Multilayered Cylindrical Triboelectric Nanogenerator to Harvest Kinetic Energy of Tree Branches for Monitoring Environment Condition and Forest Fire

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Forest fires present a great threat as they can rapidly grow and become large, resulting in tragic loss of life and property when occurring near occupied land. Here a self-powered fire alarm system based on a novel multilayered cylindrical triboelectric nanogenerator (MC-TENG) that can produce electrical power for the detection sensors by harvesting the kinetic energy of moving tree branches in a forest is presented. The major parameters for harvesting the kinetic energy using the proposed MC-TENG are investigated, including the number of triboelectric layers, the frequency, the amplitude of external excitation, and the orientation between motion direction and device configuration. The fabricated MC-TENG results in a peak power of 2.9 mW and a maximum average power of 1.2 mW at a low frequency of 1.25 Hz. The integrated self-powered forest fire alarm system, consisting of fire sensors, a carbon-based micro-supercapacitor, and the MC-TENG, is demonstrated to be able to report fire risk or hazard efficiently, accurately, and robustly. This study provides a new solution to reduce the forest fire risk through a portable and sustainable alarm system by effectively harvesting kinetic energies in natural environment with TENG technology.

1. Introduction

Forest plays a significant role in maintaining a comfortable living condition for humans and animals, regulating water cycle, and mitigating risks of climate change.[1–4] Every year, however, large forest fires occur around the world because of climatic variations, human activities, and other factors, resulting in tremendous loss of natural resources and threatening human-living environment.[5] A robust, accurate, and fast-response forest fire alarm system can effectively detect the fire problems at the very early stage to minimize the damage and casualties caused by the fast-spreading and the enormous destructive characteristics of forest fires.[6] Traditional forest fire alarm systems employ watching towers, ground patrolling, satellite monitoring, and other assistant tools,[2,7,8] which offer low efficiency with huge financial and labor input. In recent years, advanced fire sensors are more widely used to detect and monitor forest fires owing to their unique merits of low cost, high accuracy, rapid response, and stability.[9–11] Most of the fire sensors are powered by batteries, of which the capacity is highly restricted by the issues of limited lifetime, regular replacing, and potential environmental pollution. A self-powered alarm system using sustainable energy is thus much needed.

Harvesting energy directly from a forest environment is a promising and effective approach to building a self-powered alarm system. Although solar cells have been widely used for portable electronics or self-powered systems, it is challenging to install these in a forest because of the shading or covering of lush foliage. The kinetic energy associated with the shaking or the swinging of tree branches as induced by a blowing wind can be potentially harvested for powering the alarm sensors. Moreover, the temperature difference between the burning area and its surroundings may create convective air flow patterns[4] thus increasing the likelihood to harvest kinetic energy in a forest fire condition. However, the amplitude and the frequency of the vibration of tree branches are small and erratic. Thus, it is difficult to use conventional power equipment to harvest the
kinetic energy of tree branches. The triboelectric nanogenerator (TENG) was demonstrated to be a powerful technology for converting mechanical energy into electricity, with features such as ease of fabrication, diverse material selectivity, low cost, lightweight, and remarkable durability.\(^{[12-15]}\) The TENG technology is based on the coupled effect of triboelectrification and electrostatic induction, and is the new application of Maxwell’s displacement current in energy.\(^{[16–18]}\) To date, a variety of TENGs with different structure designs and material choices have been fabricated to harvest different kinds of mechanical energies in the ambient environment including vibration, wind, human motion, and ocean wave.\(^{[19–24]}\) However, there are rare studies to our knowledge exploring the harvesting of tree branches motion by TENGs for fire alarm or environmental monitoring purposes.

In this work, we present a novel multilayered cylindrical triboelectric nanogenerator (MC-TENG) working in a sliding mode of two sleeve cylinders for harvesting the kinetic energy of tree branches. The MC-TENG consists of two parts, a fixed sleeve and a sliding sleeve connected by a rubber band. As a proof-of-concept, we fabricate a four-layer MC-TENG by nesting four different sizes of cylindrical TENGs, to fully utilize the volume of the device. The significant factors that may affect the energy harvesting performance of the MC-TENG are systematically investigated, including the number of triboelectric layers, the amplitude, the frequency, the sliding height, and the vibration direction of the branches. Using this design, the peak and the average powers of MC-TENG are 2.9 mW and 1.2 mW at 1.25 Hz, respectively. Furthermore, a micro-supercapacitor (MSC) was fabricated by a cost-effective spray-printing technique to integrate with the MC-TENG and fire sensors, forming a self-powered forest fire monitoring and detection system.

