A PLANAR ELECTROMAGNETIC VIBRATION ENERGY HARVESTER WITH A HALBACH ARRAY

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Abstract: This paper presents a low-profile, planar electromagnetic vibration energy harvester integrated with a Halbach array. Halbach array is a special arrangement of permanent magnets that doubles the magnetic field on one side of the array while cancelling the field to near zero on the other side. Using this arrangement can improve electromagnetic coupling in a limited space. The energy harvester has a resonant frequency of 44.9Hz and generated an average power of over 120µW when excited at 0.3***g*** (1***g*** = 9.8m·s^{-2}). The electromagnetic vibration energy harvester reported here is only 4mm thick, which makes it one of the thinnest electromagnetic energy harvesters among existing non-MEMS devices.

Keywords: Electromagnetic energy harvester, Halbach array, planar

INTRODUCTION

Vibration energy harvesting involves the conversion of ambient mechanical energy present in the environment into electrical energy by employing certain transduction mechanisms [1]. The three main types of transducers used in vibration energy harvesting are piezoelectric, electrostatic and electromagnetic. The former two transducers usually have simple structures and thus are planar. However, electromagnetic transducers, due to the use of permanent magnets, are normally quite bulky when compared to the other two [2]. In addition, a majority of existing vibration energy harvesters are out-of-plane, i.e. the vibration direction is parallel with the thickness of the energy harvester. This kind of devices requires space out of plane to allow the inertial mass to oscillate freely, which makes them thick. In comparison, the inertial mass of an in-plane energy harvester oscillates perpendicularly to the thickness of the harvester, which makes the harvester planar.

This paper presents a low-profile, planar electromagnetic vibration energy harvester integrated with a Halbach array. Halbach array is a special arrangement of permanent magnets that doubles the magnetic field on one side of the array while cancelling the field to near zero on the other side. This arrangement can improve electromagnetic coupling in a limited space.

OVERVIEW

The Planar Electromagnetic Energy Harvester

Fig. 1 shows the structure of the planar electromagnetic energy harvester. There are two coils attached to the case. A meander spring that carries the Halbach array and the inertial mass is clamped on the case. The relative motion between the coils and the Halbach array generates electrical current. Both cases are 2mm thick, which makes the assembled electromagnetic energy harvester have a total thickness of only 4mm.

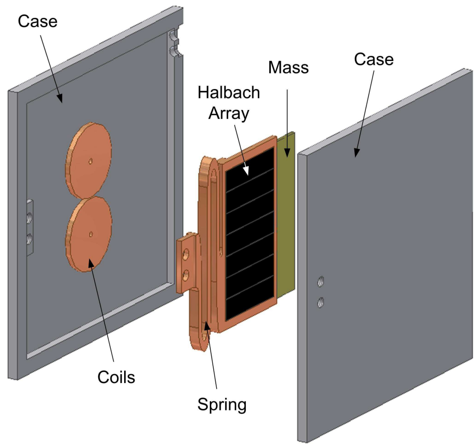

Fig. 1: The planar electromagnetic energy harvester.

The Halbach array doubles the magnetic field on one side of the array (Active side) while cancelling the field to near zero on the other side ('Quiet' side) (Fig. 2).

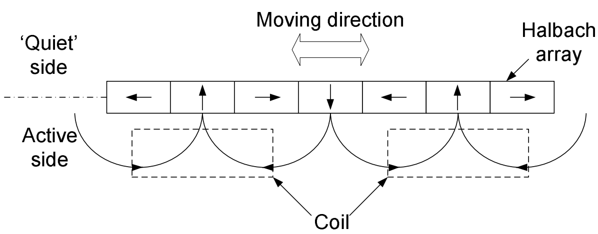

Fig. 2: Operation of the planar electromagnetic energy harvester.

Principle of the Halbach Array

Fig. 3 shows the principle of the Halbach array. The superimposition of the magnetic flux caused by the vertically and horizontally magnetized magnets results in the effect that magnetic field of one side of the Halbach array is doubled while the magnetic field of the other side of the Halbach array is cancelled out. This effect is beneficial to the planar electromagnetic energy harvester as it only requires one set of magnets rather than two as presented in [3] to achieve high magnetic flux density.

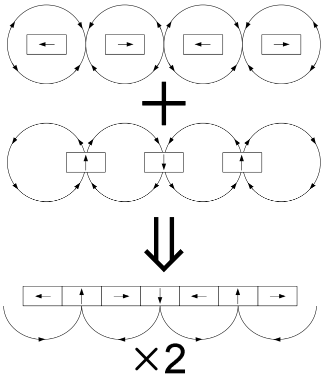

Fig. 3: Principle of the Halbach array.

