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An Ultra-high Power Density Helmholtz Resonance Acoustic Energy Converter Based on Triboelectric Nanogenerator *

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***Abstract*—Sound energy is a ubiquitous renewable energy source. How to comprehensively harvest and utilize this energy has become a hot research topic. Triboelectric Nanogenerator(TENG) can convert different forms of mechanical energy into kinetic energy, and has significant advantages in micro-nano power generation, self-driving sensing, and device performance control. This work designs an ultra-high power density Helmholtz resonant cavity based on triboelectric nanogenerator with a printed electrode(H-TENG) for harvesting acoustic energy efficiently. We proposed an optimized scheme for harvesting sound energy effectively by the special treatment of the electrode flexible film. Then we researched the structure of the resonant cavity, acoustic conditions, and the tension of flexible film, they can affect the output characteristics of the H-TENG acoustic energy converter. We find H-TENG follows the best output frequency deviation law, that is, introducing appropriate tension according to a specific sound wave range can improve the best frequency response. Compared with the best results in the early literature, the H-TENG has a high power density of 1.47 $\mathrm{W/m^2}$ sound pressure. The study showed that the high power output of H-TENG can light up 457 LEDs at the same time. Finally, this research also proposes the application potential of H-TENG in energy conversion and acoustic sensing.**

I. Introduction

Acoustic energy as a clean, abundant, and sustainable energy source exists in large quantities in our surrounding environment. Energy harvesting is the process of capturing environmental energy and converting it into electrical energy. Due to the low energy density of sound waves and the lack of effective energy harvesting technology, most sound wave energy is wasted[1]. Acoustic energy collection is usually harvested by means of an acoustic resonance device. Specifically, when the acoustic resonator is excited by the incident wave at its resonance frequency, acoustic energy in the form of a standing wave is harvested inside the resonator [2-8]. Since 2012, the triboelectric nanogenerator (TENG) has been considered the most promising way to realize distributed energy harvesting and self-powered sensing [9-15]. TENG is usually composed of dielectric materials and metal electrodes. TENG's materials are more environmental and reliable. In recent years, triboelectric nanogenerators (TENG) have made it possible to harvest sound energy with flexible electrode materials. Some previous work tried to use TENG to convert sound energy into electrical energy. For example, Cui et al. developed a new mesh TENG acoustic wave collector [16]. Yang et al. used a Helmholtz resonant cavity with an adjustable narrow neck back and a circular friction nanogenerator to make an acoustic energy harvester [17], which reached the maximum resonance frequency of 240 Hz. With a voltage of 60.5 V, a maximum current of 15.1 μA, and a maximum power density of 60.2 $\mathrm{mW/m^2}$, it can light up 17 commercial LEDs. Xing et al. developed an ultra-thin, rollable paper-based sonic energy harvester [18], with a maximum power density of 121 $\mathrm{mW/m^2}$ at 117 dB sound pressure level. Cui et al. developed a new type of mesh TENG acoustic wave harvester [19], with a maximum power density of $\mathrm{mW/m^2}$. But these TENG-based acoustic energy collectors have low output power and low collection efficiency. Therefore, advanced sound energy harvesters with high output performance and strong practicability have become a prerequisite for sound energy utilization. Our TENG-based dual-necks Helmholtz resonance acoustic energy converter (H-TENG) is easy to design and manufacture, and the generated electric energy can well be matched with the sensor system.

