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Analysis of an in-plane electromagnetic energy harvester with integrated magnet array

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ABSTRACT

In this paper, a novel MEMS electromagnetic energy harvester is designed, fabricated and tested. In-plane operation mode is utilized in the device to induce voltage in the coils, which enhances the changing rate of magnetic flux density across the coils. In order to produce larger magnetic flux density across the coil, magnetic properties of permanent magnets are simulated and optimized. Transient analysis of the induced voltage is conducted to prove the effectiveness of structural design. Comparison with the out-of-plane operation modes is carried out in the simulation, indicating that the in-plane operation mode not only enlarges the output, but also can make full use of the large vibration amplitude. In the fabrication process, instead of manually assembling bulk magnets, CoNiMnP hard magnetic alloy is electroplated onto the vibration plate. This method is MEMS compatible, which not only increases the production efficiency but also condenses the device's volume to 67.5 mm^3. Through experimental measurement, the proposed structure with integrated magnet array can generate 0.98 mV peak voltage at the frequency of 48 Hz. The maximum peak power density of this device reaches to 0.16 μW/cm^3 with a 15.8 Ω external resistance.

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1. Introduction

As the power consumption of microelectronic devices is scaled down to microwatts [1], MEMS energy harvester becomes a promising power supply method for low power consumption applications, such as remote sensor networks, biomedical implantable devices, and portable electronics. Among various energy sources in the environment, such as vibrations, solar energy and wind energy, vibrational energy exhibits unique advantages [2]. It is almost available everywhere and can be easily converted to electrical power through many applicable methods. Energy harvesters utilizing piezoelectric [3–5], electrostatic [6–8], and electromagnetic [9–11] transduction mechanisms have been fabricated and investigated. Among them, piezoelectric energy harvesters use vibration-produced mechanical force to strain a piezoelectric material such as PZT (lead zirconate titanate) [4,5] or PVDF (polyvinylidene fluoride) [12,13]. The strained piezoelectric material will produce a potential difference, which can be utilized as electrical energy source. Electrostatic energy harvesters are based on the changing capacitance value on account of vibrations, which will cause a change of the electric field, thus generating current flow in the external circuit. Compared with those two types, the internal resistance of electromagnetic energy harvester is relatively low, leading to larger output current.

Till now, several methods have been conducted to improve the output performance of electromagnetic energy harvesters. For example, Sari et al. fabricated a cantilever array instead of a single one, which not only increases the total output power but also broadens the working frequency [14]. Apart from this, by utilizing the frequency upconversion technique [15], low frequency vibration is converted into high frequency movement, which also enhances the output power obviously. However, those methods increase the total volume of the device and complicate the structure, which not really enhance the power density. Through well-designed magnet structure, in-plane movement mode of the electromagnetic energy harvester can improve the output power density by orders of magnitude, due to the larger changing rate of magnetic field [16]. To further increase the output performance of in-plane electromagnetic energy harvesters, various structures and magnet arrays have been designed and optimized [17–20]. Typically, the magnet arrays are manually assembled using NdFeB permanent magnets. Traditional fabrication of NdFeB magnet requires high processing temperature, which brings difficulty to the integration in MEMS process. Additionally, the manually assembled bulk magnet array limits the application field of the device, due to the relatively large volume. To solve the problem, NdFeB

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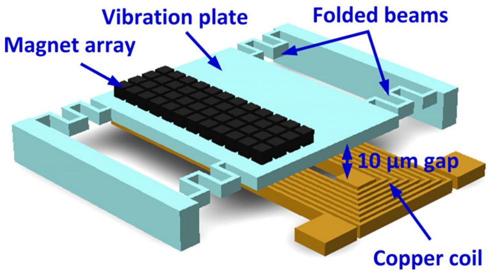

Fig. 1. Schematic of the energy harvester with integrated magnet array.

micromagnets have been batch fabricated and successfully applied in energy harvesting devices [21–24].

In this paper, we propose an in-plane electromagnetic energy harvester with integrated CoNiMnP magnet array. The magnet array is batch fabricated using MEMS technology by electroplating CoNiMnP hard magnetic alloy [25]. Taking advantage of the photolithography, shape and distribution of the magnet array can be arbitrarily designed and fabricated. The electroplated CoNiMnP array are utilized as permanent magnets and vibration masses, which reduces the resonant frequency, greatly decreases the volume of the device and makes the fabrication processes compatible with other MEMS processes. Other components of the device such as coils and beams are also designed and mass-fabricated to effectively harvest the vibration energy. The mass-fabricated small size energy harvester is promising to be integrated with other micro/nano devices, making the entire system compactable and self-sustainable. In Section 2, simulations have been conducted to optimize and analyze its structure. Detailed fabrication process is introduced in Section 3 and experimental measurement is shown in Section 4.

