Textile-based freestanding triboelectric-layer nanogenerator with alternate positive and negative grating structure

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Abstract. This paper reports a novel design of textile-based triboelectric nanogenerator (TENG) with alternate grated strips of positive and negative triboelectric material operating in freestanding triboelectric-layer mode (pnG-TENG). Whereas most grating-structured TENGs operating in a freestanding triboelectric-layer mode comprise gratings of one type of triboelectric material separated by air gaps, this design presents a replacement of the air gaps by another triboelectric material with the opposite polarity to the existing triboelectric material. The pnG-TENG with 10 gratings of PTFE and nylon fabric delivers an open-circuit voltage of 250 V, a short-circuit current of 5.94 µA and a maximum peak power of 600 µW at a load resistance of 50 MΩ and a mechanical oscillation of 2 Hz. This corresponds to a maximum power density of 186 mW/m², which is 1.73 and 2.20 times greater than the power generated by the TENG with single triboelectric material and the TENG with no grating, respectively.

1. Introduction

In spite of a substantial growth in the wearable and portable electronics market, most of these types of devices still rely on batteries, which require persistent recharging and replacement. An effective way to solve this problem is to introduce a wearable self-charging power system using an energy harvester to scavenge energy from the surrounding environment. Triboelectric nanogenerators (TENGs) are one of the most promising candidates for powering these systems. They can efficiently convert kinetic energy into electricity based on contact electrification and the electrostatic induction effect [1–3]. Various examples of TENGs have demonstrated flexibility, lightness, biocompatibility and good performance that are essential for wearable devices [4,5]. According to these properties, textile-based TENGs are determined to be highly suitable for this propose, since textiles are often used on the human body, which is one of the most powerful kinetic energy sources for powering the wearable electronics [6–10].

This paper proposes a novel structure of textile-based TENG with alternate grated strips of positive and negative triboelectric material operating in freestanding triboelectric-layer mode; defined as a pnG-TENG. Whilst most grating-structured TENGs (G-TENGs) operating in a freestanding triboelectric-layer mode comprise gratings of one type of triboelectric material separated by air gaps [2,3], this design presents a replacement of the air gaps by a triboelectric material with the opposite polarity to the existing triboelectric material. In this work, the electrical outputs of pnG-TENGs with the different grating number (N) were measured and compared with the G-TENGs with single positive triboelectric material (pG-TENGs), the G-TENGs with single negative triboelectric material (nG-TENGs) and the TENG with no grating (N=1). The objective of this work is to demonstrate that the pnG-TENGs exhibit an improvement in performance compared to the single material G-TENGs.
2. Device and working principle

A schematic illustration of the proposed pnG-TENG is shown in figure 1. It is composed of an upper substrate with $N$ alternate strips of Nylon and PTFE fabric ($N=10$ for figure 1(a)) and a lower substrate with two interdigitated Aluminium (Al) electrodes (IDEs) with matching periodicity shown in figure 1(b). The upper substrate has a size of 46x70 mm. It was made of stacks of acrylic, a double-sided tape, a 1-mm-thick fabric, a double-sided tape and the triboelectric materials (Nylon and PTFE). The acrylic layer is just for testing to make it a consistent and repeatable test, and would not be required in an actual e-textile device, whereas the 1-mm-thick fabric helps improve the flexibility and thus increases the effective contact area of the triboelectric materials. The rectangular lower substrate with a size of 100x70 mm was made of an acrylic fully covered by strips of Al tape with a width of 50/N mm separated by a 200-micron-wide cut after adhesion to the substrate to prevent a short circuit between the IDEs.

The schematic illustration of the upper substrate of G-TENG for $N=10$ with one type of triboelectric material is shown in figure 2. Firstly, the acrylic was laser-cut into grating structures with $N$ segments (including the air gaps). Then, the 1-mm-thick fabric, the double-sided tapes and the triboelectric material were stuck to the acrylic and cut into the same configuration as the acrylic by hand. Thus, alternate strips of air gaps and triboelectric material occur. The triboelectric material used for the pG-TENG and nG-TENG are nylon and PTFE fabric, respectively. The structure of the lower substrate remains the same as the pnG-TENG. For the G-TENGs with different $N$, the total effective area of the devices remains the same, thus a larger $N$ will lead to a smaller width of each grating unit.