II. Working Mechanism of the H-TENG

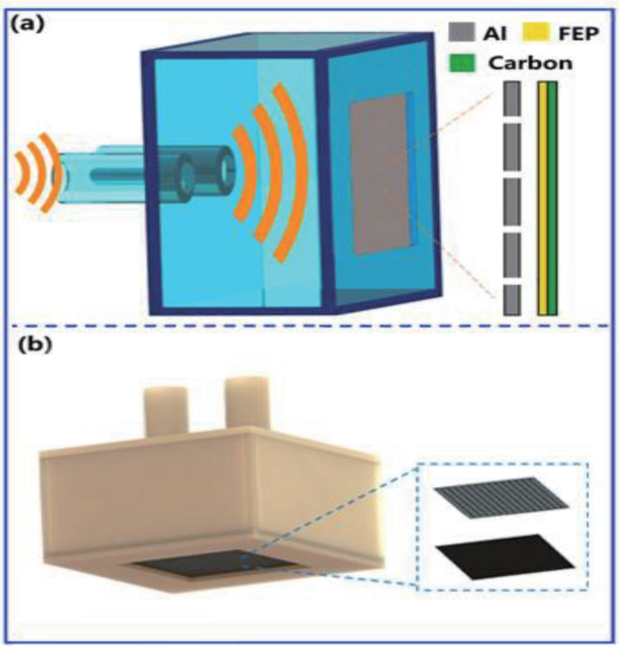

Figure 1. (a) The three-dimensional structure diagram of the dual-necks Helmholtz resonator(b) The actual detail diagram of the H-TENG.

We designed a high-power density triboelectric nanogenerator made by dual-necks Helmholtz resonator triboelectric nanogenerator. The structure of H-TENG is shown in Figure 1(a). It consists of an improved dual-necks

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Helmholtz resonator, an aluminum film with uniform acoustic hole distribution, and a fluorinated ethylene-propylene copolymer (FEP) with conductive ink printed electrodes It's photograph structure is shown in Figure 1(b), the size of the resonant cavity is 70mm × 70mm × 20 mm, the working area of H-TENG is 40 mm × 40mm × 20 mm.

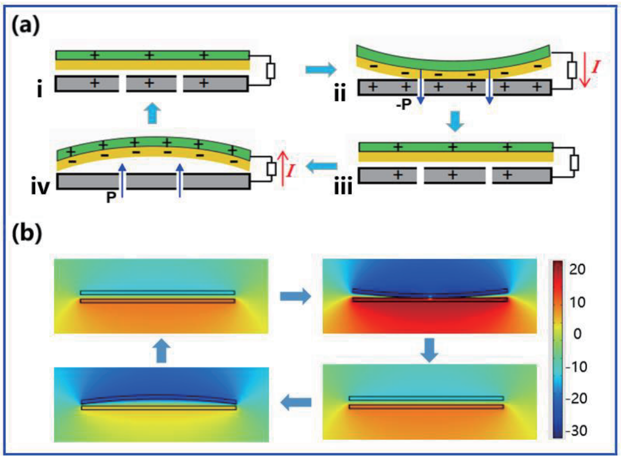

Figure 2(a) The working principle of acoustic driven H-TENG(b) COMSOL simulation of the potential distribution between the two electrodes of the H-TENG.

To describe the electric field changes in the working process of the H-TENG. The working principle of H-TENG is shown in Figure 2(a), The relative contact separation movement between FEP film and aluminum film regularly generates AC pulse output. Through the software, COMSOL MULTIPHYSICS to use the finite element method to construct a two-dimensional plane model of H-TENG. It performs related simulation calculations and analyses the electric field distribution between the dielectric film and the aluminum film. As can be seen from Figure 2(b), the relative contact and separation movement between the two films causes the electric field distribution to change significantly.

III. OPTIMAL DESIGN

In the preparation process of the triboelectric nanogenerator, the surface of the power generation material is usually with special treatment to improve the output performance. Pyramid, hemispherical and other microstructures usually are made on the surface material to increase the contact area between the dielectric material and the metal material for increasing the number of overlapping electron clouds between atoms of different materials. With the surface contact stress and the number of atoms increasing, the depth of overlap between electron clouds enhances the charge transfer between materials. Another method is to increase the negative charge on the surface of the dielectric material by ion spraying. With a stronger built-in electric field during the contact and separation process of dielectric material and metal material, so as to increase the output of the triboelectric nanogenerator. In this experiment, the FEP material was polished with 10,000-mesh fine sandpaper to destroy its smooth surface and make the surface more uneven, causing more surface structural defects. At the same time, the FEP material was treated with a high-voltage electric field of 20,000 volts for adding more charge to its surface.

