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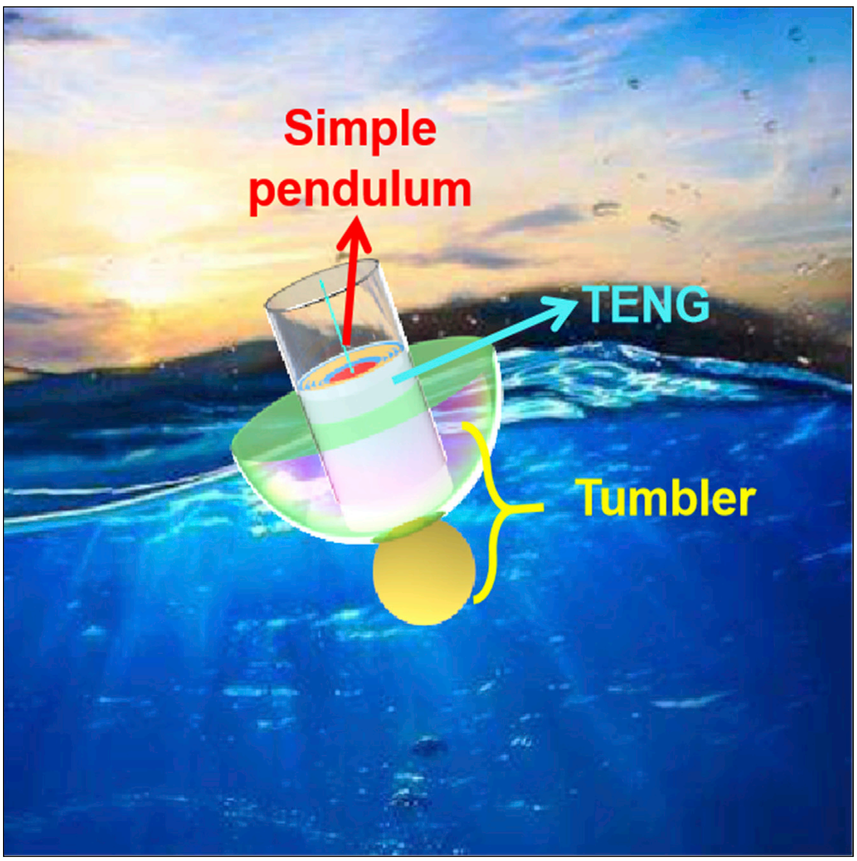

By integrating the tumbler, simple pendulum, and flexible ring triboelectric nanogenerator, the designed active resonance triboelectric nanogenerator can effectively harvest omnidirectional and frequency varying water-wave energy. Thanks to the damped motion of simple pendulum and tumbler, the output performance of AR-TENG system can be greatly improved.

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Highlights

A flexible ring TENG was designed to harvest omnidirectional water-wave energy

The ocean-wave energy was harvested by an active resonance system

The output frequency of TENG was greatly increased by a damping motion

Output of TENG in the real water wave is very close to that in simulated test

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Active resonance triboelectric nanogenerator for harvesting omnidirectional water-wave energy

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SUMMARY

Water-wave energy, as one of the important renewable energies, is greatly difficult to efficiently harvest due to its characteristics of low frequency and randomly moving direction. Herein, we report an active resonance triboelectric nanogenerator (AR-TENG) system fabricated by using simple pendulum, tumbler, and flexible ring TENG, which can harvest omnidirectional and frequency varying water-wave energy through excellent structural design and resonance effect. Besides, thanks to the high-frequency damped motion of simple pendulum and tumbler, the high-frequency output generated by the AR-TENG system under the driving condition of low-frequency water wave can greatly improve the efficiency of wave energy harvesting. More importantly, based on the low damping coefficient, resonance effect, and elimination of water screening effect, the output performance of AR-TENG system in the water wave is closest to the simulated test. This work not only can realize the omnidirectional water-wave energy harvesting by TENG but also provide a method for large-scale blue energy harvesting.

INTRODUCTION

Facing the issues of sharp decline of global fossil energy resources, the increasing demand of human development for energy, and serious environmental problems caused by the large-scale use of fossil energy, the development of clean energy with merits of renewable and green is particularly urgent for the sustainable development of human beings. Although some possible clean energy such as solar energy and wind energy have been employed to generate electricity, the intermittency of sunlight and wind is hard to satisfy the demand of energy in the whole world. Wave energy is one of the most abundant reserves owing to the large ocean area in the earth; thus, it can be used as the complementary candidate of clean energy system.[1,2] However, the low frequency and randomly changing direction characteristics of ocean wave make it difficult to be harvested effectively. In addition, although electromagnetic generators have been developed as the mainstream of mechanical energy harvesting technology, the high price, bulky volume, and poor harvesting efficiency in the low frequency make it unsuitable to harvest ocean-wave energy in large scale.[3]

