

# AN EFFICIENT LOW COST ELECTROMAGNETIC VIBRATION HARVESTER

E. Bouendeu, A. Greiner, P. J. Smith and J.G. Korvink

Laboratory for Simulation, IMTEK, Technical faculty, University of Freiburg, Freiburg, Germany

**Abstract:** This paper reports the design, fabrication and characterisation of a low-cost harvester in a standard configuration, which converts mechanical vibrations into electrical energy, based on the electromagnetic conversion mechanism. Printed circuit board (PCB) material and polycarbonate housing have been used. The influence of the load resistance as well as the relative position between the coil and the permanent magnet is investigated. The fabricated harvester yielded high performance in the case there was no gap between the coil and the permanent magnet and produced  $356 \mu\text{W}$  to a load resistance of  $40 \Omega$  under  $98 \text{ Hz}$  and  $9.8 \text{ ms}^{-2}$  excitation parameters. The lightweight concept of the presented electromagnetic vibration harvester is a great advantage for applications where the weight is an important constraint.

**Keywords:** Energy harvesting, electromagnetic conversion mechanism, low cost, vibration

## INTRODUCTION

In recent years, many research activities have been carried out in the area of micro-energy harvesting with the aim to find alternative solutions to batteries, which require regular recharging or replacement, as power supplies of low-power devices. The basic idea behind micro-energy harvesting is to capture free environmental energy and convert it into useful electrical energy which can be used to power micro-devices such as temperature sensors, pressure sensors, gas sensors, humidity sensors or micro-actuators. Free environmental energy can be found in form of solar, thermal, chemical energy or mechanical vibrations which are converted into electrical energy by piezoelectric, electrostatic or electromagnetic conversion mechanisms. The piezoelectric conversion mechanism exploits the deformation within a piezoelectric material whilst the electrostatic mechanism utilises the relative motion of a capacitor plate to generate electricity. Piezoelectric and electrostatic conversion mechanisms are widely used since they are more compatible with prevailing MEMS-fabrication processes [1]. The electromagnetic conversion technique is based on Faraday's law of electromagnetic induction which states that an induced voltage appears across a conductor situated in a changing magnetic field. Many electromagnetic vibration harvesters which are implemented in the wafer level have been investigated and reported [2]. Wafer-based implementations of electromagnetic vibration harvesters are difficult to scale for large area applications and expensive. In some applications, for instance, in avionics lightweight devices are required.

Cheap, light, scalable and capable electromagnetic vibration energy harvesters are needed for large area

applications. In this work, an electromagnetic vibration harvester that satisfies this need is presented. Polycarbonate material and printed circuit board materials are used as passive and as active building elements of the harvester.

## THEORY OF ELECTROMAGNETIC HARVESTERS

The theory behind electromagnetic vibration harvesting has been detailed earlier [3]. Here a brief summary is given. Electromagnetic vibration harvesters can be fabricated in the standard or inverse configuration. In the inverse configuration, the coil moves while the permanent magnet is immovable. In the standard configuration, the permanent magnet whose function is to generate the magnetic flux is movable while the coil is fixed. These two configurations are shown in Figure 1. Figure 2 shows the lumped parameter model of electromagnetic vibration harvesters in the standard configuration which is used to derive the equation of motion of the harvester and to study the physics of the device. Two useful energy domains are easily distinguishable: the mechanical and electrical energy domains. The mechanical energy domain contains parameters such as the proof mass  $m$ , the spring constant  $k$ , the amplitude of the vibration source  $y_0(t)$ , the deflection amplitude of the proof mass  $y_1(t)$ , the mechanical damping coefficient  $c_m$ , and the electrically induced mechanical damping coefficient  $C_e$ . In the electrical domain, the idealised voltage source  $\varepsilon(B)$ , the coil inductance  $L$ , the resistance of the coil  $R_i$ , the load resistance  $R_L$ , the magnetic flux density  $B$ , and the

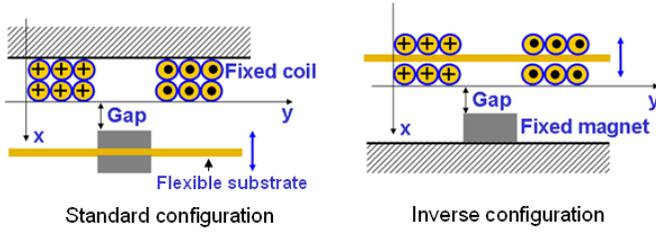


Fig. 1: Configurations of electromagnetic vibration harvesters.

