

A Self-Powered and Efficient Rectifier for Electromagnetic Energy Harvesters

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Abstract—This paper presents an interface circuit for efficient rectification of voltages from electromagnetic (EM) energy harvesters operating with very low vibration frequencies. The interface utilizes a dual-rail AC/DC doubler which benefits from the full cycle of the input AC voltage, and minimizes the forward bias voltage drop with an active diode structure. The active diodes are powered through an AC/DC quadrupler with diode connected (passive) transistors. The interface system has been validated to drive 22 μ A load at 1.1 V, with 86% efficiency, when 0.1g vibration is applied to an in house energy harvester at 8 Hz. The circuit is functional down to 150 mV input. The rectified voltage deviates at most 38 mV from the theoretical value of twice the input peak voltage. The system was demonstrated for feasibility in portable applications through a prototype placed to the waist of a jogger.

Keywords—Vibration-based energy harvesting, Electromagnetic power generation, Low voltage AC/DC conversion, Self-powered rectifier.

I. INTRODUCTION

Research on energy harvesting has gained popularity in the recent decade due to the reduced power consumption of the microelectronic devices. Ambient energy sources which can be harvested are solar, thermal, RF, and vibration [1], [2]. Vibration is one of the most attractive one among these sources due to its abundance in the environment. Three primary methods exist for converting mechanical energy into electrical energy: Electromagnetic, piezoelectric and electrostatic. Their simple structure and relatively high power density make EM harvesters one of the most promising solutions to generate electrical energy from ambient vibrations. Moreover, the high inertial mass of the utilized magnet in the EM harvester naturally leads to a low resonant frequency, and good performance under low frequency input conditions. However, the harvested voltage amplitude is low for most ambient vibrations at low frequency. Therefore, efficient conversion of the generated AC power into usable form without external batteries is challenging.

A self-powered rectifier for low-voltage energy harvesters was introduced in [3], but the maximum output DC voltage magnitude was limited to the peak value of the input signal. In [4], a fully self-powered EM energy harvesting system with dual rail DC output was presented by our group. However, the

proposed system utilized off-the-shelf components, and required two separate supplies to be fed from the harvester, which together increased the interface size. The system presented in [5] used an AC/DC doubler structure with active diodes, and was capable of producing an output as high as the peak-to-peak value of the input; however, the supply to the active diodes was lower than the input peak voltage, limiting the output voltage level.

In this paper, a self-powered and efficient rectifier for EM harvesters is presented with enhancements to eliminate the above limitations. The design accommodates low voltage and low power EM energy harvesting applications through an active AC/DC doubler structure that is powered internally by a passive AC/DC quadrupler circuit. The active structure enables low voltage drop at the output and high power efficiency. The circuit has been designed, and fabricated in UMC 180 nm CMOS technology. The performance of the circuit has been validated using an in-house EM energy harvester prototype.

II. SYSTEM DESIGN

A. Interface Electronics

Fig. 1 depicts the block diagram of the system which utilizes an active AC/DC doubler that is powered by a passive AC/DC quadrupler structure. The active diode structure minimizes voltage drops, and is more suitable to drive high load currents compared to the passive diode connected structures. The active diode structure consists of a CMOS switch and a comparator circuit. PMOS and NMOS pass transistor based switches are utilized at positive and negative output sides respectively, since PMOS has maximum conductance at high voltages, and NMOS at low voltages. The comparators used to control the switches are designed to operate with very low current consumption (several tens of nano-Amps), which can be provided by passive diodes with low drop-out voltage. The passive AC/DC quadrupler uses the input from the harvester to generate high enough positive and negative supply voltages to power-up the comparators. The performance of the AC/DC doubler is further improved through phase-customized comparators, one with NMOS input stage to process the positive phase of the input signal, and another with PMOS input stage to process the negative phase (Fig. 2(a) and (b)).