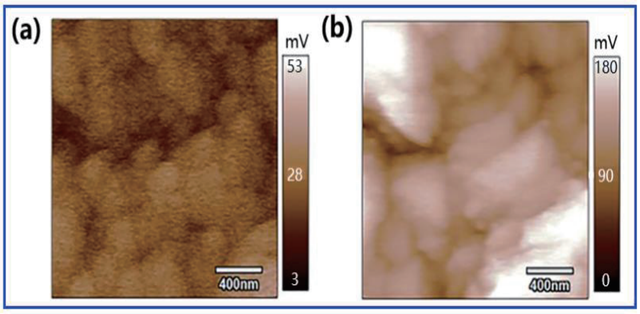

Figure 3. (a) The FEP film not treated with the electric field and sandpaper (b) The FEP film not treated with electric field and sandpaper.

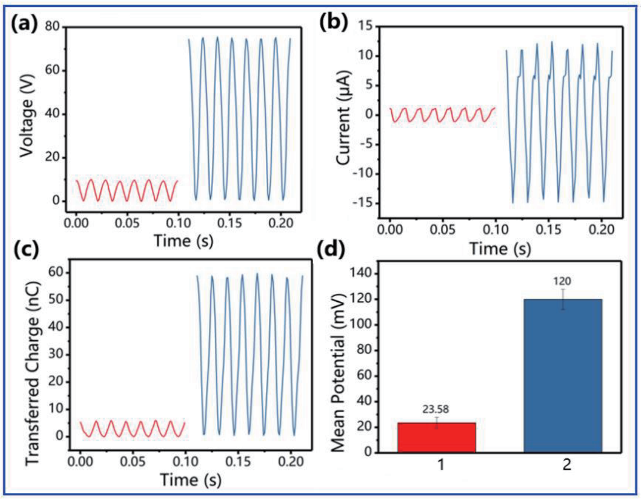

Figure 4 (a~c) Comparison of output voltage V_{oc}, short-circuit current I_{sc}, transferred charge Q_{sc} of H-TENG constructed by two different FEP films, (d) Comparing average surface potential of two FEP films.

Figure 3 shows the FEP film treated in two different ways. The experimental data is shown in Figure 4. The open-circuit voltage of the constructed H-TENG is shown in Figure 4(a). The output voltage of the H-TENG constructed with the FEP film without polishing treatment is about 10 V, and the output voltage of H-TENG constructed with polished FEP film is about 75 V, which is about 7.5 times that of the former. As the output short-circuit current shown in Figure 4(b), we can see that the unpolished FEP film is about 2.5 μA, while the polished one reaches 15 μA, which is about 5 times higher than that. In Figure 4(c), the transferred charge of the H-TENG has similar obvious results. The output performance results obtained are consistent with the theoretical derivation and prediction, which proves that the surface film treatment of the triboelectric nanogenerator has a significant effect on the improvement of electric energy output and can improve the efficiency of sound energy harvesting.

IV. EXPERIMENTAL RESULTS

In order to research the sound energy collection performance of H-TENG, a loudspeaker was used to generate a sine wave electric signal in the experiment, and a signal generator was used to adjust the frequency and sound pressure of the sound wave. As the experimental setup is shown in Figure 5.

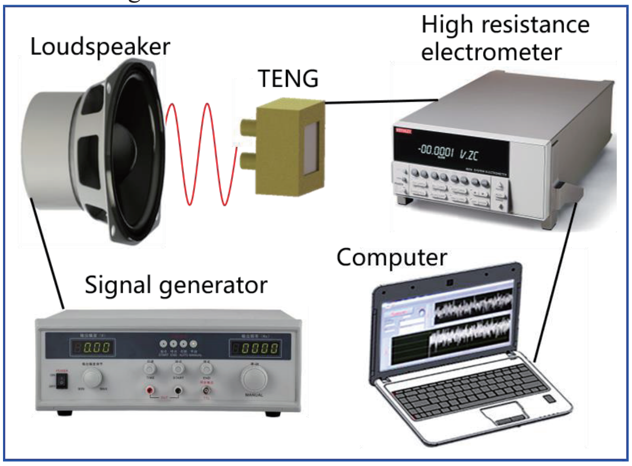

Figure 5. H-TENG's sound energy harvesting experimental equipment diagram.