The operating mechanism of pnG-TENG with nylon and PTFE fabric for $N=2$ is illustrated in figure 3. It is operated based on contact electrification and the electrostatic induction effect. When the nylon fabric and PTFE fabric are brought into contact with Al electrodes, they will become positively and negatively charged, respectively, whereas the same amount of charge with the opposite polarity is generated on the Al electrodes. Initially (figure 3(i)), the upper substrate fully overlaps with the first two fingers (from left) of the electrodes. In this state, no charge transfer occurs due to the electrostatic equilibrium between the electrodes. When the upper substrate moves further to the right-hand side and partly overlaps with the next Al finger (figure 3(ii)), the electrons flow from the first and the third Al finger to the second finger, because the electric potential of the second Al finger increases due to the presence of the positive surface charge of the above nylon fabric and the electric potential of the first and the third Al finger decreases due to the absence of nylon and the presence of PTFE fabric, respectively. As a result, a current flows from Al electrode 2 to 1 until another electrostatic equilibrium is reached at the next fully overlapping position (figure 3(iii)). When the upper substrate continues to move, the electric potential in the electrodes increase and decrease alternately resulting in an alternating current through the load. As can be seen in figure 3(ii, iv, vi, viii), four current cycles are generated in one moving cycle. The number of current cycles per moving cycle is twice the grating number.

![Figure 1. Schematic illustration of pnG-TENG ($N=10$) comprising (a) an upper substrate with alternate strips of Nylon and PTFE fabric and (b) a lower substrate with two interdigitated Al electrodes.](image1)

![Figure 2. Schematic illustration of upper substrate of G-TENG ($N=10$) with single triboelectric material.](image2)
3. Simulation and Experimental results

3.1. Simulation results
To theoretically investigate the effect of the different grating numbers on the G-TENGs, the open-circuit voltage ($V_{OC}$) of the different types of G-TENGs for $N=1, 2, 4, 6, 8, 10$ were simulated using COMSOL finite element modelling software. Based on work by Xie et al. [3], the surface charge density of the negative material (PTFE) and the positive material (Nylon) was estimated to be $-26 \mu$C/m$^2$ and $10 \mu$C/m$^2$.

Figure 3. Schematic illustration of operating mechanism of pnG-TENG with gratings of nylon and PTFE fabric for $N=2$.

Figure 4. Electric potential of pnG-TENG in 2D for $N=2$ simulated using COMSOL Multiphysics.

Figure 5. Simulation result of $V_{OC}$ for TENGs with the different grating numbers.

The simulated electric potential of the pnG-TENG for $N=2$ in 2D is shown in figure 4. In this cross-section view, the G-TENG consists of 4 Al fingers. The first and third finger, and the second and fourth finger (from left) are connected together forming the Al electrode 1 and 2 respectively. A PTFE and a nylon are placed over the first and the second Al finger, respectively. Due to the predefined surface charge densities [3], an electric potential of -24 kV and -20 kV are induced at the first and the second electrode, respectively, resulting in a $V_{OC}$ of 4 kV. The reason why the potential of the second electrode is negative, although the surface charge density of nylon is positive is that the surface charge density of the PTFE is much greater than that of the nylon and this induces a strong negative potential, which outweighs the positive potential from the nylon.
The \( V_{OC} \) of the different types of TENGs for the different grating numbers is represented in figure 5. With increasing grating number, the \( V_{OC} \) decreases for all types of the G-TENGs. The result can be explained by equation (1) below [3]:

\[
V_{oc} = \frac{\Delta \sigma_{sc} \cdot S}{C}
\]

where \( \Delta \sigma_{sc} \) is the transferred charge density, \( S \) is the total area of the Al electrode 1 or 2 and \( C \) is the capacitance between the electrodes. Because \( \Delta \sigma_{sc} \) and \( S \) are constant for \((N=2\) to \(10))\) and \( C \) increases when the electrodes are divided into small segments, \( V_{OC} \) decreases with increasing grating number. The \( V_{OC} \) of the TENG with no grating \((N=1)\) is much higher than the others, since the area of the triboelectric material for \((N=1)\) is twice as large as the area of the triboelectric material for \((N=2\) to \(10))\), which is partly replaced by air gaps. The \( V_{OC} \) of the pnG-TENGs are enhanced for all grating numbers compared to the pG-TENGs and the nG-TENGs since \( \Delta \sigma_{sc} \) rises due to the assumption that the \( \Delta \sigma_{sc} \) is proportional to the potential difference at the surface of nylon and PTFE, which relates to the different between the surface charge density.