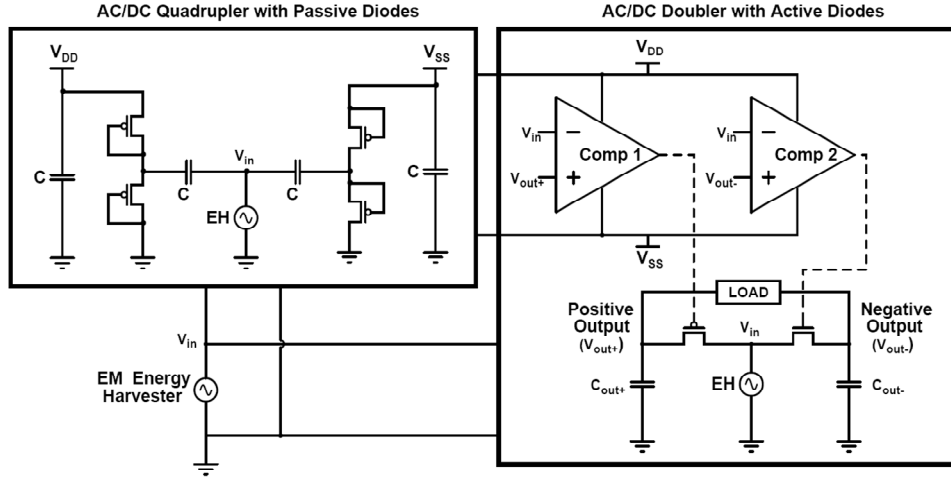


Fig. 1. Block diagram of the system consisting of and active AC/DC Doubler powered by the passive AC/DC Quadrupler.

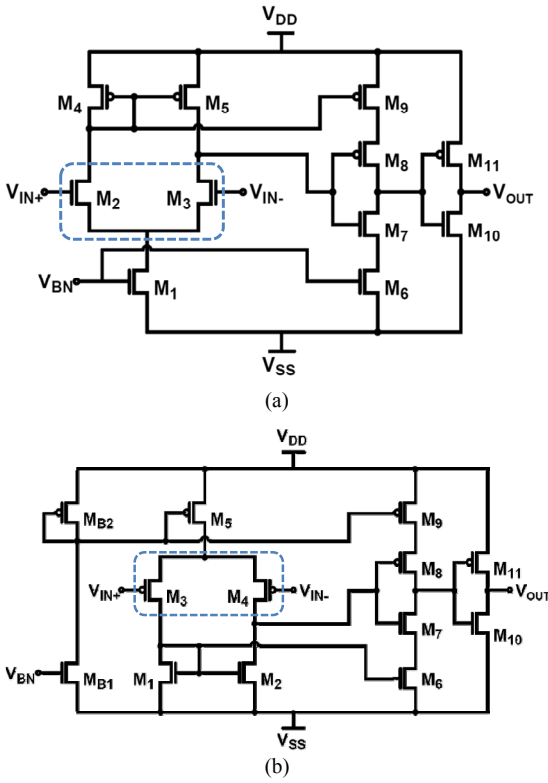


Fig. 2. Comp 1 and Comp 2 comparator circuits used to rectify the (a) positive, and (b) negative phases of the input.

Operation principle of the circuit is as follows: When the input signal is positive and higher than positive output voltage (V_{out+}), the comparator at positive output side (Comp 1) turns ON the PMOS pass transistor, and charges the positive output storage capacitor (C_{out+}). When the input signal falls below the positive output voltage, the PMOS pass transistor is turned OFF and charge is retained on the storage capacitor. Similarly, at negative output phase, the NMOS pass transistor is controlled by the second comparator (Comp 2), and negative voltage is stored on the negative output storage capacitor

(C_{out-}). Hence a dual rail output is obtained which doubles the input voltage.

The bias required by the comparator circuits is generated through a four-transistor subthreshold voltage reference [6]. The reference circuit is suitable for ultra-low voltage applications, and is thus adapted to obtain the needed bias voltage to operate the comparators at very low power dissipation.

B. Energy Harvesting Test Setup

Fig. 3 presents the block diagram of the test setup. The setup includes an EM energy harvester module, the interface circuit (ASIC) and an external output storage capacitor. The kinetic energy coming from ambient vibration is converted into electrical energy via EM energy harvester module. The generated AC signal is efficiently rectified with the AC/DC Doubler circuit, which is designed in 180 nm technology, and generated voltage is stored on a storage element. The implemented design is compared with the previously reported AC/DC Doubler circuit designed in 90 nm technology [5] under the same input conditions.