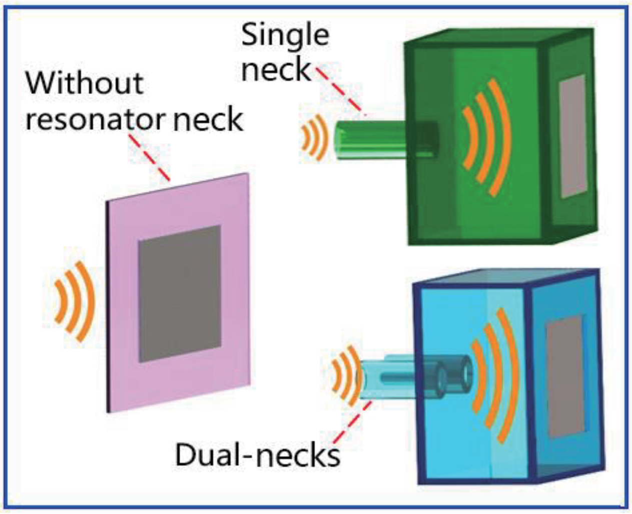

Figure 6. The structure of the TENG without neck, single-neck, and dual -necks resonant cavity.

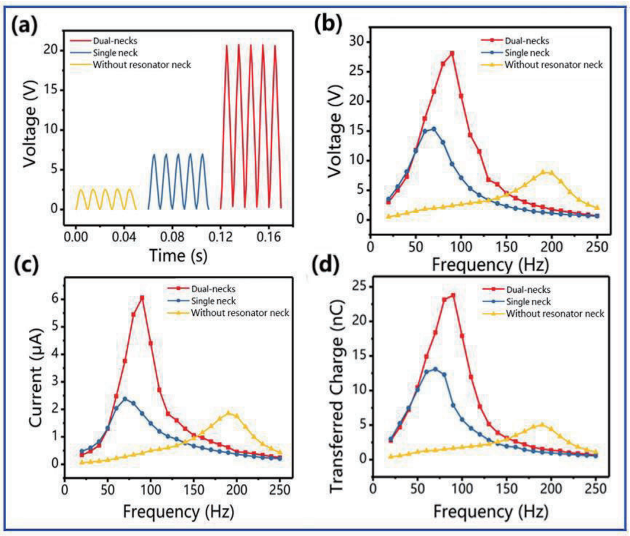

Figure 7. (a) The peak of the voltage of H-TENG with the same sound frequency and sound pressure (b~d) The output performance of H-TENG under different sound frequencies.

Experiment with three Helmhertz resonators with different structures in Figure 6. As Figure 7(a) shows the output voltages of the three resonant cavity TENGs under the 100 Hz and 80dB sound waves, their respective the peak of voltage is about 2.8V, 7.3V, and 21.7V. Compared with traditional single-neck, the output of dual-necks is improved by 197%. Figure 7(b) tests the output voltages of three TENGs with different structures at different audio frequencies. It can be clearly seen that the output voltage of the Helmholtz resonator of different necks is quite different. Among them, the maximum open-circuit voltage of the dual-necks TENG can reach 28V when it stays at the optimal frequency of 90Hz. The peak open-circuit voltage of the TENG without a resonant cavity at the optimal frequency of 190Hz is 8V, which is 269% lower than the corresponding output of the dual-necks Helmholtz cavity. The maximum open-circuit voltage of the optimal frequency of the traditional single-neck resonant cavity TENG is 15.2V, which is 87% lower than the corresponding output of the dual-necks Helmholtz cavity, and when the frequency exceeds 190 Hz, this performance difference gradually disappears. Figures 7(c) and 7(d) show the short-circuit current Isc and the transferred charge Qsc curves, we can find similar results. Compared with the TENGwithout cavity neck, with the single-neck Helmholtz cavity using, the maximum output power is significantly increased, and the best output frequency is significantly reduced. After using the dual-necks Helmholtz resonant cavity, the output performance of the H-TENG is further improved. So the experiment shows that the dual-necks Helmholtz resonant cavity not only broadens the response frequency band but also dramatically enhances the output power.