Based on the merits of low price,[4] low weight[5,6] and high efficiency in low frequency,[3,7] triboelectric nanogenerator (TENG) has been developed as self-powered sensor,[8–10] micro/nano energy,[11–15] and high-voltage source.[16] Meanwhile, TENG has been considered as one of the most effective technologies for large-scale ocean-wave energy harvesting.[17,18] Recently, various kinds of TENG have been designed to capture wave energy,[19–24] and the relative assisted technologies have to be proposed to improve

Context & scale

The major challenge for TENG to achieve efficient water-wave energy harvesting is the characteristic of ocean wave with the random varying direction and frequency. Here, an active resonance triboelectric nanogenerator (AR-TENG) system, which can harvest omnidirectional and frequency varying water-wave energy through excellent structural design and resonance effect, is provided by integrating simple pendulum, tumbler, and flexible ring TENG. Furthermore, this AR-TENG system can achieve the high-frequency output under the driving condition of low-frequency water wave, which benefits from the high-frequency damped motion of simple pendulum and tumbler. Importantly, due to the low damping coefficient, resonance effect, and elimination of water screening effect, an output performance of AR-TENG system close to that of the simulation test is realized in the water wave. This work provides a new method to harvest wave energy for the self-powered marine Internet of Things.

the efficiency of wave energy collection.[25–27] Some strategies such as increasing the contact area and improving the frequency of damping motion via spring have been used to enhance the harvesting efficiency of TENG.[28,29] However, all of these works are hard to harvest the omnidirectional water-wave energy and realize the resonance effect to maximize the efficiency of wave energy harvesting. Moreover, the output performance of TENG is always weaken because of the unavoidable water screening effect.[30] Therefore, it is important to develop a kind of TENG for harvesting the omnidirectional water-wave energy with the maximized efficiency by the resonance effect[27] and eliminating the water screening effect.

Herein, we designed an active resonance triboelectric nanogenerator (AR-TENG) system for harvesting omnidirectional water-wave energy without the influence of water screening effect, based on the omnidirectional free degree of simple pendulum and tumbler, as well as the structure design of flexible ring TENG. According to the active resonance system composed of a pendulum and a tumbler structure, the AR-TENG system can effectively harvest the different frequencies of ocean-wave energy by the resonance effect. Importantly, the hemispherical float in the tumbler structure avoids the close contact between the TENG and water, thus, eliminates the influence of water screening effect on the output performance of TENG. Therefore, very similar output performances of AR-TENG system in the real water wave and simulated test are achieved. This work provides a method to harvest large-scale renewable blue energy and can be combined with other technologies to achieve the self-powered ocean sensing.

RESULTS

Structure design and working principle

An AR-TENG system is designed for harvesting omnidirectional water-wave energy (Figure 1A). The power transfer chain of AR-TENG system for harvesting ocean-wave energy is also depicted in Figure 1B, which is composed of a simple pendulum with a circle-table-shaped pendulum cone, a cylindrical shell as support substrate, a basic TENG device with flexible ring multilayer structure, a floating tumbler structure with hemispherical float, and a steel ball. It is easy to see that the tumbler structure is served as the primary interface to intercept the power of ocean wave, the tumbler structure and simple pendulum are served as the power take-off (PTO) to capture the intercepted power of tumbler structure, and the basic TENG device is used as the generator to deliver the captured power of PTO into electricity. Based on theoretical analysis (Figure S1; Note S1), in order to improve the ability of AR-TENG system with intercepted ocean-wave power, the draft depth of the hemispherical float in the AR-TENG system should be close to its radius as much as possible. Besides, the active resonance system composed of simple pendulum and tumbler structure can produce resonance effect without coupling with external driving frequency (Figures S2 and S3; Notes S2 and S3), which can solve the problem that the previous TENG structures cannot adapt the characteristic of ocean wave with motion frequency change, and thus improve the ability of AR-TENG system to capture wave power. At the same time, the damped motion of simple pendulum and tumbler structure can also enhance the energy capture ability of AR-TENG system. The detailed structure of basic TENG device is displayed in Figure 1C, which is fabricated by Kapton as substrate, copper foil as electrodes, and fluorinated ethylene propylene film (FEP, 30 μm) as dielectric layer. The detailed fabrication and design process of TENG are shown in Figure S4, Note S4, and experimental procedures. In order to increase the energy conversion efficiency of generators, the TENG adopts flexible and multilayered structure to achieve larger contact area, and the rigorous

