fig. 1(c) shows the coil of the device, including a clockwise-winded coil on the front side of the FR4 plate and a counterclockwise-winded coil on the backside of the FR4 plate, connected through the vias in the center of the FR4 plate. In this work, the size and number of turns of the coil are limited by the resolution of the standard PCB fabrication process used. Based on the circular proof-mass with a diameter of 16 mm, spiral shaped planar coils with following parameters are fabricated: coil thickness 35 μm (1oz), spacing between coil lines 0.45 mm, coil line width 0.25 mm. In the future, the number of turns of the coil can be further enhanced, by using a PCB technology that enables lower line width and spacing, and possibly more layers of coils.

2.2. System design

According to the Faraday's law, the induced voltage in a solenoid coil moving (on Z direction in Fig. 1) in a magnetic field is given by:

$$V = -N\frac{d\varphi}{dt} = -NA\frac{dB}{dz}\frac{dz}{dt} \tag{1}$$

where N is the number of turns of the solenoid coil, A is the area of the coil, ϕ is the magnetic flux, B is the magnetic flux density, and z is the displacement of the coil on the Z direction (in Fig. 1). Eq. (1) is an approximation that ignores the magnetic field gradient on the X and Y directions. This approximation is valid when the coil is placed very close to the magnet, where the field gradient on X and Y directions is relatively small with respect to Z direction. From Eq. (1) it can be concluded that there are three ways to increase the induced voltage, namely, 1) increase the number of turns and area of the coil; 2) increase the magnetic field gradient (dB/dz) around the coil; and 3) increase the velocity of the coil (dz/dt). While the coil area and turns number is limited by the size and fabrication technology, it is possible to design the device by optimizing the magnetic flux gradient and the coil velocity.