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A Compact Electromagnetic Vibration Harvesting System with High Performance Interface Electronics

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Abstract

A compact vibration-based electromagnetic (EM) energy harvesting system utilizing high performance interface electronics, has been presented. The energy harvester module consists of an AA-battery sized cylinder tube with an external coil winding, a fixed magnet at the bottom of the tube, and a free magnet inside. The transducer is able to operate at low external vibration frequencies between 9.5 and 12 Hz. The generated AC voltage is converted to DC using a custom rectifier circuit that utilizes a gate cross coupled (GCC) input stage. This decreases the effective threshold voltage of the utilized diodes, while increasing the DC output power delivered to the load. The autonomous system, composed of an EM energy harvester module and a 0.35μm CMOS IC, delivers 11.6 μW power to a 41 μA load at an external vibration frequency of 12 Hz. The volume of the total system is 4.5 cm^3, and the overall system power density is 2.6 $\mu W/cm^3$.

Keywords: Vibration-based Energy Harvesting System; Electromagnetic Power Generation; Gate-Cross-Coupled Rectification

1. Introduction

Ultra low power wireless sensors are increasingly being proposed for many applications including medical, automotive, and structural health monitoring. This rapid increase triggers the need for energy storage elements that are continuously being charged using the ambient energy such as heat, light, and vibration, as the frequent battery replacement for these systems would be impractical. Vibration is a

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particularly attractive energy source due to its abundance. Some vibration sources in the environment are vehicle motion, human movements, and seismic vibrations that widely vary in frequency and amplitude.

The vibration energy could be harvested using several methods such as piezoelectric, electrostatic, and electromagnetic transduction. Piezoelectric energy harvesters provide higher output voltages however they are more efficient for relative high vibration frequencies. Electromagnetic energy harvesters are better candidates for low frequency vibrations [1, 2], however, their generated peak output voltage is relatively low. Therefore, the design of power electronics is crucial in delivering the harvested power to the output load efficiently. Most of the work on power electronics for vibration-based energy harvesting has been done for piezoelectric transducers [3, 4]. However, there are only a few examples in the literature that combine an electromagnetic energy harvester and its power electronics [5, 6]. Furthermore, the rectification efficiency of these systems is relatively low due to the voltage drops across the utilized diodes.

In [5], an electromagnetic energy harvesting system with high power density is proposed. However, the implemented system has a large volume and its resonance frequency is high. Another system is proposed in [6] which uses the Frequency-Increased-Generation technique that operates at 1 Hz, but the design has a similar size of [5], and the net system power density is relatively low.

In this study, a compact system-on-package EM energy harvesting system is presented which consists of a low cost, simple, and high power density energy harvester for low frequency vibrations and a high performance interface electronics for AC/DC power conversion.

2. The Proposed Energy Harvesting System

Fig. 1(a) presents the block diagram of the proposed energy harvesting system. The system consists of an energy harvester module, a power ASIC, and an external storage capacitor. The kinetic energy resulting from the ambient vibrations is converted to electrical energy by using an in-house EM energy harvester where an induced voltage is generated across a coil due to the motion of a magnet with external vibrations. The generated AC voltage is converted to DC using a custom standard 0.35 μm CMOS AC/DC converter and is stored on the external output capacitor. There is no peripheral requirement such as a start-up battery, step-up transformer, etc. for the IC in order to start or maintain its operation.