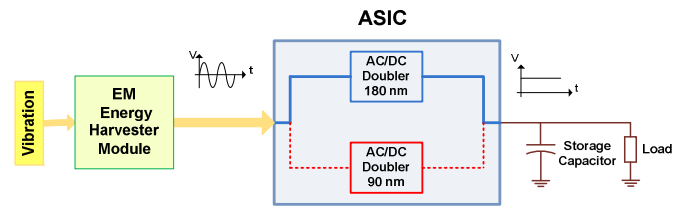


Fig. 3. Block diagram of the energy harvesting test setup.

Fig. 4 presents the EM energy harvester prototype fabricated for testing the proposed AC/DC interface circuit. The harvester module is composed of a cylindrical tube package, a fixed magnet (5.3 mm x 5.3 mm x 0.5 mm) at bottom cap, and a cylinder magnet (10 mm diameter and 7.5 mm height) suspended in the air inside the tube. A pick-up coil is wound around the designated cavity on the outer boundary of the tube. When an external vibration is applied in the axis of cylindrical tube, the suspended magnet starts to move and the voltage is induced across the coil according to Faraday's law.

The inner and outer diameters of the energy harvester are 5.5 mm and 25 mm, respectively. Length of the prototype is 52 mm which is close to a regular AA type battery. The harvester coil wound around the tube has 1100 turns, and has 98Ω internal resistance.

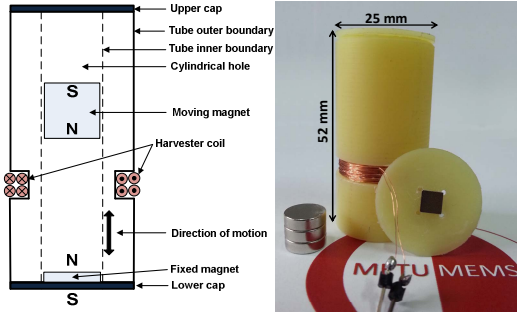


Fig. 4. The EM energy harvester prototype.

III. EXPERIMENTAL RESULTS

The input voltage performance of the circuit was tested by feeding the interface from the signal generator through which the input peak was precisely controlled. The storage capacitors at passive and active parts of the AC/DC doubler circuit were $2.2 \mu\text{F}$ and $47 \mu\text{F}$, respectively. The change of the rectified output voltage and the voltage drop at the output with respect to the input peak voltage are presented in Fig. 5. The results show that circuit is functional down to 150 mV input. The rectified voltage deviates at most 38 mV from the theoretical value of twice the input peak voltage, which is nearly impossible to achieve with passive diode connected structures.

The energy harvesting system was tested at different vibration conditions with the help of a shaker table. As depicted in the frequency response curves in Fig. 6, the resonant frequency of the prototype varies between 7.5 to 8 Hz. Hence 0.1g peak acceleration at 8 Hz was used in the remaining tests. Fig. 7 depicts the power conversion efficiency comparison of the circuit against the previously reported 90 nm circuit [5] with varying load current. The proposed structure gives considerably higher efficiency especially at higher current demands. The circuit is able to operate with a maximum of 86% efficiency at 22 μA load current and 1.1 V output DC voltage, where the maximum efficiency of the previously reported design is around 67%.

A prototype of the system was tested at different positions on a jogger, and its feasibility for portable applications was demonstrated. Fig. 8 shows pictures of the prototype that was placed at wrist, ankle, arm, and waist of a jogger. Table I presents the obtained open-load test results of the energy harvesting system at given positions on the jogger. The maximum harvested voltage and rectified output was obtained when the harvester module was placed on the waist of the jogger, which is presented at Fig. 9. The system is able to harvest 3.16 V peak-to-peak AC voltage, and the interface circuit converts this voltage into 2.83 V DC output. The high turn ratio and low resonance frequency of the prototype leads to harvest high ac signals at low vibration profile and the interface circuit able to finely rectify this harvested voltage.