2. Results and Discussion

2.1. Design and Working Principle of MC-TENG

A new MC-TENG is proposed to harvest the kinetic energy of shaking tree branches for powering wireless sensors of a fire alarm system in forest (Figure 1). The MC-TENG consists of two major functional components, a top fixed sleeve hanging on the branches and a bottom sliding sleeve connected by a highly stretchable rubber band with the top sleeve, forming a spring-mass vibration structure (Figure 1a). A mass block is bonded with the bottom sliding sleeve to tune the natural frequency of the device, aiming to change the intrinsic frequency of the
MC-TENG for a resonant response based on the shaking of tree branches in different regions or situations. The rigid cylindrical shell is made of a 3D-printed thermoplastic polymer and is set as 1.5 mm thick. Both the inside and the outside surface of the top cylindrical sleeve shell are bonded with a thin layer of Cu film, serving as the cylindrical triboelectric material and the electrode (Figure 1a,b). A polytetrafluoroethylene (PTFE) film of 50 μm is used as the electrification contact material and is bonded onto the surface of the Cu film electrodes of the bottom sliding sleeve, because of its strong ability of electron attraction and low friction coefficient. To improve the output performances of the MC-TENG, the corona charging method is used to inject electrons onto the surface of PTFE film to increase the surface charge density of the film significantly (Figure 1c).[25,26]

It is verified that the proposed device is sensitive to external mechanical excitation, and even a very small vibration from tree branch will generate a relative sliding motion between the two sleeves.

As a proof-of-concept, we fabricated a four-layer MC-TENG by incorporating four cylindrical triboelectric layers to enhance space utilization (Figure 1b). The detailed fabrication process of the MC-TENG device is reported below in Section 4. The working principle of the MC-TENG is based on the conjugation of contact triboelectricity and electrostatic induction.[11,27] The relative sliding motion between the PTFE layer and Cu film generates an alternating flow of electrons between the top and the bottom electrodes. For a better illustration of the working mechanism, the electricity-generating process of the MC-TENG is elaborated through a single layer device as shown in Figure 1d. The whole process can be divided into four stages. First, the PTFE film is fully overlapped with the top Cu electrode (Figure 1d-i). At this state, electrons are injected from the top Cu electrode to the surface of PTFE film, thereby generating positive and negative triboelectric charges on the Cu and the PTFE surfaces in the saturated state, respectively, due to the difference of the electron affinity between the two triboelectric materials. Second, as the two surfaces slide under an external mechanical excitation, an electrical potential difference is built between the PTFE back electrodes (Figure 1d-ii). Third, as the PTFE films are separated from the top Cu electrodes, all the electrons will be driven to the bottom electrodes, and the induced potential difference between the two electrodes reach the maximum value (Figure 1d-iii). Finally, the upward movement of the PTFE films from the separate state to its initial position generates a reverse current in the circuit and forms a complete cycle of the electricity generation process (Figure 1d-iv).

### 2.2. Effect of the Number of Layers on Energy Harvesting Performance of MC-TENG

The output performance of the designed MC-TENG is strongly affected by the number of structural layers of the sleeves. To reveal the change of the output performance of a MC-TENG, we have investigated four different configurations for the device, as shown in Figure 2a. The output voltage and the transferred charge of the MC-TENG with the different number of layers (1, 2, 3, and 4) are presented in Figure 2b,c. Although all the MC-TENGs can generate stable electric output, both the output voltage and the transferred charge of the device increase with the number of layers of the sleeves under the same excitation. The output voltage is enhanced from 680 to 2240 V and the transferred charge from 0.34 to 1.88 μC, when the number of layer increases from 1 to 4. The peak values of the output voltage and the transferred charge generated by devices with different number of layers are plotted in Figure 2d, also indicating that more number of layers for the MC-TENG will generate a larger energy output due to the increased surface area of friction. It is noted that the relation is nonlinear and the slope shows an increasing trend because the outer layer with larger diameter has a larger surface area than the inner layer. Furthermore, it is also more efficient to charge a supercapacitor for a MC-TENG with more layers due to its higher output performance (Figure 2e). For example, a MC-TENG prototype with four layers takes 15.6 s to charge a 10 μF capacitor up to 5 V, however, a single layer TENG needs 100 s to charge the capacitor to 5 V, agreeing well with the theoretical analysis.