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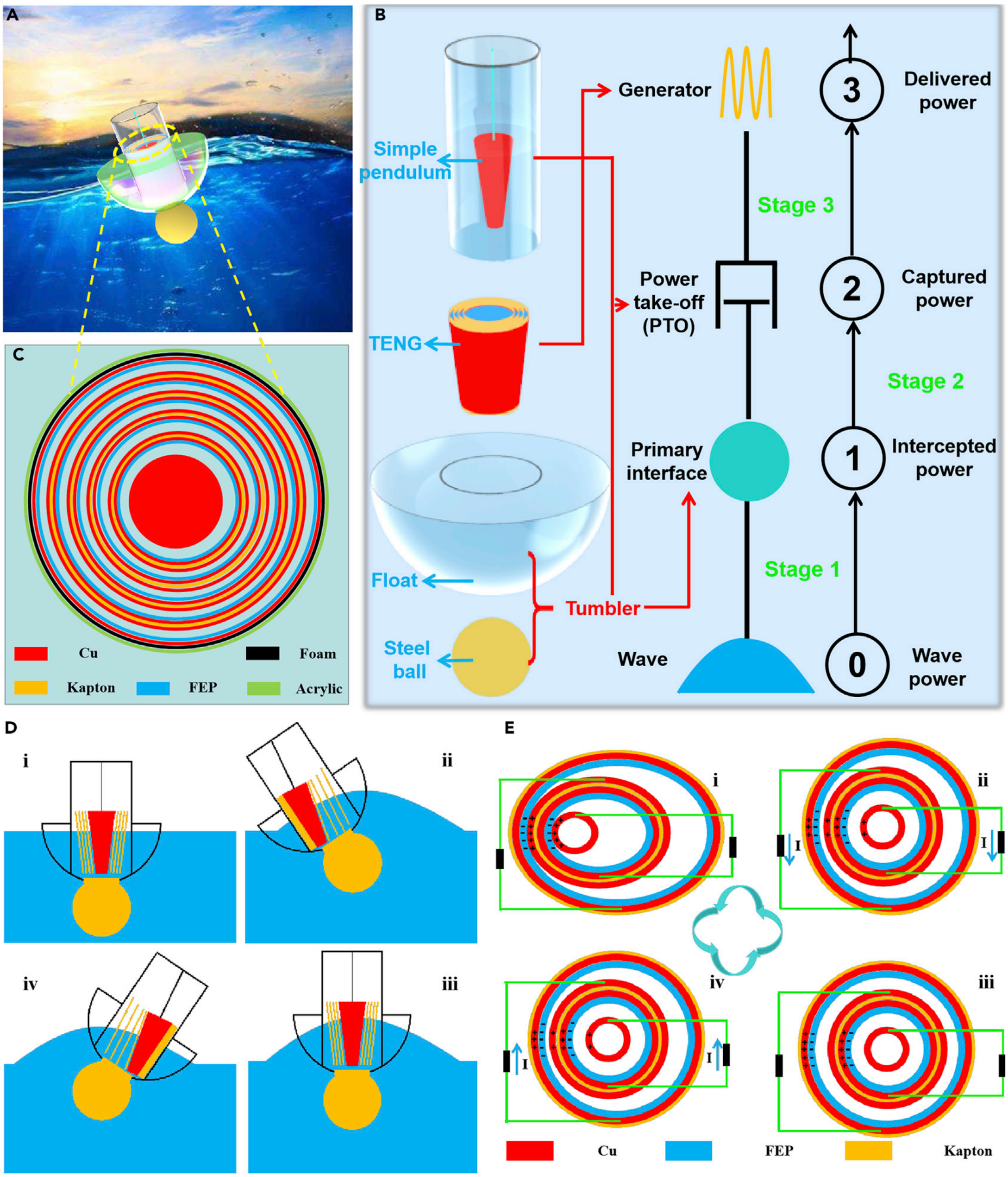

Figure 1. Structural design and working mechanism of AR-TENG system

(A) Schematic diagram of the fabricated AR-TENG system in ocean wave.

(B) Schematic diagram of the fabricated AR-TENG system and the power transfer chain of AR-TENG system for harvesting ocean-wave energy.

(C) Schematic representation for the internal TENG structure.

(D) Working principle of AR-TENG system in ocean wave.

(E) The working mechanism of AR-TENG system unit.