DESIGN AND FABRICATION

Halbach array

The Halbach array in the energy harvester consists of seven permanent magnets. Each of them has dimensions of 16mm×4mm×1mm. To provide a strong magnetic field, permanent magnet, NdFeB, was used. These magnets had different orientation and were placed in the position as shown in Fig. 2.

The magnetic field strength of this Halbach array was predicted in Maxwell 3D. Fig. 4 shows the simulation result. It is found that at the position that is 1mm below the magnets, the magnetic field strength is about 0.2T at the active side and 0.02T at the 'Quiet side'. Orientations of these magnets are the same as in Fig. 2.

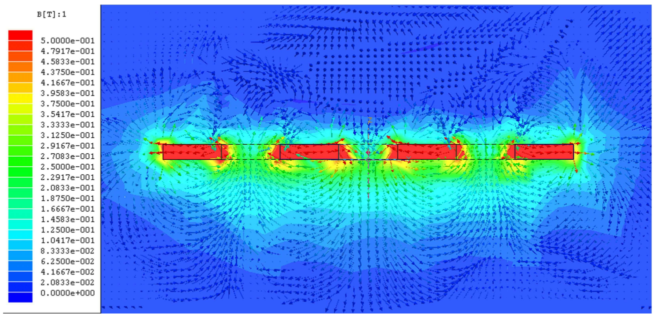

Fig. 4: Simulation result in Maxwell 3D.

Spring Frame

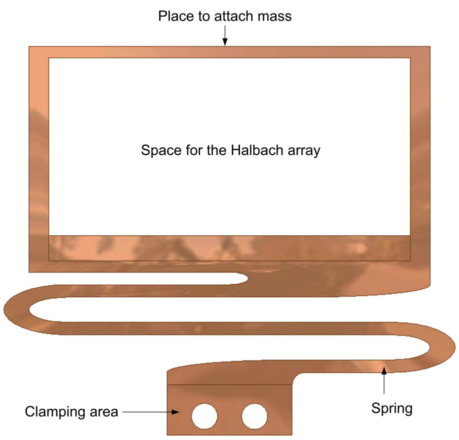

Fig. 5: Top view of the spring frame.

Fig. 5 shows the spring frame. It was made of BeCu for its good mechanical properties. The structure has a meander spring that allows the resonator to move in-plane. In addition, the spring was designed to be stiff enough to prevent the resonator from oscillating other directions. There is a frame connected to the spring. It holds the Halbach array and the inertial mass. The resonant frequency of the resonator can be adjusted by selecting an appropriate mass before installation.

Coil

Two identical coils were used in the energy harvester. Each coil has an outer and inner diameter of 12mm and 1mm, respectively. They are both 1mm thick and each has about 2500 turns. The coil was made of 50μm thick copper wire and its resistance was measured as around 600Ω. The two coils were connected in series to provide high output voltage.

Final Device

The housing of the electromagnetic energy harvester has dimensions of 55mm × 55mm × 4mm. Fig. 6 shows the base of the energy harvester with two coils attached to it.

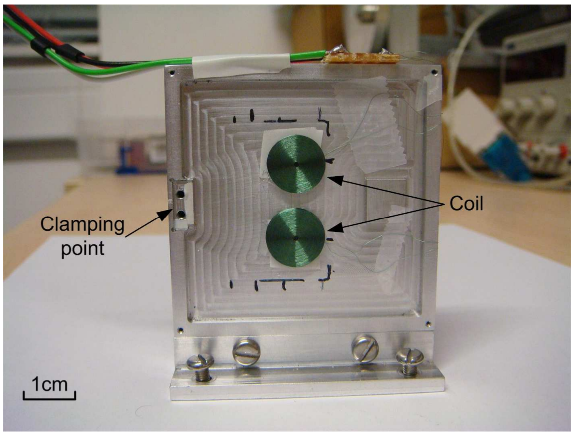

Fig. 6. Base of the energy harvester.

Fig. 7 shows the resonator of the energy harvester. Some tungsten pieces were placed at the free end of the resonator as the inertial mass. The resonator was placed on top of the coil with a 0.5mm gap in-between.

