TRIBOELECTRIC ENERGY HARVESTER USING FREQUENCY UP-CONVERSION TO GENERATE FROM EXTREMELY LOW FREQUENCY STRAIN INPUTS

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ABSTRACT

We developed a flexible triboelectric energy harvester that can generate from extremely low frequency strain inputs. The harvester consists of flexible substrate, cantilever, sagged film which is partially bonded beneath the cantilever and permanent magnets. When the cantilever is deformed, contact and separation motion between the cantilever and sagged film occurs and it makes electricity by triboelectric effect. By adopting frequency up-conversion mechanism, the cantilever vibrates at its natural frequency and it makes higher output power by fast contact and separation. The peak-to-peak and RMS output power were 267.38 μW and 0.20 μW for a resistive load of 2 MΩ at 0.5 Hz strain input, respectively.

INTRODUCTION

Diverse mobile devices make great strides but still need improvement of the capacity and life cycles of its batteries. Harvesting mechanical energy from ambient energy sources has been considered as an alternative or supplementary technique to supply power for these devices because of its advantages, such as abundance of energy source and semi-permanent feature [1, 2].

Conventional piezoelectric and electromagnetic energy conversion mechanisms have been popularly used to harvest mechanical inputs such as strain and vibration for their simplicity and high electromechanical coupling effect [3-7]. Recently developed Triboelectric Nanogenerators (TENGs) based on the coupling of triboelectrification and electrostatic induction also have attracted much attention due to their high voltage output, low cost and various selection of the contact material pair [8]. In order to maximize output power of these harvesters, large and high speed mechanical inputs are required. For example, vibration energy harvester usually generates maximum output power when the input frequency coincides with its resonant frequency. However, many mechanical energy sources, such as human motion, water wave and vibrating artificial structures [9-11], usually have motion frequency under 10 Hz which is much lower than the resonant frequency of typical vibration energy harvesters [3-6, 12, 13].

To enhance the energy generation from low frequency inputs in piezoelectric and electromagnetic energy harvesters, several frequency up-conversion techniques have been proposed [14, 15]. In our previous work [16], we also demonstrated mechanical frequency up-conversion technique which can convert low frequency strain input into resonance of the harvester at higher frequency. TENGs are operated in two different modes, lateral sliding [17] and vertical tapping [18]. Interdigital electrodes on lateral sliding surface may serve as frequency up-converting structures as demonstrated earlier [19 ,20]. However, there has never been reported any frequency up-converting techniques for TENGs based on tapping motion, and this is possibly due to the difficulties in actually increasing the number of tapping, the out-of-plane motion, in a given time.

In this paper, we developed a flexible triboelectric energy harvester with frequency up-converting structural design using a cantilever and a sagged film. Thus it allows enhanced generation of electricity from out-of-plane motion triboelectric generator with low frequency strain input. To the best of our knowledge, this is the first work that developed out-of-plane motion triboelectric energy harvester using frequency up-conversion technique.

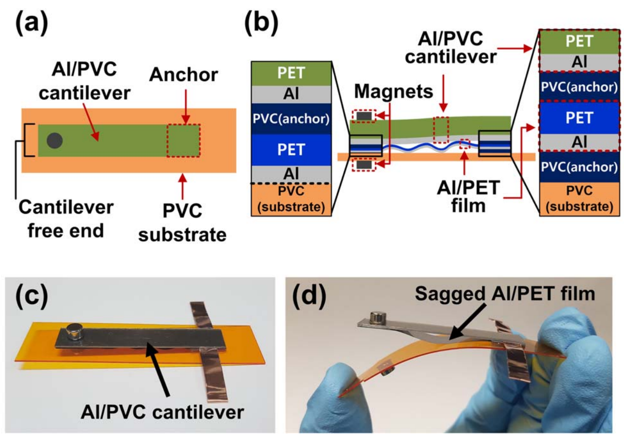

Figure 1: Schematic diagrams and photographs of the proposed triboelectric energy harvester with frequency up-converting design. (a) Top view. (b) Side view. (c) Original flat shape without external strain. The cantilever is bound by two NdFeB magnets. (d) The cantilever and film released from the substrate. The film is sagged down below the cantilever.