geometric mathematical calculation is used to ensure the effective contact of AR-TENG system (Figure S5; Note S5). Additionally, the micro/nano-structured FEP film (Figure S6) and a foam as buffer layer was used to improve the output performance of TENG by enhancing contact intimacy and efficiency.[31] More importantly, the design of hemispherical shell applied to avoid the close contact between the TENG and water so that it can eliminate the influence of water screening effect on the output performance of TENG and improve the output performance of AR-TENG system in the ocean wave. Finally, based on the omnidirectional freedom of simple pendulum and tumbler structure and the ring structure design of TENG, it is easy to realize the effective collection of omnidirectional water-wave energy for AR-TENG system (Figures S7 and S8). The working process of AR-TENG system in harvesting wave energy is schematically illustrated in Figure 1D. When AR-TENG system floats on the sea, the TENG is in a separate state (Figure 1Di). Because an ocean-wave spread to the AR-TENG system from the right direction and will lean to the left, the simple pendulum will drive the TENG to a full contact state at the same time (Figure 1Dii). Then the wave comes under the AR-TENG system, and the TENG transfers to a state of complete separation (Figure 1Diii). Propagation of ocean wave to the left side will make the system lean to the left. Meanwhile, the simple pendulum will bring the TENG into full contact again (Figure 1Div). Since the ocean wave will leave the AR-TENG system, the whole device will then recover to the initial state (Figure 1Di). Therefore, AR-TENG system will generate two contact separation processes in one ocean wave. The working mechanism of TENG with two units is depicted in Figure 1E, which is based on the triboelectrification and electrostatic induction effect. At first, the dielectric FEP film and the copper (Cu) electrodes are uncharged, then static charges are generated by triboelectrification effect when they come into contact with each other. More specifically, when the two Cu electrodes contact with the two FEP films, the triboelectric effect will make FEP films to be charged negative and Cu electrodes to be charged positive, respectively (Figure 1Di). With the inner two Cu electrodes and FEP films gradually separated, the positive charges will flow from the inner two Cu electrodes to the outer two Cu electrodes via the outer circuit to screen the local electric field of the non-mobile negative charges on the FEP films, respectively (Figure 1Dii). As the inner two Cu electrodes completely separate with the corresponding FEP films, all positive charges will be driven to the outer two Cu electrodes (Figure 1Diii). Since the two FEP films are close to the relative Cu electrodes again, the positive charges of outer two Cu electrodes will transfer to the inner related Cu and electrodes generating a reverse current in the load (Figure 1Div). Therefore, when the ocean waves continuously drive the AR-TENG system to work, a steady stream of ocean-wave energy will be converted into electricity by AR-TENG system. Finally, the damping active resonance of AR-TENG system is vital to improve the harvesting efficiency of wave energy by the higher frequency output performance and the high wave following performance.

The output performances of AR-TENG system at horizontal motion

In order to research the output performance of AR-TENG system in the direction of ocean-wave propagation, a linear motor is applied to simulate the horizontal motion of ocean waves and drive the AR-TENG system. The detailed working process of each cycle is shown in the Figure 2A. When the whole device is at the left state, the simple pendulum will arrive at the right side, which will make the inner Cu electrodes contact FEP films (Figure 2Ai). As this device comes to the medium state, all the inner Cu electrodes will separate with the FEP films (Figure 2Aii). Since this device moves to the right state, the AR-TENG system will completely change to the state opposite to the state on the left (Figure 2Aiii). The characteristic of simple pendulum with high-frequency damped motion is displayed in Figure 2B, the relevant reason is that when the simple pendulum is driven by external force, it can convert part of its energy into its own gravitational potential energy. Then, when the external force is removed, the stored gravitational potential energy will be released to produce a continuous state of motion. First, the linear motor movement distance is set as 60 mm, and the acceleration is fixed at 1.0, 1.5, and 2.0 m s^{-2},

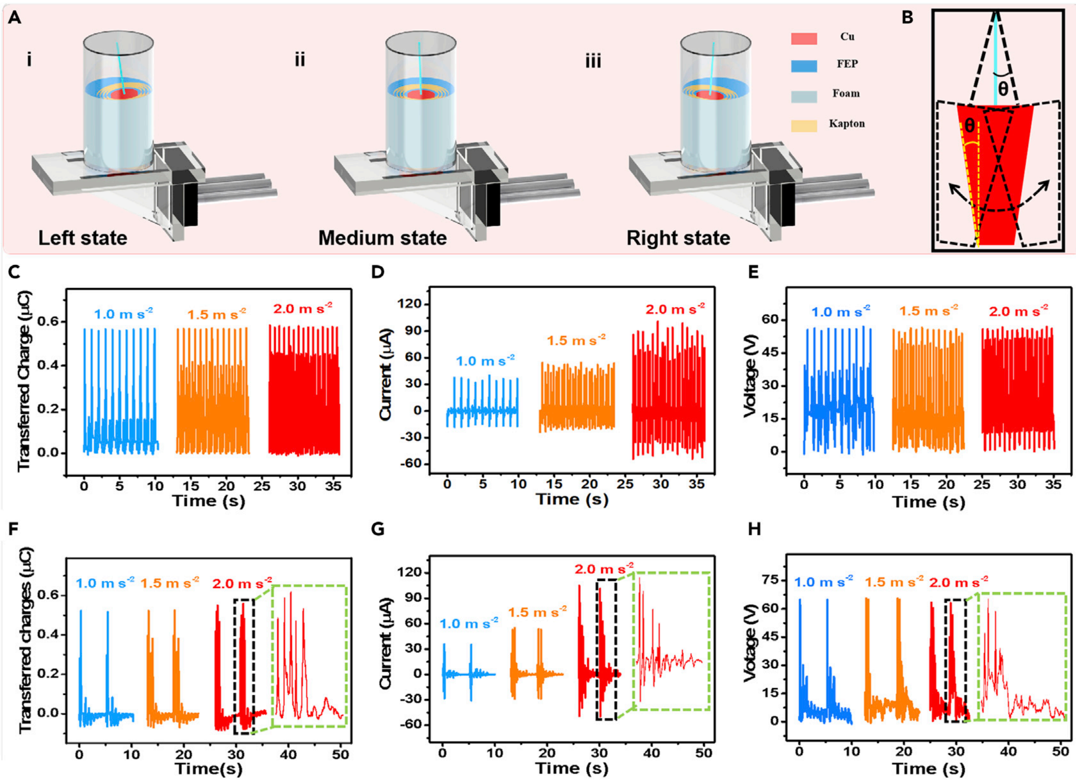

Figure 2. Output performance of AR-TENG system driven by linear motor

(A) Working process of AR-TENG system in full cyclic period.

