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Connection Configurations to Increase Operational Range and Output Power of Piezoelectric MEMS Vibration Energy Harvesters

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Abstract. Among the various methods of extracting energy harvested by a piezoelectric vibration energy harvester, full-bridge rectifiers (FBR) are widely employed due to its simplicity and stability. However, its efficiency and operational range are limited due to a threshold voltage that the open-circuit voltage generated from the piezoelectric transducer (PT) must attain prior to any energy extraction. This voltage linearly depends on the output voltage of the FBR and the forward voltage drop of diodes and the nature of the interface can significantly limit the amount of extracted energy under low excitation levels. In this paper, a passive scheme is proposed to split the electrode of a micromachined PT into multiple (n) equal regions, which are electrically connected in series. The power output from such a series connected MEMS PT allows for the generated voltage to readily overcome the threshold set by the FBR. Theoretical calculations have been performed in this paper to assess the performance for different series stages (n values) and the theory has been experimentally validated. The results show that a PT with more series stages (high n values) improves the efficiency of energy extraction relative to the case with fewer series-connected stages under weak excitation levels.

1. Introduction

Along with increasing research interests on piezoelectric vibration energy harvesting (PVEH), efficient interface rectification circuits have drawn much attention and interests with respect to extracting as much energy as possible from miniaturized piezoelectric transducers (PT) [1,2]. A typical PT can generate a raw output power of around 10 - 500 $\mu\text{W cm}^{-2}$, and hence interface circuits should be designed to be power-efficient and stable [3]. Full-bridge rectifiers (FBR) are widely employed in commercial energy harvesting systems due to its stability and simplicity; however, they set high threshold voltages for the generated energy in the PTs to be extracted by the rectifiers [4]. This limitation prevents the system from operating if the environmental excitation is not high enough to attain the required operational threshold voltage, particularly considering miniaturized formats. Hence, the vibrational energy under such conditions is not transferred to the energy storage device [5,6]. Furthermore, for excitation resulting in harvester output slightly greater than the threshold voltage, a very significant amount of energy is wasted as a result.

A full-bridge rectifier (FBR) usually consists of four diodes connecting, whose input is connected to the piezoelectric harvester and output is connected to a capacitor C_S in most implementations. A PT vibrating at or close to its resonance frequency can be modeled as a current source I_P in parallel with a capacitor C_P and a resistor R_P [7]. In order to transfer energy



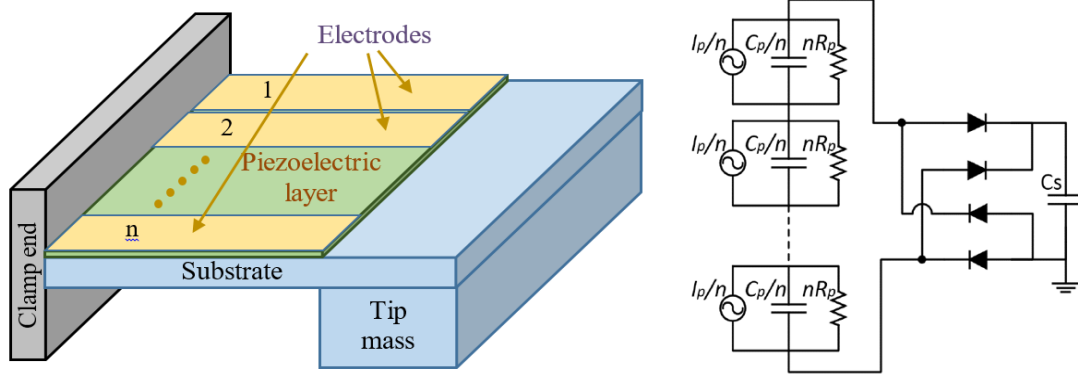


Figure 1: Segmentation of a monolithic cantilevered PT into multiple regions (left) and series connection with a FBR (right).

through the FBR, the voltage across the PT (V_{piezo}) needs to attain $V_S + 2V_D$ (or $-(V_S + 2V_D)$) to overcome the threshold voltage set by the FBR, where V_S is voltage across C_S and V_D is the voltage drop of the diodes. In order to charge the internal capacitor C_P from $V_S + 2V_D$ to $-(V_S + 2V_D)$ (or vice-versa), some charge is wasted, which can be expressed as:

$$Q_{wasted} = 2C_P(V_S + 2V_D) \quad (1)$$

Assuming $V_{pp(open)}$ as the peak-to-peak open-circuit voltage generated from the PT, the condition $V_{pp(open)} > 2(V_S + 2V_D)$ should be satisfied to transfer energy from the PT to C_S . Otherwise, all of the generated energy by the PT is wasted for discharging and charging C_P . In this paper, a passive approach is proposed to segment the top and bottom electrode layers of a monolithic piezoelectric transducer (PT) into multiple regions and electrically connect these regions in series before the PT is connected to a FBR. Figure 1 shows the electrode segmentation of the proposed scheme. In the following sections, the power performance for different number of series stages is theoretically studied and experimentally validated.