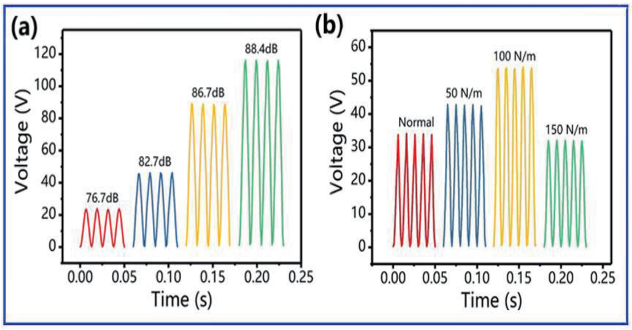

Figure 8. (a)Comparison of open-circuit voltage of H-TENG with four types of sound pressure levels. (b) Comparison of the output voltage of H-TENG with different FEP film tension at 100 Hz frequency.

The experiment researched the effect of sound pressure level on the H-TENG. It is mainly reflected in the effect of sound pressure level on the vibration amplitude of H-TENG's FEP film generates different output voltages. Figure 8(a) depicts the output characteristics at 100 Hz corresponding to four groups of different sound pressure levels. At 77dB sound pressure level, the peak voltage of H-TENG is 24.8 V. At 88dB sound pressure level, its peak voltage is 118.6 V, which is about 4.8 times than the former. It also can be seen that the open-circuit voltage obviously enhanced with the increasing sound pressure.

To further study the influencing factors of the output performance of the Helmholtz cavity. We use the fixed sound wave frequency at 100 Hz and the sound pressure level at 85 dB, Figure 8(b) shows four types of tension at an interval of 50N/m to compare the open circuit of the H-TENG by different film tensions. It can be clearly seen that under tension conditions from none to 150N/m, the output voltage of H-TENG does not simply increase with the increase in tension. And when the film tension reaches 100 N/m, H-TENG has the best output voltage. It Shows that proper film tension is beneficial to AC output.

V. Application of the H-TENG

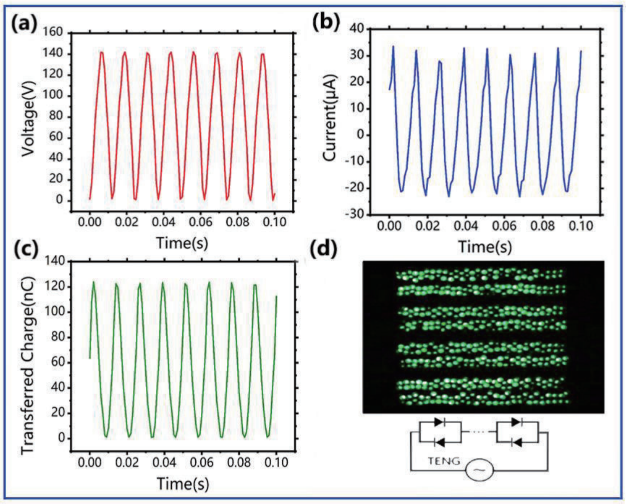

Figure 9. (a~c)The output performance of H-TENG at 85 frequency（d） H-TENG lights up the LED lights.

As a good output performance sound energy harvester, H-TENG can be used to be a power source . When the H-TENG harvesting acoustic wave circuit is connected in series with an internal resistance of 2MΩ, we can see the output performance of H-TENG from Figure 9(a~c), the short circuit current reaches 34.3 μA at 85 frequency. As shown in Figure 9(d), the output power can be directly supplied to the LED lights, making 457 LEDs light up at the same time. It can be calculated that H-TENG has a high power density of 1.47 $\mathrm{W/m^2}$.

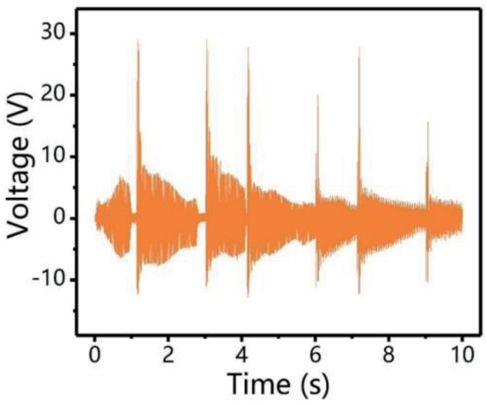

Figure 10. The voltage waveform of H-TENG used as a self-driven acoustic sensor.

