T-shaped Piezoelectric Vibratory MEMS Harvester with Integration of Highly Efficient Power Management System

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Abstract. This paper introduces a T-shaped piezoelectric vibratory MEMS energy harvester. The prototype measurement results clearly demonstrate that the T-shaped harvester can achieve higher normalized power efficiency by a factor of 1.95 in comparison with the conventional piezoelectric harvester. Since the magnitude of harvested voltage in this type of energy harvesters is only a few millivolts, utilizing the traditional power electronic components is impractical. Thus, in this paper we also propose a highly efficient power management system without requiring external bias voltages. The numerical simulation illustrates that our proposed power management system can rectify and boost the harvested voltage up to 5V. In order to keep the output voltage on the load side at a stable level, a JFET transistor is utilized as a voltage limiter. Thus, the processed output voltage cannot exceed 4V even if a higher harvested voltage may be produced by the harvester.

1. Introduction

Energy harvesting from environmental resources has been recognized as a vivid solution for providing power supplies with no life time worries. Among the harvestable energy resources, energy harvesting from vibrations (including, wind flow, ocean wave, human motions and etc.) has gained higher attention, due to their ubiquity in environment and ease of trapping. Kinetic energy of vibration can be converted to electricity, by electrostatic-, electromagnetic- and piezoelectric-based techniques. Each technique above has its own advantages as well as drawbacks. Among them, the piezoelectric-based technique features sound advantages for MEMS or portable energy harvesters [1].

In the literature, various approaches, such as tuning proof mass size [2] or optimizing piezoelectric film and beam aspects [3][4], have been proposed to enhance energy conversion efficiency of the piezoelectric harvesters. Although those methods can enlarge efficiency to some extent, considerable efficiency enhancement is not possible due to the utilized conventional cantilevers with clamped-free boundary in the harvesters. On the other side, the magnitude of the harvested voltage by this type of energy harvesters is only a few millivolts. Therefore, utilizing the conventional rectifier circuitry (e.g., a silicon diode bridge) as a power management system for vibratory MEMS harvesters is impractical.

To overcome this aforementioned issue, Tan et al. [5] proposed an active rectifier. The proposed converter can rectify low input voltage ($V_{in}=1.2V$) with 70% efficiency. However, this converter includes two op-amps to magnify the harvested voltage, which are supplied with 3.3V external power supplies. Unfortunately this required external power supply makes this proposed method less useful for practical energy harvesters. To eliminate the required external power supply, Wahbah et al. [6] proposed
a voltage doubler rectifier. Since this circuit can rectify minimum 1.8V AC signal with efficiency of 24%, most of the harvested voltage would be dissipated due to its low efficiency. In a recent study [7], efficiency of the rectifier interface circuit for piezoelectric MEMS harvesters has been largely improved up to 80% with a pre-charge battery required. However, this efficiency is valid only if the amplitude of the generated voltage is at least 2V. For the voltage at the millivolt level, the reported efficiency is zero.

Therefore, besides introducing a T-shaped MEMS energy harvester with the feature of high power density, we are motivated to propose a novel self-supplied power management circuit with extremely high efficiency in AC-to-DC signal conversion when the amplitude of the AC input signal is adequately low. This paper is organized as follows. A brief literature review on the MEMS efficiency improvement methods and different architecture of power management circuitry is surveyed in this section. In Section 2, the proposed structure of T-shaped piezoelectric MEMS harvesters is explained. The architecture of proposed power management system is discussed in Section 3. Section 4 reports the experimental results. Eventually, the conclusion is made in Section 5.

2. T-shaped piezoelectric MEMS harvester

The cantilevers with clamped-free boundary are recognized as the most common structure for piezoelectric vibratory MEMS harvesters. However, this type of energy harvesters have quite narrow operational bandwidth and in turn low efficiency in conversion of vibration to electricity [8]. Therefore, to eliminate these aforementioned issues, we are aimed to develop a novel piezoelectric MEMS harvester that can feature high power density. Our proposed harvester has a T-shaped structure with an integration of two proof masses at tip locations. This new structure allows our proposed harvester to vibrate in both torsion and bending modes, while the conventional harvesters just oscillate in the bending mode.