2. Theoretical derivation

In this section, theoretical models are developed to establish the effect of series connected PTs on the output power of a full-bridge rectifier. Assuming that the input excitation is sinusoidal, the current source generated by the monolithic model (before splitting the electrode) can be written as $I_P = I_0 \sin \omega t$, where $\omega = 2\pi f_P$. The total charge generated by the PT in a half cycle ($\frac{T}{2}$) should first be calculated, which can be written as:

$$Q_{total} = \int_0^{\frac{T}{2}} I_0 \sin(\omega t) dt = \frac{2I_0}{\omega} \quad (2)$$

After the electrode is split into n equal regions, the piezoelectric layer area for each region is $1/n$ times of the monolithic model; hence, values of the corresponding current source, inherent capacitor and resistor for each region are $\frac{1}{n}$, $\frac{1}{n}$ and n times of the monolithic model respectively, where the number n is the number of regions that the electrode is split into.

Before the FBR becomes conductive, a certain amount of generated charge is used to charge the internal capacitor C_P from $V_S + 2V_D$ to $-(V_S + 2V_D)$, or vice-versa. For the monolithic model, this amount of charge is specified by equation (1). In the split electrode case, the wasted charge from each individual region can be expressed as $Q_{wasted1} = C_{p1} \frac{2}{n} (V_S + 2V_D) = \frac{2C_P}{n^2} (V_S + 2V_D)$. After V_{piezo} attain $V_S + 2V_D$ (or $-(V_S + 2V_D)$), the FBR becomes conductive transferring the charge from C_P to C_S . As only one region is considered, the current sources of all other $n - 1$ regions can be turned off using superposition theory. Therefore, the charge transferred into C_S from one single source can be calculated and the total charge flowing into C_S from all of the n sources is n times of the charge from one source:

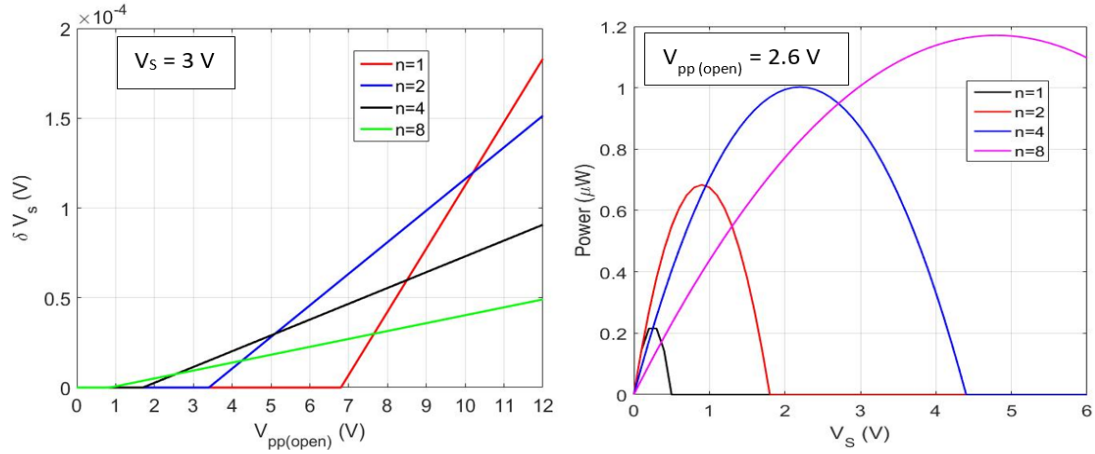


Figure 2: Theoretical output power for different numbers of series stages ($n = 1, 2, 4$ and 8)

$$Q_{S(n)} = \sum_n Q_{S1} = \frac{2C_P}{n} \left(\frac{I_0 R_P}{\sqrt{1 + \omega^2 R_P^2 C_P^2}} - \frac{V_S + 2V_D}{n} \right) \quad (3)$$

The voltage increase of C_S in half an oscillation period for series-connected n sources is:

$$\Delta V_{S+(n)} = \frac{2C_P}{C_S} \left(\frac{V_{pp(open)}}{2n} - \frac{(V_S + 2V_D)}{n^2} \right) \quad (4)$$

where the subscript “+” represents series and “ n ” is the number of series stages. The open-circuit voltage is calculated as $V_{pp(open)} = \frac{2I_0 R_P}{\sqrt{1 + \omega^2 R_P^2 C_P^2}}$. As the energy extracted and stored in C_S is calculated as $\Delta E_{T/2} = \frac{1}{2} C_S ((V_S + \Delta V_S)^2 - V_S^2)$. The corresponding reactive output power by a FBR for a n -region series PT can be expressed as:

$$P = \frac{\Delta E_{T/2}}{T/2} = 2f_P \Delta E_{T/2} = f_P C_S ((V_S + \Delta V_S)^2 - V_S^2) \quad (5)$$

where f_P is the excitation frequency and ΔV_S is given in equation (4). While n is set to 1, 2, 4 and 8, the output power is plotted in figure 2 under different excitation levels and different V_S values.