DESIGN AND WORKING PRINCIPLE

Figure 1(a) and (b) shows the schematic diagrams of the proposed triboelectric energy harvester with frequency up-converting structures. The harvester consists of flexible polyvinyl chloride (PVC) substrate, Al-coated PVC cantilever and Al-coated polyethylene terephthalate (PET) film that is placed between the PVC substrate and the PVC cantilever. Both ends of the PET film that is cut to be a little longer than cantilever is bonded to the anchor and free-end of the cantilever.

The photographs of the proposed energy harvester are shown in figure 1(b) and (c). We chose Al and PET contact pair for strong triboelectrification based on the triboelectric series and also for simple fabrication processes. The 150 nm-thick Al was evaporated on PET (0.025 mm in thickness) and PVC (0.8 mm in thickness) to form electrodes, and the Al layer on PVC also served as a triboelectric charging material. Since the length of the flexible Al/PET film was slightly longer than the Al/PVC cantilever (1 mm × 50 mm × 0.8 mm), the film was sagged down below the cantilever about 4.5 mm at the center, creating smooth sag curve. One end of the cantilever was anchored to the flexible PVC substrate (2 mm × 70 mm × 0.5 mm). The free end of the cantilever was bound to the substrate by two NdFeB magnets (ϕ 5 mm × 2 mm); one on the top side of the cantilever and the other on the bottom side of the substrate.

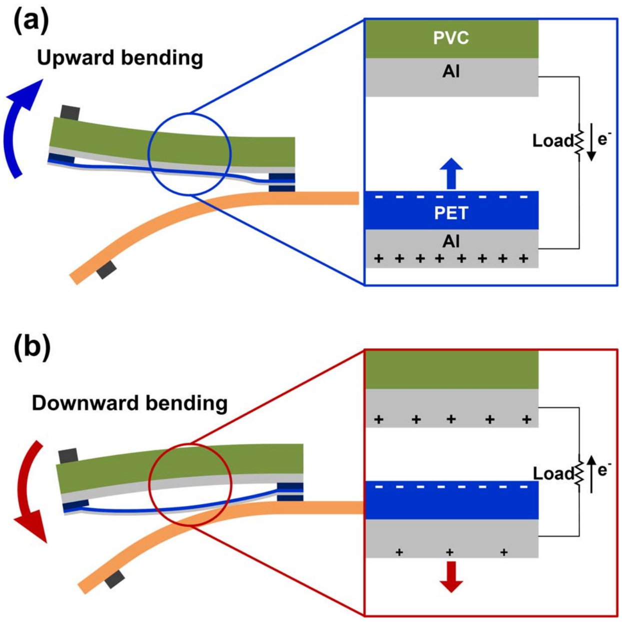

Figure 2: The working principle of the harvester. When the elastic restoring force of the bent cantilever exceed the attraction force of the two magnets, the bent cantilever is detached from the substrate and it oscillates at its resonant frequency until it releases all of the stored potential energy. (a) During the upward bending motion of the released cantilever, the sagged film is flattened. (b) During the downward bending motion, the film sags and moves away from the cantilever.

The working principle of the harvester is shown in Figure 2. Since the cantilever is bound to substrate through the anchor at one end and two magnets at the other end, they bend together for a strain input. As the amount of bending increases, the potential energy stored in the cantilever also increases. When the elastic restoring force of the bent cantilever exceed the attraction force of the two magnets, the bent cantilever is detached from the substrate and it oscillates at its resonant frequency until it releases all of the stored potential energy. During the upward bending motion of the released cantilever, the sagged film is flattened as shown in figure 2(a). Thus, the film approaches and touches the cantilever surface. These two surfaces in contact, the PET side of the film and Al surface of the cantilever, are negatively and positively charged respectively by triboelectrification. Whereas, during the downward bending motion (figure 2(b)), the film sags and moves away from the cantilever. The relative motion of the charged cantilever and film induces electrical charge flow through the external load.