3. Power management system

The overall block diagram of the proposed power management system with the capability of working under extremely low input voltage is displayed in Figure 1. Thanks to low threshold-voltage MOSFET, the rectifier can rectify the harvested AC signal to DC with the least voltage difference. And this converted DC voltage is accumulated in the start-up capacitor (C_startup). Once its level reaches 1V, the voltage detector, which is a supervisory circuit, is activated so that the microcontroller is turned on. Thus, the microcontroller can generate constant PWM control signal for switching the boost-converter transistor. Consequently, the harvested voltage, whose amplitude can be boosted, is stored in load capacitor (i.e., C_boost). In order to provide a passive feedback control, the amount of the delivered voltage to load can be limited to a certain level by using a JFET transistor. By using numerical simulation, the performance of the system will be demonstrated in the following section.

![Figure 1. The overall block diagram of the proposed power management system.](image)

4. Experimental results and discussion

In first step, the proposed T-shaped piezoelectric MEMS harvester, by using a commercial microfabrication process, i.e., PiezoMUMPs, was fabricated. In order to demonstrated and compare the proposed harvester superiority in terms of the energy conversion efficiency, we also fabricated the conventional piezoelectric harvester, which is a simple clamped-free cantilever. The SEM images of the fabricated piezoelectric harvesters with their sizes are illustrated in Figure 2.
Figure 2. Fabricated piezoelectric MEMS energy harvesters (A) conventional unimorph cantilever, (B) top view and (C) side view of the proposed T-shaped harvester.

The prototyped harvesters were excited by a shaker (4809 manufactured by Brüel & Kjaer), while the shaker excitation frequency is equal to resonant frequencies of the harvesters. Then, the Normalized Power Density (NDP) with various load resistances were measured for display in Figure 3. It is worth noting that the measured NDP for the T-shaped harvester is greater than the conventional piezoelectric one by a factor of 1.95, while the optimum load resistance for both harvesters is around 0.1MΩ.

Figure 3. Measured normalized power density of the proposed T-shaped harvester (red) and conventional unimorph piezoelectric cantilever (blue).

The performance of the proposed power management system has been verified by numerical simulation. In this way, the schematic in Figure 4(A) was implemented in LTspice and it was assumed the piezoelectric generator can generate maximally 1.5V. It should be noted that all the utilized components are available in the market as commercial discrete devices. Therefore, their models were defined according to the provided information by the foundries. The performance of each individual part of the proposed power management system is demonstrated in Figure 4(B). It is obvious that generated 1.5V by the piezoelectric generator can be boosted up to 5V shortly. To limit the boosted voltage to a constant level, the JFET transistor with 4V threshold-voltage is utilized. As shown in Figure 4(B), the proposed power management system, without requiring external bias voltage, can enlarge the harvested voltage sufficiently as the power supply for low-voltage consumer electronics products.
Figure 4. (A) Schematic of the implemented power management system in LTspice, (B) The performance evaluation of the proposed power management system.

5. Conclusion
In this study, we presented a T-shaped piezoelectric MEMS energy harvester. The prototype measurement results show that it can achieve higher normalized power efficiency by a factor of 1.95 in comparison with the conventional piezoelectric harvester. Since the harvested voltage magnitude by this type of harvesters is only a few millivolts, we proposed a highly efficient power management system for converting AC signal to DC, and also enlarging the harvested voltage magnitude on the load side. The numerical simulation results clearly showed that the proposed power management system could boost the magnitude up to 5V when the harvested voltage was only 1.5V. To maintain a stable output voltage level, a JFET transistor as a voltage limiter was utilized. Thus, the delivered voltage at the load side cannot exceed 4V if a higher harvested voltage by the harvester is expected.

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