### 2.3. Energy Harvesting Performance of MC-TENG under Different Excitation Conditions

In the forest, tree branches may move or vibrate in semirandom directions due to the uncertainty associated with local wind conditions and weather patterns. To reveal the output characteristics of the proposed MC-TENG under different excitation conditions, we mainly investigate two basic motions (up-and-down vibration; back and forth swing/shaking) of a MC-TENG device using a linear motor, which can be accurately controlled for specific motion modes with assigned acceleration, speed, and displacement amplitude. For the up-and-down vibration mode, a MC-TENG device is fixed onto a linear motor vibrating up and down. Figure 3a-c shows the output voltage, the current, and the charge of a MC-TENG as the functions of vibration amplitude at the frequency of 1 Hz. It is found that a larger vibration amplitude results in a higher electric output. The voltage, the current, and the charge can reach 1.07 kV, 8.33 μA, and 1.41 μC, respectively, at the vibration amplitude of 120 mm. This trend is attributed to the larger inertial acceleration of the bottom sliding sleeve induced by a larger vibration amplitude. The influence of the vibration frequency of the sleeves on the output performance of the MC-TENG is also studied by sweeping the frequencies from 0.5 to 1.5 Hz for a fixed vibration amplitude of 100 mm. As shown in Figure 3d, all the peak values of voltage, current, and charge increase significantly with the increasing vibration frequency. The maximum electric output is obtained at the frequency of 1.5 Hz, with a voltage of 2.45 kV, a current of 12 μA, and a transferred charge of 1.81 μC. For other possible vibration frequencies (e.g., 0.5 Hz), the MC-TENG has also generated stable output, which demonstrates that the designed device maintains good sensitivity to the external mechanical stimulus of low frequency. Figure S1, Supporting Information, shows the relationship between the electric output and the frequency with different vibration amplitudes. Remarkably, for a small vibration amplitude and
a low frequency, less kinetic energy can be transferred to the bottom sliding sleeve, thus generating a much lower electric output. The output performance can be further enhanced by tuning the sliding sleeve's mass and the string/spring's properties for achieving a resonant vibration mode within the range of the major swing frequencies of tree branches.

In addition, we have studied another agitation form—swing mode to simulate free swings of the device in horizontal directions, where the device is hung on the liner motor and swings back and forth like a pendulum (Figure 3e). We first adjust the sliding distance of the liner motor, while keeping the frequency of linear motor at 1 Hz during the measurement. Figure 3f demonstrates that the voltage, the current, and the charge all gradually increase with the increasing sliding distance, which is mainly ascribed to the larger swing amplitude induced by the bigger inertia force under a larger sliding distance. Besides, the effect of excitation frequency in the swing mode is addressed. Figure 3g shows that the peak values of voltage, current, and charge all increase dramatically to reach their maximum values of 1.86 kV, 11.2 µA, and 1.6 µC at the excitation frequency of 0.75 Hz, then significantly decrease at even higher frequencies. When the excitation frequency is beyond 0.75 Hz, the motion period is not long enough for the device to swing sufficiently, resulting in the degradation in output performance. Furthermore, the output performance of the MC-TENG is tested by changing the horizontal excitation angle from 0° to 360° at a fixed suspension height of 35 mm and an excitation frequency of 1 Hz. As shown in Figure 3h,i, owing to the cylindrical structure design, the voltage and the charge at different angles have the same output values, which demonstrate that our device has the ability to harvest kinetic motions of tree branches along an arbitrary direction. Note that very large excitation frequency or amplitude will lead to a complete separation of the top and the bottom triboelectric layers, which may dysfunction the MC-TENG. This problem can be solved easily by increasing the length of each sleeve or using a sturdier rubber band.