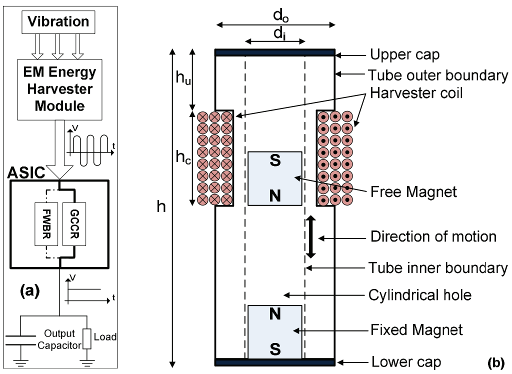

Fig. 1. (a) The proposed block diagram, (b)the schematic of the energy harvester module

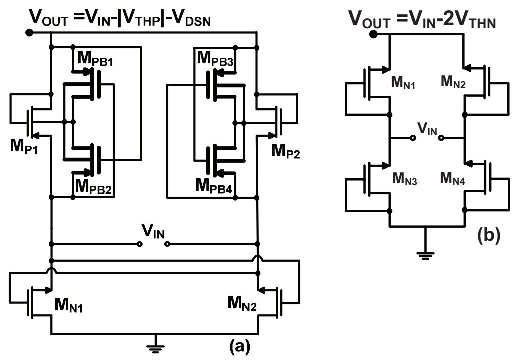

Fig. 2. The schematic of the interface circuits (a) GCCR and (b) the FWBR

Fig. 1(b) depicts the utilized energy harvester module which consists of a cylinder tube with an external 1200-turn coil winding, a fixed magnet at the bottom of the tube, and a free magnet inside. The same poles of the magnets face each other to suspend the free magnet. The free magnet starts moving in presence of external vibrations.

Fig. 2 depicts two alternate interface circuit designs: (a) the optimized Gate-Cross-Coupled Rectifier (GCCR) design to achieve higher conversion performance and (b) a commonly used Full Wave Bridge Rectifier (FWBR). Both designs have been fabricated on the same chip, and tested with the same harvester module to provide a realistic comparison. In GCCR, a pair of diode connected transistors are replaced with a pair of cross-connected nMOS transistors (Fig. 2(a)) at the first stage. In this configuration, the threshold voltage of the diode connected transistors (M_{N3} and M_{N4} in Fig. 2(b)) is replaced with the drain-source voltage of the nMOS transistors (M_{N1} and M_{N2} in Fig. 2(a)), resulting in a significantly higher conversion performance [7].

3. Experimental Results

The fabricated prototype is shown in Fig. 3. The total volume of the system is 4.5 cm^3 including the energy harvester module, the interface electronics, and the external storage capacitor. A small-sized 10 µF SMD capacitor, mounted on the same substrate next to the IC, is used for storing the output DC voltage. Fig. 4 presents the generated RMS voltage across the coil for different excitation frequencies. The highest induced RMS voltage (650 mV) is reached for 12 Hz excitation, and the operation bandwidth of the harvester is 2.5 Hz.

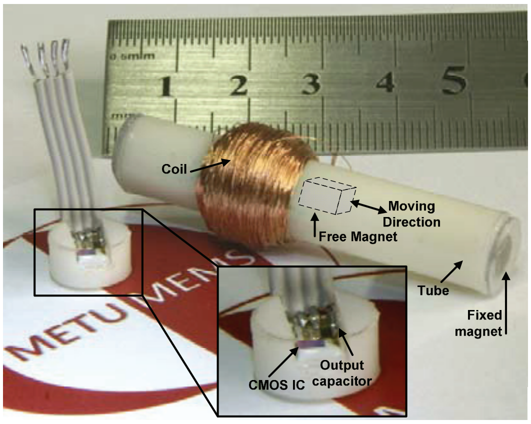

Fig. 3. The fabricated system prototype

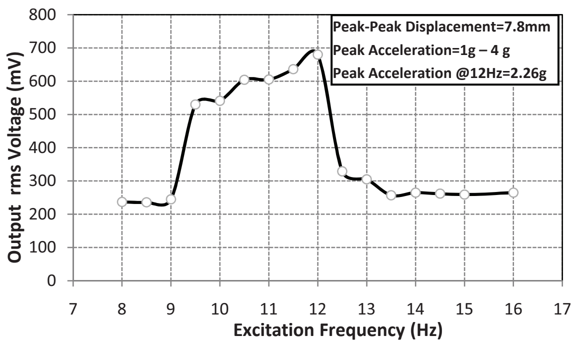

Fig. 4. The output RMS voltage of the energy harvester for different excitation frequencies.