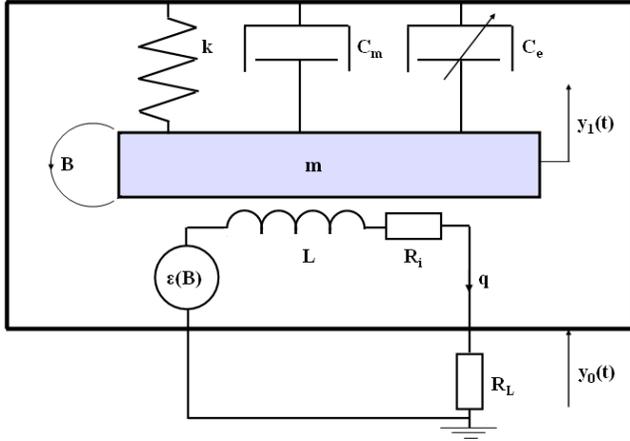


Fig. 2: Lumped parameter model of electromagnetic vibration harvesters.

flowing electrical charge  $q$ , are represented. The electromagnetic coupling factor is given by Equation 1. Equation 2 gives the open circuit voltage of electromagnetic vibration harvesters while Equation 3 expresses the electrical output power of the harvester at the resonance. The overall bandwidth of the electromagnetic vibration harvesters is given by Equation 4. The excitation frequency by which the harvester delivers the maximum output power is called optimum excitation frequency. It depends upon the resonant frequency of the harvester, its mechanical damping and electrically induced mechanical damping. This dependence is expressed by Equation 5.

$$k_{em} = B l \quad (1)$$

Where  $l$  is the active wire length of the coil.

$$|U_0| = \frac{k_{em} \omega a}{\sqrt{(\omega_0^2 - \omega^2)^2 + (2 \zeta_m \omega_0 \omega)^2}} \quad (2)$$

Where  $a$  represents the acceleration of the vibration source,  $\zeta_m$  is the mechanical damping factor,  $\omega$  and  $\omega_0$  are respectively the circular excitation frequency

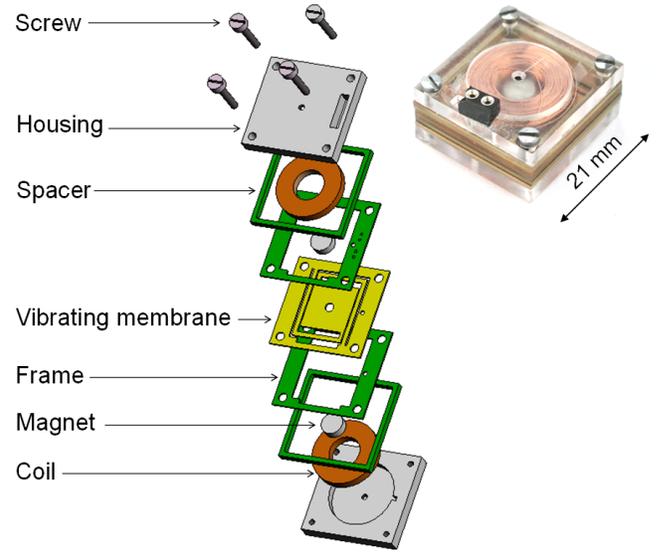


Fig. 3: Split and assembled view of the fabricated electromagnetic harvesters.

of the vibration source and resonant frequency of the harvester.

$$P_{out} = \frac{m \zeta_e a^2 R_L}{4\omega(\zeta_e + \zeta_m)^2 \sqrt{(R_L + R_i)^2 + (L\omega)^2}} \quad (3)$$

Where  $\zeta_e$  is the electrically induced mechanical damping factor.

$$\beta = \frac{k_{em}^2}{m \sqrt{(R_L + R_i)^2 + (L\omega)^2}} + \frac{C_m}{m} \quad (4)$$

$$\omega_{opt} = \omega_0 \sqrt{2 - 4(\zeta_e + \zeta_m)^2 - \sqrt{(4(\zeta_e + \zeta_m)^2 - 2)^2 - 3}} \quad (5)$$

## FABRICATION OF THE LOW-COST ELECTROMAGNETIC HARVESTER

The construction of the electromagnetic vibration harvester is straightforward and basically consists of stacked layers of housing, coil, spacer and mechanical resonator. The mechanical resonator is a flexible PCB-part sandwiched between two rigid PCB-parts (FR4) that serve as a frame. The flexible part of the resonator is a polyimide film that is 50  $\mu\text{m}$  thick; on each side of the polyimide film a copper layer of 35  $\mu\text{m}$  thickness is electro-deposited. The flexible part is laser-cut to the appropriate shape to fix the resonant frequency of the resonator. Since the harvester is in the standard configuration, two permanent magnets are magnetically attached to both sides of the flexible