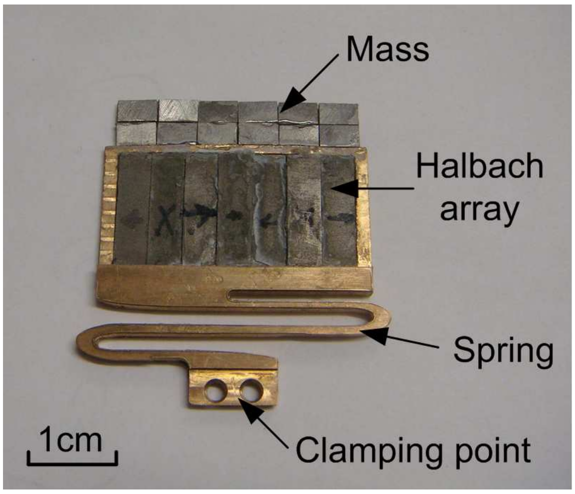

Fig. 7. Resonator with Halbach Array.

EXPERIMENTAL RESULTS

Measurement of Magnetic Field Strength

Comparisons of the magnetic field strength measured 1mm from the magnets are shown in Table 1. It shows that field at the Active side is not perfectly doubled and field at the 'Quiet' side does not perfectly cancel due to the discrete magnets used. Compared to the normal layout of magnets, the Halbach array increases the magnetic field by 56%. Field strength at the Active side is about 9 times that at the 'Quiet' side.

Table 1.Comparisons of magnetic field strength.

		Magnetic field strength (T)
Halbach array	Active side	0.14
	'Quiet' side	0.016
Normal layout		0.09

Experimental Setup

The energy harvester was tested on a shaker as shown in Fig. 8. Unlike most existing vibration energy harvesters, this planar electromagnetic energy harvester has in-plane displacement, which allows more space for the resonator to move within a planar structure. A total mass of 4 grams was attached to the energy harvester giving a resonant frequency of 44.9Hz. The total coil resistance was measured as 1220Ω.

Fig. 8. Experimental setup.

Experimental Results

In the experiment, the energy harvester was excited at vibration levels of 100, 200 and 300m***g*** (1***g*** = 9.8m·s^{-2}). Fig. 9 shows the open-circuit RMS voltage of the energy harvester at various vibration levels. Table 2 summarizes the resonant frequencies and output voltage at the three excitation levels. It is found that the energy harvester showed slightly soft nonlinearity. The voltage level is high enough to turn on shottky diodes, whose typical threshold voltage is 0.2V, for rectification. Furthermore, the output voltage increases linearly with acceleration levels.

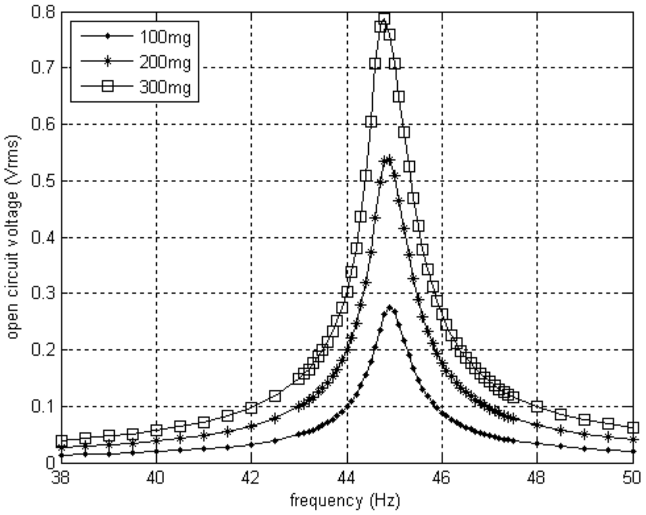

Fig. 9. Open circuit voltage (RMS).

Table 2: Output voltage at various acceleration levels.

Acceleration (m*g*)	100	200	300
Resonant frequency (Hz)	44.9	44.9	44.8
RMS voltage (V)	.27	0.54	0.79
Peak voltage (V)	0.38	0.76	1.12
Normalized voltage	1	2	2.9

Fig. 10 compares the output RMS power when connected to various resistive loads at the resonant frequency. It is shown that the optimum resistive load is around 1200Ω, which is close to the total coil resistance of the device.