Fig. 5 depicts the comparison of the output voltage and the output power of the implemented circuits against the load current within a 1 µA to 64 µA range. The maximum output power of 11.6 µW is achieved using the GCCR design, however the maximum extracted power of the FWBR is 2.35 µW which highlights the improved performance of threshold-voltage reduction effect of the GCCR design. Fig. 6 illustrates the generated AC voltage of the energy harvester module and output DC voltage for an external vibration at 12 Hz frequency and 2.26g peak acceleration at an output load current, I_{Load}, of 41 µA (R_L=7 kΩ), where maximum output power is achieved. The induced peak-to-peak voltage is 2.75 V with 650 mV rms value and converted output DC voltage is 285 mV.

Table 1 summarizes the system specifications, and Table 2 provides a comparison of the proposed system with the ones reported in the literature.

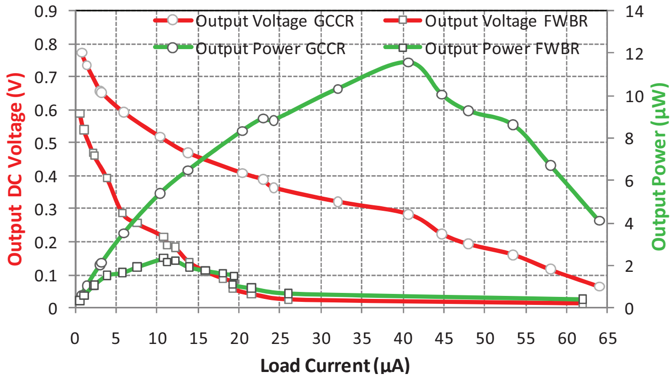

Fig.5. The output voltage and output power of two rectifiers versus load current which is swept from 1 to 64 µA.

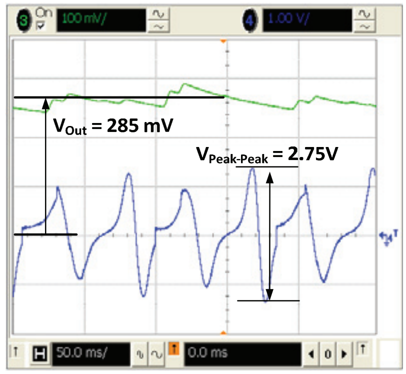

Fig. 6. The output of the energy harvester module (blue) and converted DC voltage (green) at I_{Load}=41 µA.

Table 1. The system specifications.

Operation Frequency	12 Hz
Magnet Dimensions	4x4x4 mm^3
Number of coil turns	1200
Coil resistance	60 Ω
IC Technology	0.35 µm CMOS
The System Volume	4.5 cm^3
Max. Output Power	11.6 µW
Max. Power Density	2.6 µW/cm^3

Table 2. Comparison with state-of the art on EM energy harvesting systems.

Ref.	Volume (cm^3)	Power Density (µW/cm^3)	Frequency (Hz)	Circuitry	Additional Req.
[5]	31.5	126	41	Diode AC/DC - DC/DC PWM Boost Conv.	Additional 3.3V battery
[6]	43	1.32	1	Cockcroft Multipliers	Discrete Components
This work	**4.5**	**2.6**	**12**	**Passive GCCR**	**-**

4. Conclusion

The operation and performance results of a compact EM vibration-based energy harvesting system utilizing high performance GCCR interface electronics is demonstrated. The autonomous system, composed of an EM energy harvester module and a 0.35µm CMOS IC with no peripheral component requirements, delivers 11.6 µW power to a 41 µA load at an external vibration frequency of 12 Hz. The volume of the total system is 4.5 cm^3, and the overall system power density is 2.6 µW/cm^3. The delivered maximum DC power level is improved five times with respect to the common FWBR circuit.

Acknowledgements

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