(B) Diagram of simple pendulum with high-frequency damped motion.

(C–E) (C) Transferred charges, (D) short-circuit current, and (E) open-circuit voltage of AR-TENG system at different acceleration of linear motor.

(F–H) (F) Transferred charges, (G) short-circuit current, and (H) open-circuit voltage of AR-TENG system at adding static time gap of linear motor motion.

respectively, which can test the output performances of AR-TENG system under all kinds of operative conditions. Figures 2C–2E and S9 show the relative output performances of AR-TENG system. It is obvious that the transferred charges are basically stable at 0.57 μC, open-circuit voltage is almost stable at 55 V, and short-circuit current increases with the acceleration from 38 μA at 1.0 m s^{-2} to 100 μA at 2.0 m s^{-2}, respectively. Because the transferred charge and open-circuit voltage do not have the corresponding relationship with the changing rate of time while the short-circuit current increases with the changing rate of time, which is based on the acceleration. Meanwhile, the output performance of AR-TENG system is further measured by charging capacitor of 4.7, 22, 47, and 100 μF. The corresponding circuit diagram and charging curves are showed in Figures S10 and S11. The AR-TENG system is driven by liner motor, the voltage of capacitor with 4.7 μF can be charged from 0 to 4.1 V at 1.0 m s^{-2}, 7.3 V at 1.5 m s^{-2}, and 8.8 V at 2.0 m s^{-2} in 15 s, respectively. For the capacitor with a higher capacitance, such as 100 μF, AR-TENG system can still charge it to 9.6 V in 400 s. In addition, to further verify the function of AR-TENG system with high-frequency damped motion, which can assist TENG to largely improve the harvesting efficient of ocean wave with low frequency, we simulate the real motion state of AR-TENG system in the low-frequency wave by adding a pause in the motion of linear motor. The relative output performances of AR-TENG system are presented in Figures 2F–2H and the inset picture, and it is easy to find that more electricity outputs are generated by AR-TENG system under a periodic motion of linear motor. The main reason of this result is that the damped motion produced by simple pendulum can continuously drive AR-TENG system to operate and generate electric energy. Thus, the AR-TENG system can continuously generate electricity after the wave leaves the system and then improve the whole efficiency of wave-energy harvesting. Moreover, it can obviously find that the decay rate of corresponding electrical signals is much slower than that of traditional spring-assisted structure, and the correlative reason is that simple pendulum has very small damping coefficient and more efficient energy storage function. More importantly, the characteristic of simple pendulum with small damping coefficient also ensure AR-TENG system to harvest the energy of tiny water waves. As depicted in Figure S12, the output performance of AR-TENG system, which consists of transferred charges and short-circuit current, increases with the ring number of M-TENG. Therefore, the output performance of AR-TENG can be further increased by increasing the ring number of TENG. Finally, we research the output performance of AR-TENG under different humidity and temperature (the acceleration is 2 m s^{-2} and the linear motor movement distance is 60 mm) conditions, which are the two important factors that affect the output performance of TENG. The output performance of AR-TENG decreases with the increasing humidity and temperature (Figures S13–S15), owing to the water molecules adsorbing on the surface of dielectric films and the fact that hot electron emission of electrons on the surface of dielectric films will weaken the surface charge density of dielectric films.[32,33] These factors will be solved by the packaging and surface modification.[34]