2.4. Output Power and Charging Performance of the MC-TENG

External load resistors are utilized to measure the output power of the MC-TENG device to demonstrate the harvesting energy capacity of the MC-TENG. Figure 4a shows the maximum instantaneous peak power ($P = I^2R$) of the device at different frequencies in the up-and-down vibration mode. It can be seen that the output power at 1.25 Hz is the highest, reaching 2.9 mW with a matched load resistance of 80 MΩ. The average
power obtained with a specific load resistance is calculated according to the equation:

$$P = \frac{1}{T} \int_0^T I R \, dt$$

where $I$ is the output current, $T$ is the period, and $R$ is the load resistance.

Figure 4b presents the average power of the MC-TENG as a function of the external resistance at different frequencies, exhibiting the same variation trend as the peak power. A maximum average power of 1.2 mW is demonstrated when an external resistance of $\approx 200 \, \Omega$ is utilized for the MC-TENG. Figure 4c shows the charging curves of a few capacitors with different capacitance powered by a MC-TENG at the frequency of 1.0 Hz. The results indicate that the MC-TENG is able to charge a smaller capacitor to achieve a higher voltage with a faster charging speed. We also use the MC-TENG to charge a capacitor with a capacitance of 10 $\mu$F under different working frequencies. As shown in Figure 4d, the charging rate increases with the frequency and more energy can be harvested with a higher frequency. For example, the voltage of the capacitor can reach 7.7 V by the MC-TENG at 1.25 Hz, but only 2.4 V at 0.5 Hz in 30 s. The MC-TENG prototype can light a Spartan Logo patterned with dozens of green light-emitting diodes (LEDs) (Figure 4e). The MC-TENG also demonstrates excellent repeatability and stability in energy harvesting (Figure 4f). It can be seen that the generated voltage can be maintained very stable after 10 000 cycles of vibration at a frequency of 1.0 Hz. It should be noted that the triboelectric materials of Cu film and PTFE film and the 3D-printed structures have good wear and corrosion resistance, and maintain a low friction coefficient in vibration, which are suitable for long-term monitoring applications. Considering the possible extreme weather like raining or storms in the forest, a protective shell made of lightweight or even transparent materials can prevent the influence of humidity on the MC-TENG performance, although the low risk of fires in such kinds of weather.

### 2.5. Demonstration of a Self-Powered Fire Alarm System via MC-TENG

To store the electric energy harvested by the MC-TENG, a carbon nanotube (CNT) based MSC with poly(vinyl alcohol)
(PVA)/H₃PO₄ gel electrolyte is fabricated by a cost-effective printing technique (Figure 5a). Cyclic voltammetry (CV) curves of the MSC at different scanning rates from 1 to 30 mV s⁻¹ are shown in Figure 5b. As shown, quasi-rectangular shapes at all the scanning rates are presented, indicating the typical electrochemical double-layer capacitance behavior. Figure 5c depicts the galvanostatic charge/discharge (GCD) profiles of the MSC at various current densities (0.01, 0.02, 0.05, and 0.08 mA cm⁻²). Symmetric triangle-curves are shown, implying rapid charge and discharge properties. To extend the potential window and meet the energy power requirement, a few MSCs are connected in series. Figure 5d shows the GCD curves of a single MSC and three MSCs connected in series. A 2.4 V voltage output of the MSC array connected in series is reached, about three times of a single MSC. In addition, an excellent performance under charging/discharging testing at a current density of 0.02 mA cm⁻² for 200 cycles (Figure 5e) can be maintained for MSC, exhibiting superior cyclic stability for long time operations.

Based on the above verification, we integrated the MC-TENG, fire sensors, and a MSC together to build a self-powered forest fire alarm system (Figure 5f). The alternating current electricity will be converted to direct current electricity by a rectifier. When the switch K₁ is on and K₂ is off, the serially connected MSCs will be charged by the MC-TENG. Once the charged voltage reaches a specific value (shown in a voltmeter), the switch K₂ is then switched on and the stored energy will drive the sensors to work. As a demonstration, a commercial carbon monoxide (CO) sensor (ULPSM-CO 968-001) with high sensitivity and short response time is used to detect the CO gas from the fires. The integrated MSCs can be charged to 3 V in ≈7 min by the MC-TENG under the vibration of tree branches at a frequency of 1.25 Hz. Then, switching on the system enables the CO sensor to detect CO concentration. Here we use a burning wood branch to generate CO for the testing. As shown in Figure 5g, when the fire approaches the sensor, the output signal of the sensor increases significantly, and when moving away the firewood, the detected signal reduces dramatically to around zero, demonstrating the sensing and alarming functions of the self-powered system. For each charge, the sensors can keep working for a reasonable period and report multiple times of the warning signals (Video S1, Supporting Information). The slight difference in the peaks and the response times of each cycle in Figure 5g comes from the controlled distance between the firewood and the sensor and the holding time or moving speed at the sensing region in the experiments.