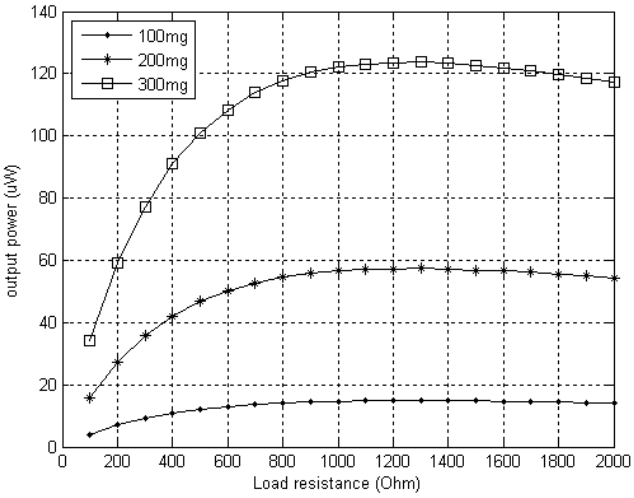

Fig. 10. Output RMS power vs. load resistance.

Fig. 11 compares the output RMS power at the optimum resistive load versus frequency. Table 3 summarizes the resonant frequencies and output power at the three excitation levels. The maximum output power of the energy harvester is over 120µW which is sufficient for powering wireless sensor nodes. Theoretically, the output power of a vibration energy harvester is proportional to the square of acceleration [4]. However, the output power measured in the experiment is slightly less than suggested by the theory. This is because soft nonlinearity of the energy harvester causes some loss in conversion of mechanical energy into electrical energy.

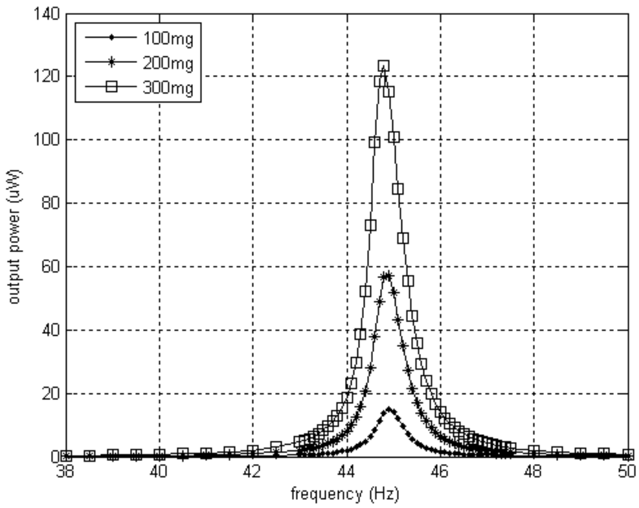

Fig. 11. Output RMS power at the optimum resistive load.

Table 3: Output power at various acceleration levels.

Acceleration (m*g*)	100	200	300
Resonant frequency (Hz)	44.9	44.9	44.8
RMS output power (µW)	14.9	57.4	123.8
Normalized voltage	1	3.85	8.3

CONCLUSION

This paper presents a low-profile, planar electromagnetic vibration energy harvester integrated with a Halbach array. Halbach array is a special arrangement of permanent magnets that doubles the magnetic field on one side of the array while cancelling the field to near zero on the other side. This arrangement can improve electromagnetic coupling in a limited space. Unlike most vibration energy harvesters, the resonator of the energy harvester presented in this paper has in-plane, rather than out-of-plane, displacement. This design provides more space for the resonator to oscillate within a planar structure. The electromagnetic vibration energy harvester reported here is only 4mm thick, which makes it one of the thinnest electromagnetic energy harvesters among existing non-MEMS devices.

The energy harvester consists of a 1mm thick Halbach array made of seven NdFeB permanent magnets. Measurement of the magnetic field strength measured shows that field on one side is not perfectly doubled while field at the other side does not perfectly cancel. This is because of the discrete magnets used. Compared to the normal layout of magnets, the Halbach array increases the magnetic field by 56%. Field strength at the Active side is about 9 times that at the ‘Quiet’ side.

The energy harvester has a resonant frequency of around 44.9Hz. The total coil resistance was measured as 1220Ω.

In the experiment, the energy harvester shows slightly soft nonlinearity. The output voltage level is high enough to turn on diodes for rectification. The optimum resistive load is around 1200Ω, which is close to the total coil resistance of the device. The maximum output power of the energy harvester is over 120µW at 300m***g*** which is sufficient for powering wireless sensor nodes. It is worth mentioning that the output power is slightly less than predicted by the linear modelling. The reason is that the nonlinearity of the energy harvester causes some loss in energy conversion from the mechanical domain to the electrical domain.

Future work includes optimizing the existing energy harvester and designing power conditioning circuit for this energy harvester. In addition, the energy harvester will be tested on the practical vibration taken from a helicopter for further calibration.

ACKNOWLEDGEMENT

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