The output performance of AR-TENG system on seesaw

In real ocean-wave environment, the working state of AR-TENG system will always be in swing state (Figure 1D). Therefore, in order to better simulate the output performance of AR-TENG system in real ocean-wave environment, a seesaw is used to simulate the swing state of AR-TENG system and characterize its output performance (Figure 3A). At first, with the device at the left ascending state, the simple pendulum falls to the right barrel wall, resulting in the inner Cu electrodes contact with the dielectric layers of AR-TENG system (Figure 3Ai). With the device recovering to the medial equilibrium state, the simple pendulum will be back to the vertical state, and the FEP of AR-TENG system separates from the inner electrodes simultaneously (Figure 3Aii). As the device reaches to the right ascending state, the device has an opposite state with the left ascending state (Figure 3Aiii). At the same time, the change in the gravity center of the AR-TENG system in the vertical direction has a precise mathematical relationship with the rotation angle of the seesaw during the swing process. Furthermore, the swing angle of AR-TENG system is closely related to the wave height. Therefore, we can study the influence of wave height on the output performance of AR-TENG system by changing the rotation angle of seesaw. Figures 3B–3D and S16 present the transferred charges, short-circuit current, and the open-circuit voltage of AR-TENG system at the different rotation angle of seesaw, respectively. It is obvious to find that the transferred charges remain at 0.7 μC and do not change with the rotation angle of seesaw. This result is crucial to harvest water-wave energy with the low energy density because the minimum damping coefficient and the reasonable structure design of AR-TENG system can achieve a maximum output performance under a small driving force. Meanwhile, the output performance of AR-TENG system on the seesaw is higher than that on the linear motor because the swing state of the simple pendulum on the seesaw can make AR-TENG system contact more tightly. Therefore, the new structure can also increase the layer of AR-TENG system to further optimize its output performance. Since the velocity of simple pendulum increase with the rotation angle of seesaw, the short-circuit current increases with the rotation angle of seesaw from 90 μA at 5° to 122 μA at 15°. Furthermore, the open-circuit voltage of AR-TENG system almost remains at 66 V. The load current and voltage of AR-TENG system with different resistance are researched at the

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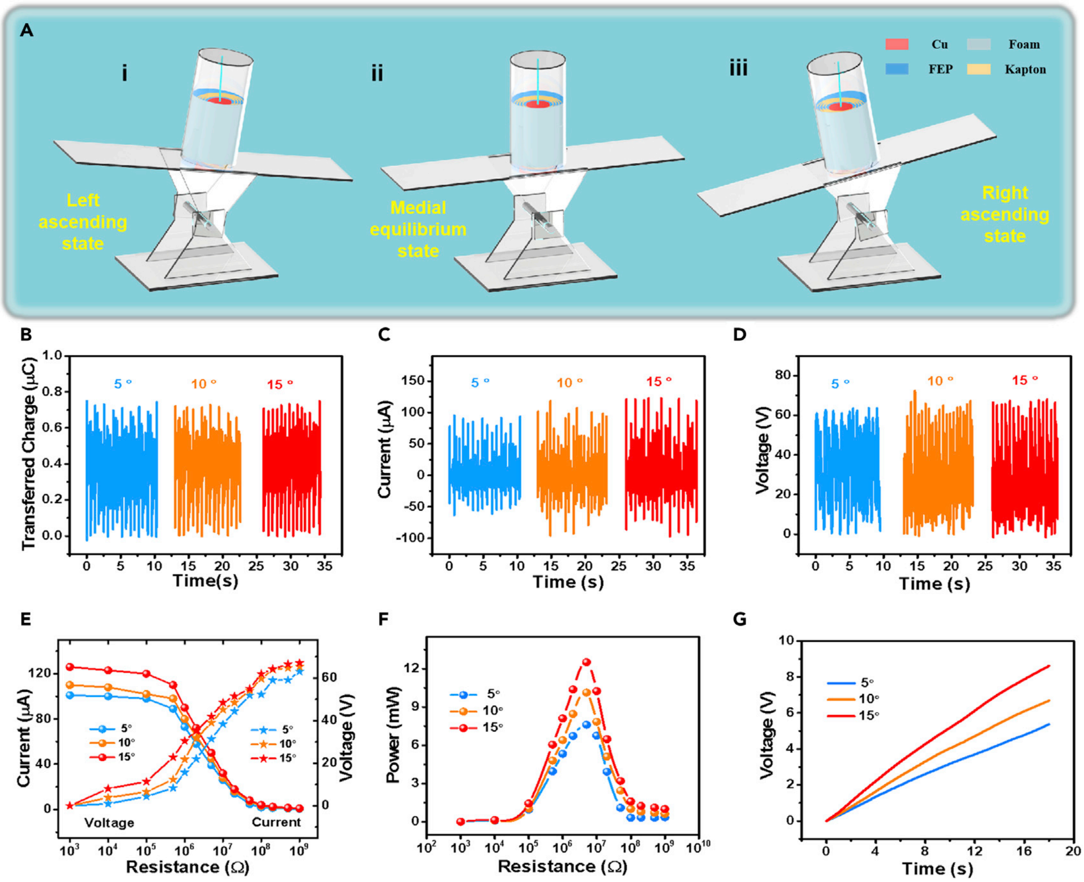

Figure 3. Output performance of AR-TENG system by driven seesaw

(A) Working process of AR-TENG system in full cyclic period.

(B–D) (B) Transferred charges, (C) short-circuit current, (D) open-circuit voltage of AR-TENG system at different rotation angle of seesaw.

(E) Resistance dependency of the output current and voltage of AR-TENG system.

(F) Output peak-power-resistance profiles of AR-TENG system.