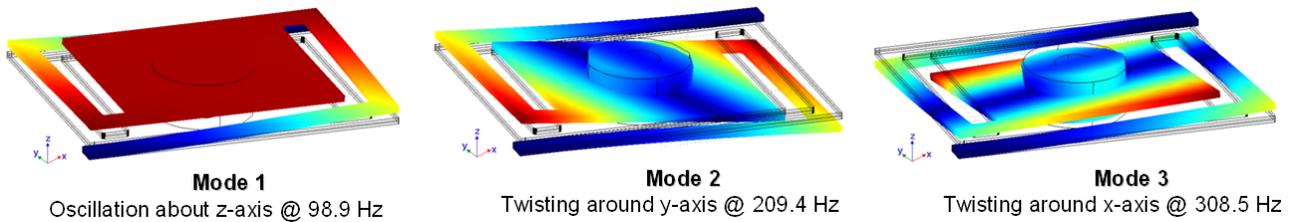


Fig. 4: Three first vibration modes and corresponding resonant frequency of the resonator.

parts to generate the required magnetic field. These magnets also act as active proof mass which define the resonant frequency of the harvester. Each NdFeB-magnet has 5 mm as diameter and 2 mm as thickness. Two copper wire-wound coils are used as electrical transducers that convert the deflection of the resonator into an electrical signal. Each coil has an inductance of 842  $\mu\text{H}$ , a resistance of 10.7  $\Omega$  and is contained in the chamber of the polycarbonate housing. The volume of the chamber is 1.45  $\text{cm}^3$ . FR4-spacers are placed between the coil and the resonator to adjust the gap between magnet and the coil which affects the electromagnetic coupling factor of the harvester. Figure 3 shows the split and assembled view of the fabricated electromagnetic vibration harvester. This stacked architecture is important for the modularity of the harvester and can be extended to an array-based architecture to address large area applications.

## MODELLING OF THE RESONATOR OF THE LOW-COST ELECTROMAGNETIC HARVESTER

The finite element method (FEM) was used to model and analyse the mechanical resonator of the harvester. The structural mechanics of the MEMS module of COMSOL Multiphysics 3.4 was used; a mechanical damping factor of 0.02 was assumed. Since commonly available vibration sources are low frequency mechanical vibrations, only the first three vibration modes have been investigated with the FEM-simulation. The plot of the three first vibration modes of the resonator and the corresponding resonant frequency is given in Figure 4. In the first mode, the resonator oscillates about the z-axis with a resonant frequency of 98.8 Hz. The resonator twists around the y-axis with a resonant frequency of 209.4 Hz in the second mode. In the first mode, the resonator twists around the x-axis with a resonant frequency of 308.5 Hz.

## EXPERIMENTAL RESULTS AND DISCUSSION

Experiments were performed to investigate the influence of the load resistance, excitation frequency and gap on the device performance and behaviours. All measurements were carried out with the constant acceleration of 9.8  $\text{ms}^{-2}$  in ambient condition at 25  $^{\circ}\text{C}$  and 45 % relative humidity. Figure 5 shows the dependence of the output power and optimum excitation frequency upon the load resistance. With increasing load resistance, the optimum excitation frequency decreases due to the reduced electrically induced mechanical damping, which brings the optimum excitation frequency closer to the resonant frequency of the harvester. The harvester delivers a maximum electrical output power of 356  $\mu\text{W}$  when it is connected to a load resistance of 40  $\Omega$  which represents the optimum load resistance of the harvester. When the harvester is lightly loaded, its electromagnetic coupling factor as well as its overall bandwidth is nearly constant. Near to the short circuit condition, the electromagnetic coupling factor and the total bandwidth of the harvester drastically increase due to the high electrical current flowing in the circuit. This behaviour is illustrated by Figure 6.

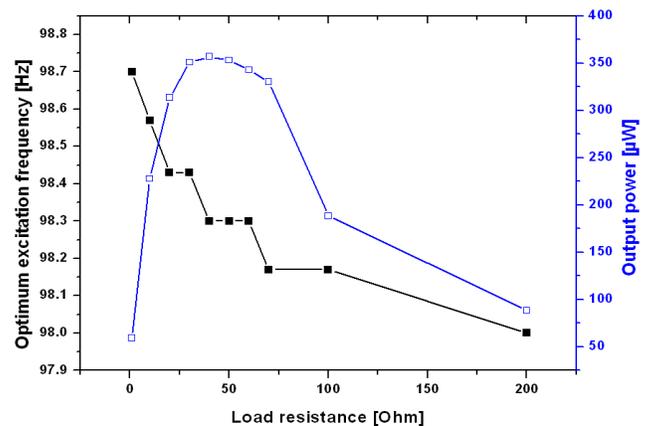


Fig. 5: Load dependence of the optimum excitation frequency and output power of the fabricated electromagnetic vibration harvester.