In addition, temperature is a useful factor that can be detected for sending forest fire alarms. Thus, we can also integrate a thermometer together with the CO sensor with the MC-TENG to form a self-powered multiparameter forest fire alarm system to avoid possible false alarm and improve the accuracy of fire warning. As shown in Figure 5h, the voltage of the MSCs can be charged to 1.8 V in ≈200 s, and after turning the switch on, the thermometer is powered to measure the temperature and display the value on its screen or wirelessly send the signal to the sensor hub/server. It is noted that in the left inset in Figure 5h, when the thermometer starts to monitor the ambient temperature, it will consume a reasonable amount.
of electric energy, leading to a quick drop of the stored energy (i.e., voltage) in the MSC. After that, the thermometer is in a low power state and the voltage will slightly increase again through the continuous working of the MC-TENG. For each full charging of the MSC, the thermometer can measure the temperature effectively for six times with a measuring period of 10 s. The working performance of this system in both vibration and swing mode is demonstrated in Videos S2 and S3, Supporting Information.

3. Summary and Conclusion

In summary, we have developed a novel MC-TENG operating at a sliding mode to harvest the kinetic energy of tree branches. The MC-TENG shows excellent energy harvest performance with higher space utilization. A MC-TENG with four layers could achieve an output voltage of 2240 V and an amount of transferred charge of 1.88 µC. The influence of the excitation frequency, amplitude, and orientation between the shaking direction and the device configuration on the energy harvesting performance of a MC-TENG under two motion modes has been studied. The MC-TENG device reached a maximum peak power of 2.9 mW and a maximum average power of 1.2 mW at 1.25 Hz. Finally, a self-powered forest fire alarm system is developed by integrating the MC-TENG, the MSC and the fire sensors in a compact way. This study provides a new solution to effectively use the TENGs to harvest kinetic energy of tree branches for fire detection and environment monitoring in forest.

4. Experimental Section

Fabrication of the MC-TENG: The two sleeve components of the cylindrical model were designed with a software package Solidworks, and then, the 3D-printed by a commercial 3D printer (Zmorph-2.0-SX). The height and the thickness of the sleeve shell were 85 mm and 1.5 mm, respectively. The Cu films were then pasted onto the inside and the outside surfaces of cylindrical shells. Thereafter, PTFE films were...
obtained. Finally, the PVA/H3PO4 electrolyte was drop-cast on the CNT
interdigitated electrodes were measured by a electrochemical workstation (SP-300). The
performance of the MSC was further calculated according to the resistance ratio of the resistors in the circuit. A linear motor (LinMot MBT-37 × 120) was employed for actuating the MC-TENG. The software LabVIEW was programmed to acquire real-time control and data extraction. The electrochemical properties of the MSC were measured by a electrochemical workstation (SP-300). The output signals of the CO sensor were measured by a digital storage oscilloscope (GDS-2202).

Fabrication of the Integrated Supercapacitor: Figure S2, Supporting Information, schematically illustrates the main process of fabricating the MSC. In this work, Kapton film (100 μm thick) was used as the substrate for fabricating the MSC. First, a paper tape was pasted on the surface of the Kapton film as the mask layer. Second, a laser cutter (Glowforge Pro) was used to fabricate the mask consisting of six interdigitated electrode patterns, in which the electrode length is 6 mm, the electrode width is 1.5 mm, and the gap between electrodes is 1 mm. Third, the thin-films of CNTs (3021 B3-R, Brewer science, Inc.) were spray-printed with an air brush (SB-844) as the electrodes. Fourth, peeling off the mask, the CNT interdigitated electrodes were obtained. Finally, the PVA/H3PO4 electrolyte was drop-cast on the CNT interdigitated electrode area, and cured at ambient conditions for 12 h to ensure that the electrolyte had completely wet the electrodes and the excess water was evaporated.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest
The authors declare no conflict of interest.

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energy harvesting, forest fire alarm systems, multilayered cylindrical structures, triboelectric nanogenerators, vibration kinetic energy

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