3.2. Experimental results

All experiments were performed using a belt drive linear actuator at a mechanical oscillation frequency of 2 Hz and a contact force of 5 N, which cyclically slides the upper substrate over the bottom substrate. The \( V_{OC} \) measurements were carried out using an oscilloscope (Agilent DSO3062A) with a load resistance of 1 GΩ and the short-circuit current \((I_{SC})\) was measured using a DC power analyzer (Agilent N6705B). In figure 6, the experimental results for \( V_{OC} \) shows the same decreased tendency and is in good agreement with the simulation result. In contrast to \( V_{OC} \), the \( I_{SC} \) of the pnG-TENGs rises significantly with increasing grating number and is greater than that of the TENG with no grating \((N=1)\), the pG-TENGs and the nG-TENGs for almost all the grating numbers as shown in figure 7. The increase in \( I_{SC} \) follows equation (2) below:

\[
I_{sc} = \frac{\Delta Q_{SC}}{t}
\]

Since the time taken \( t \) for a certain transferred charge \( \Delta Q_{SC} \) is significantly reduced due to the reduction in the width of the Al fingers, when the sliding velocity is fixed, the \( I_{SC} \) rises. In figure 8, the load dependence measurements were performed to find the maximum power point of the G-TENGs by measuring \( V_{OC} \) and \( I_{SC} \) at different external load resistances varying from 0.1 MΩ to 10 GΩ. The powers were calculated from the product of \( V_{OC} \) and \( I_{SC} \). For the pnG-TENG (Nylon/PTFE, \( N=10 \)), the maximum peak power reaches 600 µW at a resistance of 50 MΩ, corresponding to a power density of 186 mW/m². For the nG-TENG (PTFE, \( N=10 \)), the maximum power is 346 µW at the same load. For the TENG with no grating (PTFE, \( N=1 \)), the maximum power of 273 µW is generated at a load resistance of 1 GΩ. The result shows that the peak power of the pnG-TENG increases by a factor of 1.73 and 2.20, compared to the nG-TENG and the TENG with no grating, respectively.

![Figure 6](image_url) Experimental results of \( V_{OC} \) for TENGs with different grating numbers.

![Figure 7](image_url) Experimental results of \( I_{SC} \) for TENGs with the different grating numbers.
To provide a more complete picture of the energy harvesting potential, the outputs of the TENGs were used to charge up a 10-µF capacitor. The capacitor voltages at a charging time of 600 s for the different TENGs and the different grating numbers are shown in figure 9. It shows an increased tendency similar to the \( I_{SC} \). The average charging power calculated from the capacitor voltage for the pnG-TENG with \( N=10 \) is 41.29 µW, corresponding to a power density of 12.82 mW/m\(^2\).

4. Conclusions
This paper has introduced a novel textile-based triboelectric generator design, using two alternate grated strips of positive and negative triboelectric material, defined as a pnG-TENG. The pnG-TENGs show significant improvement in performance compared to single positive material (pG-TENGs), single negative material (nG-TENGs) and TENGs with no grating. With this novel structure, the \( I_{SC} \) increases with increasing grating number, whereas \( V_{OC} \) shows a reducing trend due to the increasing capacitance of the electrodes. Both, the \( I_{SC} \) and the \( V_{OC} \) of the pnG-TENGs are considerably greater than those of the pG-TENGs and the nG-TENGs for almost all the grating numbers. The maximum power generated by the pnG-TENG with 10 grating is 1.73 and 2.20 times greater than the power generated by the TENG with single triboelectric material and the TENG with no grating, respectively.

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