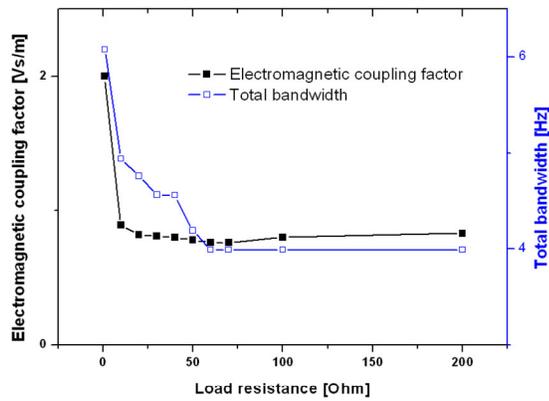


Fig. 6: Load dependence of the electromagnetic coupling factor and overall bandwidth..

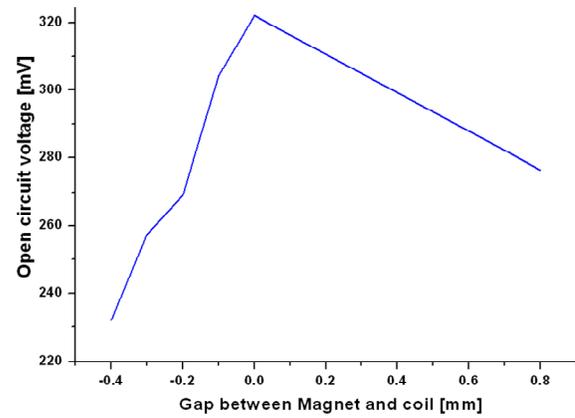


Fig. 7: Influence of the gap on the open circuit voltage of the electromagnetic vibration harvester.

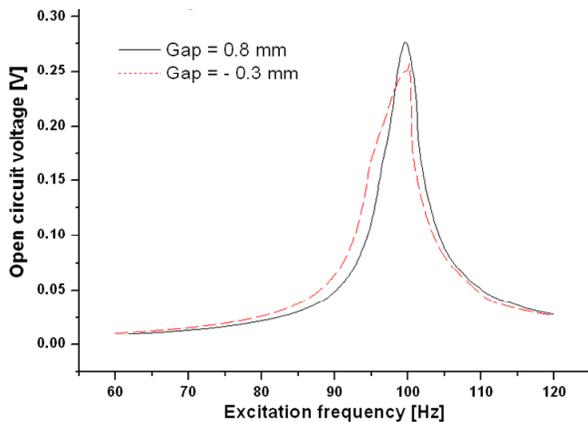


Fig. 8: Frequency response of the fabricated electromagnetic vibration harvester.

The dependence of the open circuit voltage on the gap between the permanent magnet and coil is shown in Figure 7. The open circuit voltage of the harvester reaches its maximum in the case where there is no gap between the permanent magnet and the coil. In this position of the permanent magnet and the coil, the electromagnetic coupling factor is optimal. Away from the optimum position, the active magnetic flux lines that cross the coil decrease, therefore reducing the open circuit voltage of the harvester.

Figure 8 shows the plot of the frequency response of the harvester at different values of the gap. This plot clearly illustrates the resonant character of the harvester. In the case where the gap between the magnet and the coil is 0.8 mm, there is a good agreement between simulation and experimental results of the resonant frequency. The hard spring effect was observed when the gap between the coil and the magnet was  $-0.3$  mm. In this position, the restoring force of the resonator becomes a nonlinear function of its displacement. A tension force effectively appears and increases the stiffness of the reson-

ator, therefore shifting the resonant frequency to a higher value than when the resonator operates in the linear range. The fabricated harvester weighs 8.12 g and is 83 times smaller than a commercially available harvester [4].

## CONCLUSION

This paper has presented a low-cost approach to implement electromagnetic vibration harvesters which can be modular and scalable for large area applications. Based on PCB-materials and polycarbonate material an electromagnetic vibration harvester in the standard configuration has been designed and characterised. Investigations have shown that no gap between the magnet and the coil is required for high performance. A hard spring effect was observed for a negative gap. The fabricated harvester has a power density of  $44 \mu\text{W/g}$  and weighs 8.12 g, therefore is a good candidate for applications where the weight is an important constraint.

## REFERENCES

- [1] Chalasani S, Conrad J M 2008 A Survey of Energy Harvesting Sources for Embedded Systems *Southeastcon IEEE* p. 442-447
- [2] Serre C et al Vibrational Energy Scavenging with Si-Technology Eelectromagnetic Inertial Microgenerators *DTIP of MEMS & MOEMS 2006*
- [3] Bouendeu E et al Design synthesis of electromagnetic vibration-driven energy generators using a variational formulation *JMEMS* (submitted on 6<sup>th</sup> June 2009)
- [4] <http://www.perpetuum.co.uk>, Webpage accessed on September 18, 2009