(G) The charging curves of AR-TENG system by seesaw for capacitor (4.7 μF).

different rotation angle of seesaw, which includes 5°, 10°, and 15°, respectively (Figure 3E). It displays that the load current of AR-TENG system decreases with the external load-resistance increasing, and the load voltage of AR-TENG system increases with the external load resistance. The peak power of AR-TENG system with the different rotation angle of seesaw is depicted in Figure 3F, the highest power of AR-TENG system increases from 7 to 12.5 mW with the rotation angle of seesaw increasing from 5° to 15°. Furthermore, we also investigate the output performance of AR-TENG system under the different rotation angle of seesaw by charging a capacitor of 4.7 μF (Figure 3G). The corresponding test circuit diagram is identical to Figure S8. Within the working time of 17.5 s, the voltage of capacitor is charged to 5, 6.5, and 8.5 V under the rotation angle of seesaw range from 5° to 15°, respectively. In addition, for the capacitor with higher-rated capacitance (Figure S17), the AR-TENG system can effectively achieve the related charging task at the same driving condition.

Output performance and applications of AR-TENG system in water

In order to demonstrate the output performances of AR-TENG system for harvesting ocean-wave energy, an AR-TENG system device is placed in a water tank to harvest the energy of simulated water wave (Figure 4A). As depicted in Figure 4B and

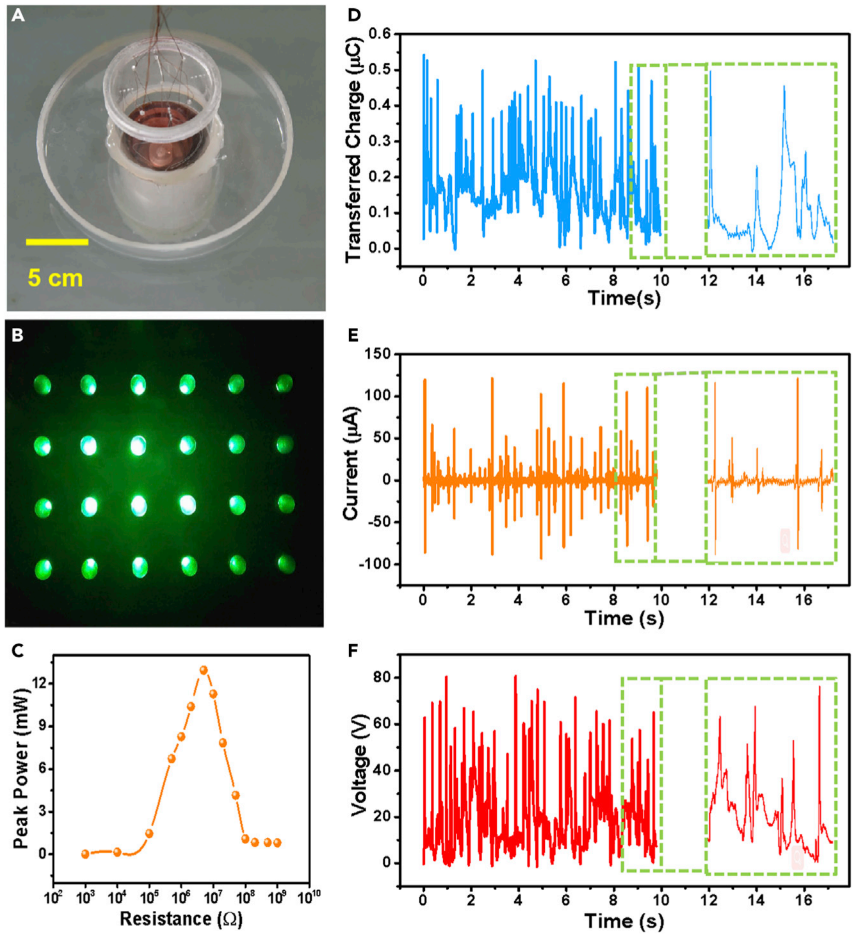

Figure 4. Application and output performance of AR-TENG system in water wave

(A) The photo of AR-TENG system in water tank.

(B) Demonstration of AR-TENG system as a power source to light LEDs array.

(C) Peak-power-resistance profiles of AR-TENG system.

(D–F) (D) Transferred charges, (E) short-circuit current, and (F) open-circuit voltage of AR-TENG system in simulative water waves.