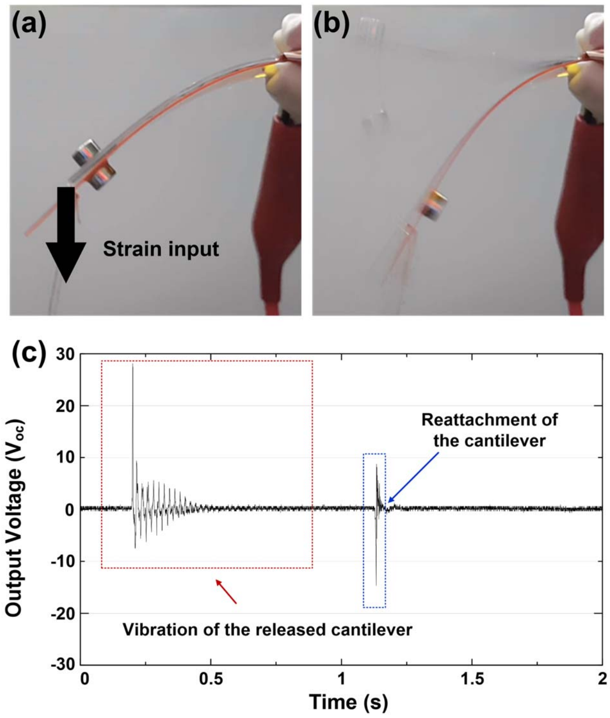

Figure 3: (a) Photograph of the cantilever right before the separation from the substrate. The radius of curvature of the substrate is 36 mm. (b) Photograph of the vibrating cantilever. (c) Output voltage response of the fabricated harvester during a single cycle of the 0.5 Hz input.

RESULTS AND DISSCUSSION

The photograph of the cantilever right before the separation from the substrate is shown in figure 3(a). The cantilever is released and vibrates as shown in figure 3(b), when the radius of curvature of the substrate reaches 36 mm. Figure 3(c) shows the open circuit voltage of the harvester generated during a single cycle of the 0.5 Hz input. The generated peak-to-peak voltage and root-mean-square voltage were 42.81 V and 1.138 V, respectively. The vibrating frequency of the cantilever was 49 Hz. When the deformed substrate returns, it reattaches to the cantilever, which causes rapid distance change between the sagged film and the cantilever, resulting in additional voltage peaks as shown in the figure. It also shows that the first peak of the voltage output was the highest and the following peaks decreases as the cantilever vibration decays. However, the decay is somewhat different from typical viscous damping, and the first voltage peak is much higher than the following peaks. This is possibly from the severe collision between the film and the cantilever at their first contact and sizable energy loss from that collision.

It is noted that this high frequency oscillation of voltage output in triboelectric generation has never been reported before. In the majority of previous works, single voltage peak is generated by single mechanical input, unlike the current result. It also implies that the RMS power can be much enhanced through the proposed approach, compared to existing triboelectric harvesters.