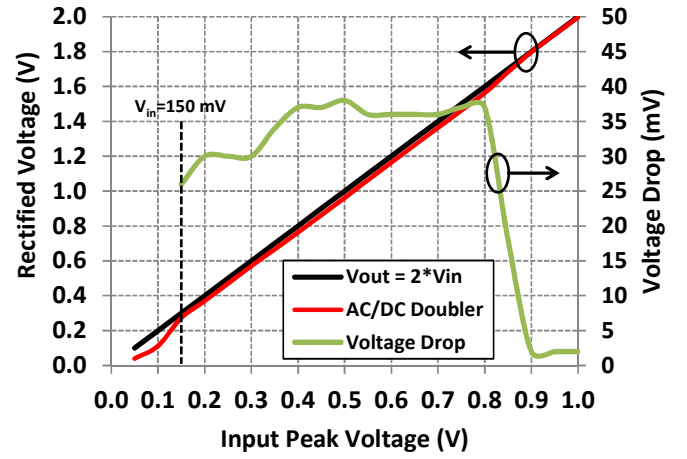


Fig. 5. The output DC voltage versus the input amplitude at 10 Hz input frequency and open load condition (Voltage Drop= $2*V_{in}-V_{Rectified}$).

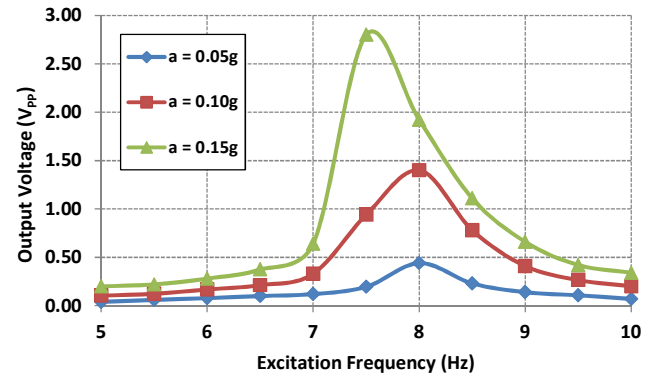


Fig. 6. Harvested AC voltage versus the vibration frequency at 0.05g, 0.10g, and 0.15g peak accelerations.

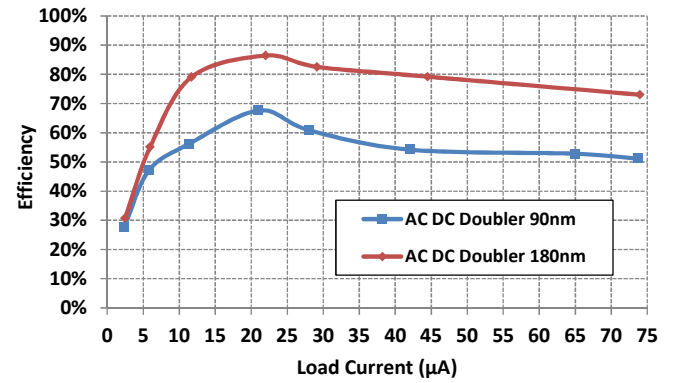


Fig. 7. Efficiency comparison against the previously designed 90 nm circuit with varying load current for 0.1g peak acceleration at 8 Hz.

TABLE I. TEST RESULTS OF THE SYSTEM WHEN PLACED ON THE JOGGER.

Prototype Position	Harvested Voltage (V_{pp})	$V_{out} = V_{out+} - V_{out-}$ (V)
Wrist	2.01	1.73
Ankle	1.72	1.13
Arm	2.36	2.28
Waist	3.16	2.83

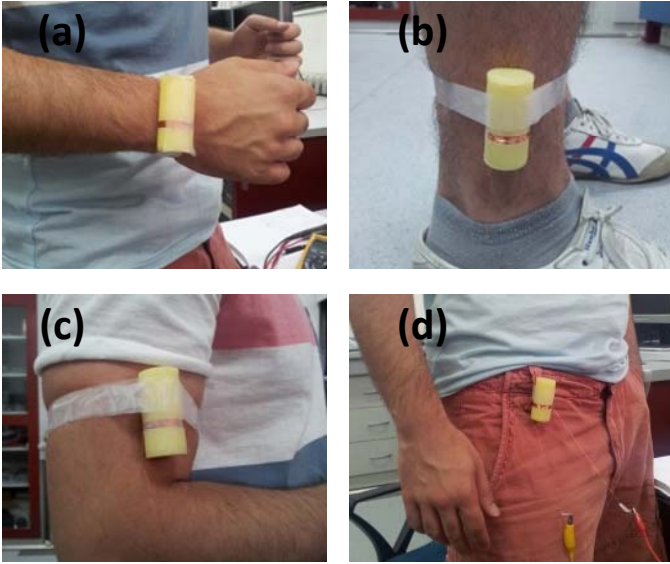


Fig. 8. Pictures of the prototype that is placed at (a) wrist, (b) ankle, (c) arm, and (d) waist of a jogger.