3. Experiment

In this section, experiments are performed to validate the theoretical results and demonstrate the performance improvement of the proposed approach. Figure 3 shows the optical micrograph of the test MEMS device and the measured output power for different series stages. The device consists of 8 cantilevers, which are strongly coupled with a monolithic proof mass at their free ends. Hence, the eight cantilevers vibrate in the same amplitude, phase and frequency and their electrodes can be perfectly connected in series or in parallel. The cantilever is excited on a shaker at its natural frequency of 211 Hz under an excitation level of 2.0 g. The open-circuit peak-to-peak voltage generated by the cantilever while all the 8 regions are connected in parallel is 2.6 V. In the experiment, the storage capacitor connected at the output of full-bridge rectifier is a super capacitor of value $C_S = 1$ mF. A full-bridge circuit is built using four diodes with a measured forward voltage drop of around 0.5 V each.

For each cantilever, there are 2 electrode pads shown in the figure, summing up to 16 electrode pads for 8 cantilevers. The experiments have been performed by connecting the electrodes in

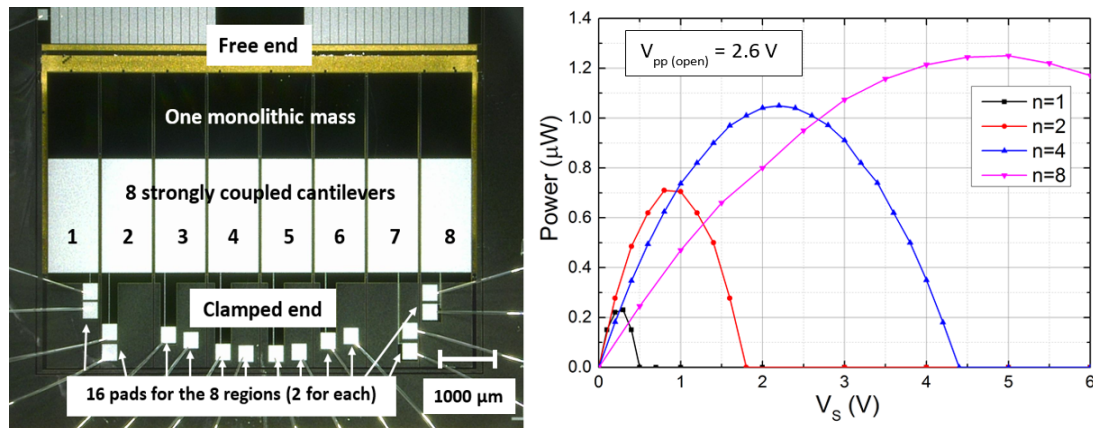


Figure 3: Optical micrograph of the test MEMS device and measured electrical output power

parallel and in series for $n = 1, 2, 4$ and 8 series stages. The results show that splitting the electrode into 8 regions in series can increase the output power by up to $5.4\times$ compared to the monolithic model when all the 8 regions are connected in parallel. The slight deviation on power for theoretical and measured results is due to the non-ideal diodes used in the experiment.

4. Conclusion

This paper addresses the issue of the high threshold voltage that exists in a full-bridge rectifier (FBR), which should be overcome prior to any energy extraction from the piezoelectric transducer (PT). In order to flip the voltage generated by the PT between the positive and negative threshold voltages, a significant amount of energy is wasted. A passive scheme of segmenting the electrode layers of a PT into n equal regions connected in series is proposed to lower threshold voltages and decrease the energy wasted to overcome the thresholds, hence, increasing the power efficiency. Compared to active interface circuits, this scheme significantly decreases system volume without an inductor and increases stability without consuming any quiescent power by simply employing a single FBR. Furthermore, the performance of a 8 -region PT is improved by $5.4\times$ compared to a monolithic PT and this approach is particularly preferred in MEMS piezoelectric harvesters due to their relatively low open-circuit voltage compared to macroscopic harvesters. A MEMS cantilever with segmented electrodes has been integrated with a FBR circuit and experimentally tested to validate the theory.

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