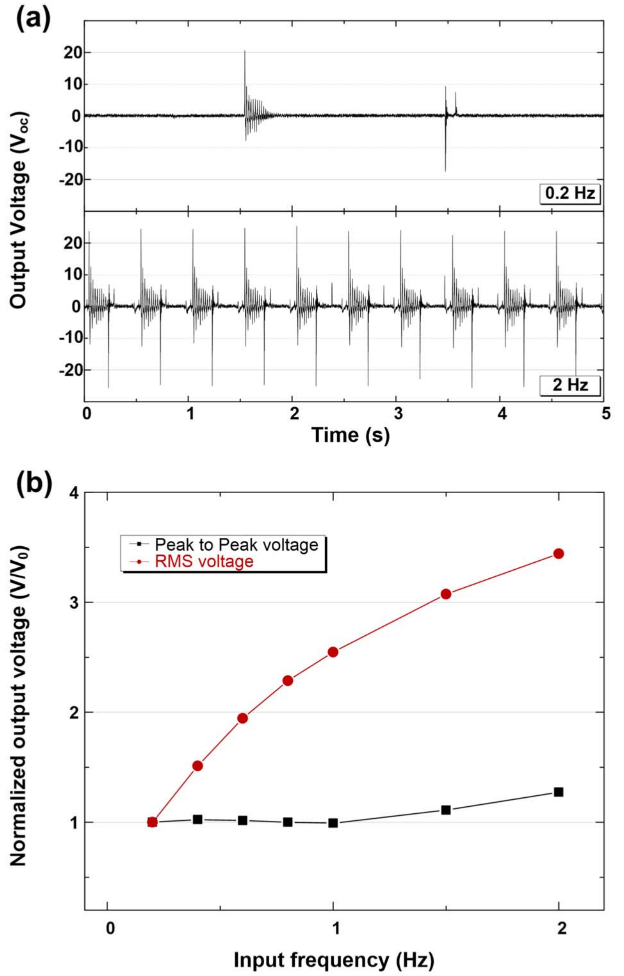

Figure 4: (a) Output Voltage response of the fabricated harvester with 0.2 and 2 Hz input vibration. (b) The voltage output from the harvester for different frequency input. The RMS voltage decreases as the input vibration frequency decreases, but the peak-to-peak voltage change was relatively small (~27 % at 0.2 Hz).

The comparison of the output voltages for the inputs of 0.2 and 2 Hz at constant strain amplitude is shown in figure 4(a). Even though the input frequencies change, the waveform of the oscillating output voltage remains almost the same because resonant frequency of the cantilever is not affected by the frequencies of input bending motion. On the other hand, the negative peak values caused by the reattachment of cantilever increases as the input frequency increases, because the reattachment speed is higher at higher input frequencies. Figure 4(b) shows the peak-to-peak and RMS voltages normalized to the voltages of the 0.2 Hz inputs for different frequency of inputs. As the input bending motion frequency decreases from 2 Hz to 0.2 Hz, the RMS voltage decreases from 2.44 V to 0.71 V (~ 344 %) due to the decrease of the number of output cycles in the same time period. In contrast, peak-to-peak voltage decreases from 50.93 V to 40 V (~27 % decrease) and other peaks, except for the first peak and the reattachment peak, remains almost the same.

Output voltage and power of the harvester under various resistive load for 0.5 Hz strain input was also tested to determine optimal load resistance as shown in Figure 5.

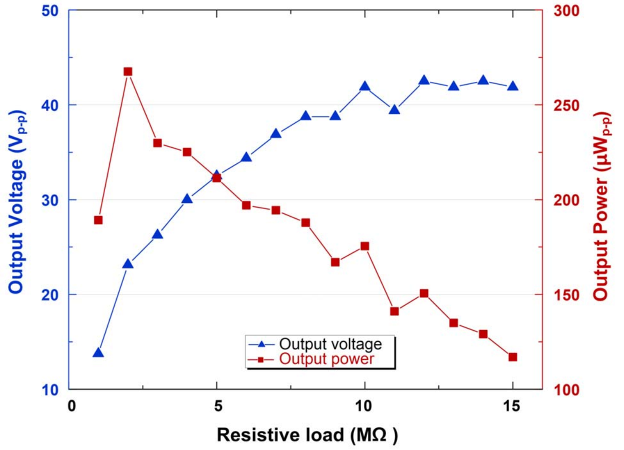

Figure 5: Output voltage and power of the harvester under various resistive load for 0.5 Hz vibration input. The peak-to-peak and RMS power were 267.38 µW and 0.20µW for a resistive load of 2 MΩ.

The measured peak-to-peak and RMS power were 267.38 µW and 0.20 µW for a resistive load of 2 MΩ.

CONCLUSION

Flexible triboelectric energy harvester with the structures that can convert low frequency strain input to higher frequency mechanical vibration has been designed, fabricated and tested. It consists of flexible substrate, Al-coated PVC cantilever and Al-coated PET film. Using this harvester, the strain inputs with the frequency less than 2 Hz was converted to 49 Hz, allowing multiple output voltages generation from single bending motion input. The open circuit voltage for 0.5 Hz strain input was 42.81 V_{p-p} and 1.138 V_{rms}. After impedance matching, the measured power output for 0.5 Hz vibration input was 267.38 μW_{p-p} and 0.20 μW_{rms} for a resistive load of 2 MΩ.

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