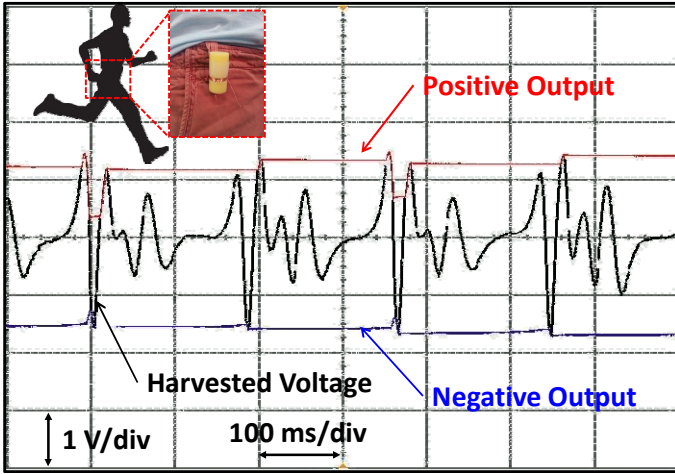


Fig. 9. The positive and negative AC/DC Doubler outputs with input fed from the harvester placed on the waist of a jogger.

Table II shows the system specifications of the fabricated EM energy harvester prototype, and the AC/DC doubler structure. With 0.776 mm peak-to-peak vibration at 8 Hz (corresponding to 0.1 g acceleration), 1.4 V_{peak-to-peak} AC voltage is generated and rectified with 86% efficiency at 1.1 V and 22 μ A load conditions.

TABLE II. THE SYSTEM SPECIFICATIONS.

Vibration Conditions		8 Hz, 0.776 mm, 0.1g
Magnet Dimensions	Moving	$\phi=10$ mm, $h=7.5$ mm
	Fixed	5.3x5.3x0.5 mm ³
Saturation Magnetization		1.2 T
Number of Coil Turns		1100
Coil Resistance		98 Ω
IC Technology		UMC 180 nm CMOS
Harvested AC Voltage		1.4 V _{peak to peak}
Max. power conversion efficiency		86% (@ 1.1 V & 22 μ A load)
Min. operation voltage		150 mV peak

Table III shows the comparison of the proposed rectifier circuit with other recently reported studies. The presented AC/DC doubler circuit gives the best solution for satisfying high power conversion efficiency at ultra-low input voltages.

TABLE III. PERFORMANCE COMPARISON WITH RECENTLY REPORTED RECTIFIERS.

Ref	Min V_{in} [V _{peak}]	PCE _{max} [%]	Rectification	Technology
[3]	0.50	94	Full-wave	0.35 μ m
[5]	0.10	67	AC/DC Doubler	90 nm
This work	0.15	86	AC/DC Doubler	180 nm

IV. CONCLUSION

A self-powered and efficient interface circuit has been presented for processing EM energy harvester outputs at ultra-low vibration frequency and amplitude. The AC/DC quadrupler structure leads to the rectification of the input to be used as a local power supply. Active components utilize this supply for highly efficient rectification of the same input by minimizing the voltage drop at the output. The resulting self-powered interface circuit has been tested with an in-house EM energy harvester prototype, and functionality at ultra-low vibration levels has been verified. The system operates with a maximum of 86% efficiency at 1.1 V and 22 μ A load conditions. The interface circuit preserves functionality down to 150 mV input peak voltage, with a maximum of 38 mV voltage drop at the output. The application performance of the energy harvesting system has been tested by placing it at different positions on jogger. Self-powered systems hosting the proposed interface circuit can be used in portable and wearable autonomous systems, especially when supplying low impedance sensors.

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