2. Design and simulation

2.1. Structure of the device

The electromagnetic energy harvester is designed to work with low frequency horizontal vibration input. In order to increase the output performance, in-plane movement mode is utilized in this device. As illustrated in Fig. 1, the device consists of four parts: fixed series coils, supporting pillars, vibration plate (including the folded beams) and permanent magnet array. The coils are placed in the bottom of the device and the vibration plate is supported by two copper pillars, leaving a 10 μm gap between the coils and the vibration plate. The vibrating beams are designed to be winding shape, which is beneficial to respond to low frequency vibrations in the environment. Permanent magnet array are fabricated on to the vibration plate to produce magnetic field across the coils. In the device, the coils are fixed while the magnets are movable. Therefore, the movement of electrical connections can be avoided which enhances the reliability of the device. Besides, the permanent magnet array works as the masses of the vibration plate, which lowers the resonant frequency (f_R) of the device and enhances the power output (p) according to Eqs. (1) and (2) [26],

$$f_R = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{1}$$

$$p = \frac{mY^2\varsigma_e(f/f_R)^3(2\pi f)^3}{[2\varsigma(f/f_R)]^2 + [1-(f/f_R)^2]^2} \tag{2}$$

where m is the mass of the system, k is the effective spring constant, Y is the vibration amplitude, f is the vibration frequency, ς is the damping ratio which includes electrical (ς_e) and mechanical (ς_m) parts.

2.2. Comparison of the magnetic flux density distribution

Given an external vibration source along the vibration plate, magnetic field over the coils will be changed, thus producing induced voltage in the coils. Compared with out-of-plane type, in-plane operation mode has larger changing rate of magnetic flux density, which leads to larger induced voltage. For traditional out-of-plane electromagnetic energy harvesters, the change of magnetic flux density is caused by varying the distance between the magnet and coil. Taking the common cylindrical magnet as an example, the magnetic flux density (B) along its central axis can be expressed as [27],

$$B(d) = \frac{B_r}{2}\left(\frac{H+d}{\sqrt{R^2+(H+d)^2}} - \frac{d}{\sqrt{R^2+d^2}}\right) \tag{3}$$

where B_r is the residual magnetic flux density determined by the material property, d is the distance from the magnet surface, H and R are the height and radius of the cylindrical magnet, respectively. For a CoNiMnP cylindrical magnet with the retentivity of 8887 Gs [28], height of 10 μm and radius of 2000 μm, the magnetic flux density and its gradient along the central axis are shown in Fig. 2(a) and (b), respectively. In this case, the maximum changing rate appears at 0.95 mm, with a value of 0.0095 T/mm.

In the out-of-plane type, the gradient of magnetic flux density cannot be largely increased. However, in-plane operation mode offers opportunity to enhance the changing rate of magnetic flux density, because large magnetic field appears only at the edge of a permanent magnet and the value sharply decreases to zero at other region. Therefore, at the edge of a permanent magnet, large changing rate of magnetic flux density can be obtained. Replacing a whole block magnet with magnet array, the length of the magnet edge will increase, thus enhancing the changing rate of magnetic flux density. A finite element method (FEM) simulation is also

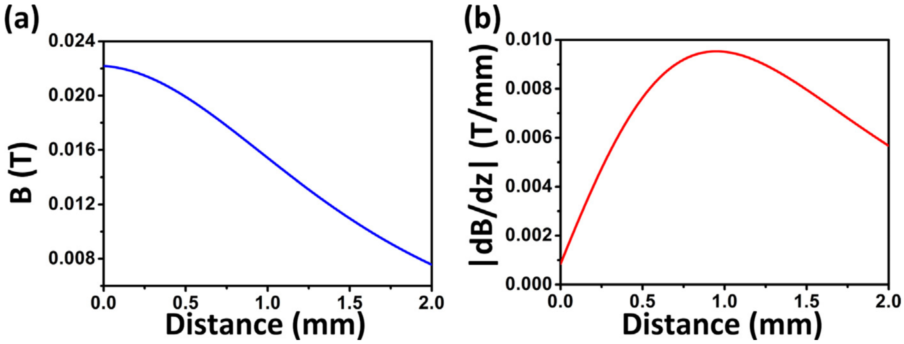

Fig. 2. Magnetic flux density and its changing rate for out-of-plane operation mode.

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