H-TENG can be used as a self-driven sensor. In the experiment, H-TENG recorded 10s of audio. Figure 10 shows the voltage waveform of the sensor's response. When the audio plays, the H-TENG output voltage changes with the continuous changes of the audio sound wave characteristics. In addition, we can also use MATLAB's neural network algorithm to restore the response voltage waveform to the original audio. The neural network is shown in Figure 11 shows the high degree of restoration. At the same time, a certain amount of power output will be generated during the recording process, which can achieve the effect of self-driving. So the H-TENG can be optimized for applications such as microphones, recorders, mobile phones, and other devices.

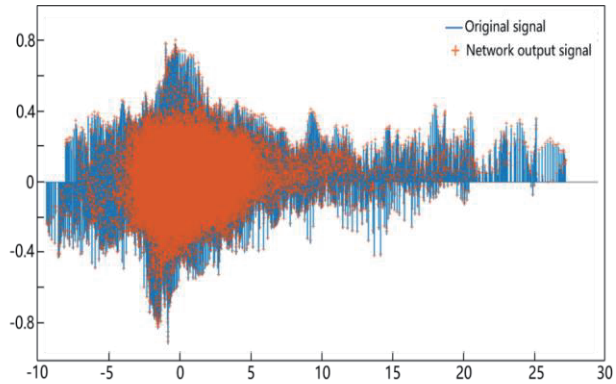

Figure 11. MATLAB's neuron network when H-TENG restores the music waveform.

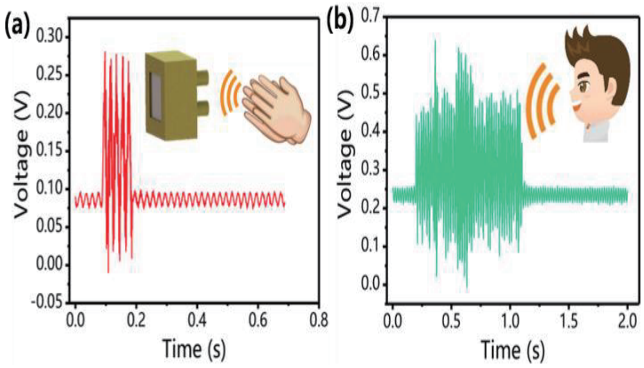

Figure 12. HR-TENG is used to perceive people's (a) applause and (b) voice.

H-TENG can also be used to sense people's applause and voice, and generate corresponding voltage and current output. As shown in Figure 12(a), a person is 5 meters away from the H-TENG. When a person claps his palms, the sound produced by the H-TENG is sensed by the H-TENG 5 meters away, and a set of signals is output. At the same distance of 5 meters, Figure 12(b) shows when a person makes a voice, H-TENG senses the sound wave of the voice, and the power generating film vibrates with the voice and generates a voltage output. It can be seen that the two waveforms are not the same. It can be seen that the characteristics of the two signals are quite different, which can be used for speech analysis and recognition.

VI. Conclusion and Future Work

This paper proposes a novel ultra-high power density Helmholtz resonance acoustic energy converter based on a triboelectric nanogenerator. And its maximum output voltage is increased by 87%. Then studied the influence factors of the output characteristics of the H-TENG. The result shows that optimal treatment of the film is beneficial to H-TENG's output. The number of necks of the Helmholtz resonator affects the resonance frequency and transmission loss, so has a significant effect on the output voltage among them, the dual-necks H-TENG has the best output performance. In addition, the acoustic conditions and the tension of flexible film will also affect the output characteristics of the H-TENG acoustic energy converter. H-TENG follows the best output frequency deviation law, and with appropriate tension according to a specific sound wave range can improve the best frequency response, thereby improving the acoustic-electric conversion performance. Finally, through experiments, it is found that H-TENG has a high power density of 1.47 W/m^2.Obviously, H-TENG can be used for acoustic energy harvesting in the environment. It can also be used as a stable power supply with high power output, It also can sense people's applause and voice as an acoustic sensing, music recording for special detection. Therefore, H-TENG has good output performance in acoustic energy harvesting and self-driving sensing and has great application potential in the sensing and energy supply of wireless sensor networks and the Internet of things.

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