Video S1, the AR-TENG system working in simulating waves can drive 24 green LEDs (rate power of each LED, 45 mW). The LEDs can be lit alternately due to the pulse type alternating current generated by AR-TENG system, and the relative circuit diagram is displayed in Figure S18. In addition, we assemble a self-powered beacon light using AR-TENG and a commercial beacon light, and then tested the system on real water waves in the Huai River near Beijing to verify another potential application of AR-TENG (Figure S19; Video S2). Meanwhile, to verify the ability of AR-TENG to collect the omnidirectional water-wave energy, we marked the top of AR-TENG with a red arrow (Figure S20). It is obvious that the AR-TENG still can achieve the stable output performance under the condition of random change of direction (Video S3). Therefore, it is easy to prove that the AR-TENG can collect omnidirectional water-wave energy. The dependent relationship of peak power with load resistance are presented in the Figure 4C. In the simulated water wave, a peak power of 12.3 mW for the AR-TENG system can be achieved with a matched impedance around 5 MΩ. As displayed in Figures 4D–4F, the transferred charge, short-circuit current, and open-circuit voltage of AR-TENG system are 0.55 μC, 120 μA, and 65 V, respectively. Here, we define the ratio (R_Q) between the transferred charge of TENG in simulated water waves and that in the simulated test as an index to estimate the structure design of TENG for harvesting water-wave energy (Note S6), where a higher ratio indicates a better design of TENG. It is easy to find that the output performance of AR-TENG system in real water-wave is basically consistent with the output performance in seesaw experiment, where the R_Q nearly close to 0.8 (Figure S21). Compared with some previous reported work, it has been significantly improved (Table S1),[20,35–37] indicating the huge advantage of AR-TENG system for harvesting water-wave energy. The reasons for the high ratio of AR-TENG system are as follows: (1) the tumbler structure with large motoring torque in the water wave and that the draft depth of the hemispherical float with the precise design is very beneficial to the power of intercepting the water wave (Figures S22 and S23; Note S7), (2) the active resonance system composed of simple pendulum structure and tumbler structure is conducive to the power capture of PTO in the whole wave-energy-harvesting device (Figure S3 and Note S3), which has been fully verified by the highly consistent signal between the spectrum of water wave and the outputs of AR-TENG system (Figures S24 and S25; Video S3), and (3) the hemispherical float avoids the close contact between TENG and water, thus eliminating the influence of water shielding effect on the TENG output performance. Therefore, compared with the previous random passive resonance TENG, the AR-TENG system can keep the resonance state in the wave with frequency change, thus greatly improving the harvesting efficiency of wave energy. More importantly, comparing the output signal of AR-TENG system with the corresponding water-wave spectrum signal, it can be found that the TENG has multiple signal outputs in a water-wave period.[38] The related reason is that the simple pendulum and the tumbler structure can produce a high-frequency damping motion driven by low-frequency water waves. After the water-wave passes through the AR-TENG system, the high-frequency damping motion will continue to drive the TENG to work. This function of AR-TENG system is also significant to improve the harvesting efficiency of low-frequency ocean-wave energy. In addition, compared with the previous devices that can only harvest wave energy in one or more directions, this work will be a great progress for harvesting ocean wave with omnidirectional motion. Therefore, these results will lay a solid foundation for TENG harvesting ocean-wave energy in large scale.

DISCUSSION

In this work, we design an active resonance triboelectric nanogenerator system (AR-TENG system) to realize the efficient wave-energy harvesting. First, the AR-TENG system can harvest omnidirectional water-wave energy depending on the omnidirectional freedom of pendulum and tumbler structure and the circular structure design of TENG. Second, the resonance system composed of simple pendulum and tumbler structure can effectively harvest the ocean-wave energy with frequency variation. Meanwhile, the high-frequency damping motion of simple pendulum and tumbler structure driven by low-frequency ocean waves can improve the overall efficiency of AR-TENG system in harvesting wave energy. Finally, contributing to simultaneous improvement efficiency of AR-TENG system for energy harvesting in the three stages of the power transfer chain, the ratio of output performance of AR-TENG system between real water-wave test and simulated test is close to 0.8, which has been highly enhanced compared with previous works. Therefore, this work not only play a huge role in promoting the large-scale ocean-wave energy harvesting of TENG but also provide a new scheme to realize self-powered ocean monitoring by integrating TENG with current float technology.

In order to achieve effective water-wave energy collection, it is crucial to improve the power extraction rate of the three stages in the power transfer chain of TENG with wave energy collection. First, in the state of primary interface with intercepted power, the structure and size design of primary interface should fully consider the parameters of wave height, wavelength, and period in the specified sea area to achieve the maximum power interception of the primary interface. Second, for the state of PTO with captured power, the application of PTO with fast mechanical energy storage and slow mechanical energy release function, such as pendulum, spring, and hydraulic equipment, is an important direction of efforts. Finally, as the direct conversion stage of electric energy, the improvement of TENG with the delivered power as much as possible plays a decisive role in the collection of wave energy.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources and materials should be directed to and will be fulfilled by the lead contact, Jie Wang (wangjie@binn.cas.cn).

Materials availability

The materials in this study will be made available on request.

Data and code availability

The published article includes all data generated or analyzed during this study.

For full details, please refer to supplemental experimental procedures.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.joule.2021.04.016.

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AUTHOR CONTRIBUTIONS

C.Z. and J.W. conceived the idea, analyzed the data, and wrote the paper. C.Z. and L.H. designed the structure of AR-TENG system. C.Z. and J.W. optimized the structure of the triboelectric nanogenerators. L.H., L.Z., Y.W., O.Y., X.W., L.L., and Y.L. helped with the experiments. All the authors discussed the results and commented on the manuscript.

DECLARATION OF INTERESTS

C.Z., J.W., and L.Z. hold the Chinese patents (no. ZL201911192196.8). The authors declare no competing interests.

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