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Self-powered sensors driven by Maxwell's displacement current wirelessly provided by TENG

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ABSTRACT

Electrodeless triboelectric nanogenerator (EL-TENG) is a kind of novel TENG that has no metal electrodes and the power is transmitted via Maxwell's displacement current. For a rotation EL-TENG, the power is collected by an induction coil at a vertical distance of 20 cm. A self-powered sensor is demonstrated based on Maxwell's displacement current supplied wirelessly by EL-TENG. Such a design can use one EL-TENG to drive multiple wireless senses for the purposes such as control switches for desk lamps and alarm system. This kind of wireless and self-powered sensor has broad applications in the fields of Internet of Things, big data and artificial intelligence.

1. Introduction

With the rapid development of artificial intelligence (AI) technology, a variety of AI related electronic products have entered people's life. But the energy supply of electronic products is always a key for their sustainable operation. At present, the traditional power supply mode is based on electromagnetic induction, such as hydropower generation, wind power generation and thermal power generation. The generated energy is used to charge batteries, supercapacitors, and then supplied to electronic devices [1–3]. The signal acquisition in the field of Internet of things and big data is inseparable from the support of power supply, and the corresponding wireless charging technology and wireless sensor technology are in urgent need of development. Wireless sensor network (WSN) is one of the key technologies in the emerging fields of artificial intelligence, Internet of things and big data. Fig. 1a shows the relationship between WSN, nanogenerators and Maxwell's displacement current. Maxwell's displacement current is the basic principle of nanogenerators [4,5]. The WSN powered by nanogenerators will make human history enter into a new era of distributed energy. In the Internet of things, distributed energy based on nanogenerators will have advantages over traditional power generation, such as low cost, self-powered and so on [6–9].

Self-powered device based on Triboelectric Nanogenerators (TENGs) technology has become a focused research area [10–13]. At present, there are many reports about self-powered devices [12,14–16]. Such as a self-powered tactile sensor system for touch pad technology [17–19], natural wood-based TENG as self-powered sensing, etc. [20]. Wang has proved theoretically that the second term in Maxwell's displacement current is the source of both TENG and PENG [21,22]. The demonstration of Maxwell's displacement current perfectly affects Maxwell's equations, which is a new advance in physics. It is proposed that nano generator energy system is widely used in the Internet of things, sensor networks, blue energy and even big data, which will affect the development of the world in the future [11,14,22]. Chen et al. invented an electrodeless TENG (EL-TENG), which can generate a three-dimensional Maxwell's displacement field in the space and transmit the electric energy wirelessly via Maxwell's displacement current [23,24]. The newly expanded Maxwell's equations are as follows [21]:

$$\nabla \cdot D' = \rho' \tag{1.1}$$

$$\nabla \cdot \boldsymbol{B} = 0 \tag{1.2}$$

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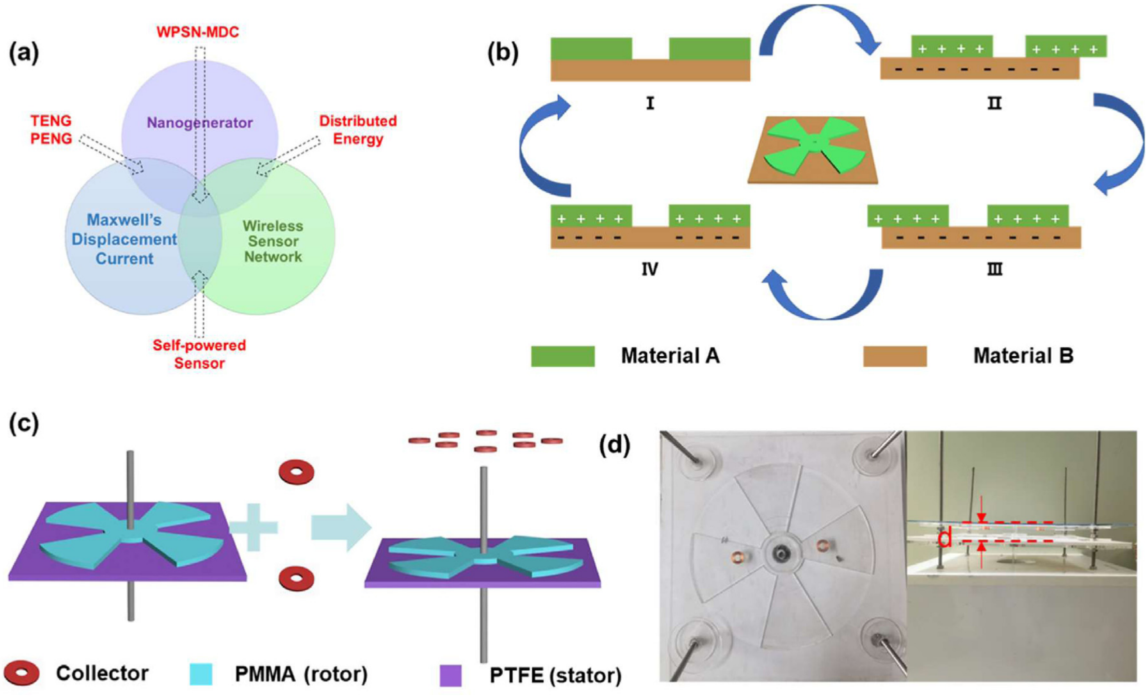


Fig. 1. (a) Relationship diagram among nanogenerator, Maxwell's displacement current and wireless sensor network. (b) Working principle of EL-TENG. (c) The diagram of experimental model. (d) In-kind image of EL-TENG.

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} \tag{1.3}$$

$$\nabla \times \boldsymbol{H} = \boldsymbol{J}' + \frac{\partial \boldsymbol{D}'}{\partial t} \tag{1.4}$$

$$\boldsymbol{D} = \varepsilon_0 \boldsymbol{E} + \boldsymbol{P} + \boldsymbol{P}_s, \tag{1.5}$$

where $\boldsymbol{P}_S$ is added in displacement vector $\boldsymbol{D}$ by Wang [21], which is mainly due to the existence of the surface charges that are independent of the presence of electric field. and

$$\boldsymbol{D}' = \varepsilon_0 \boldsymbol{E} + \boldsymbol{P} \tag{1.6}$$

the volume charge density and the density of current density can be redefined as

$$\rho' = \rho - \nabla \cdot \boldsymbol{P}_s \tag{1.7}$$

$$\boldsymbol{J}' = \boldsymbol{J} + \frac{\partial \boldsymbol{P}_s}{\partial t} \tag{1.8}$$

In Eq. (1.8), the term that contributes to the output current of TENG is related to the driving force of $\frac{\partial \mathbf{P}_s}{\partial t}$, which is simply named as the *Wang term* in the displacement current. In Eq. (1.8), the $\boldsymbol{J}$ is the conduction current that is observed at the external circuit of TENG, and $\frac{\partial \mathbf{P}_s}{\partial t}$ is the displacement current observed at the inner circuit of TENG. Both of them meet at the electrodes to form a complete loop for current transport.

Herein, we present a newly designed EL-TENG that utilizes the relative rotation between polypropylene (PTFE) plate and polymethylmethacrylate (PMMA) sectors to achieve wireless energy transmission and sensor from the time-varying electric displacement field based on Maxwell's displacement current $\frac{\partial \mathbf{P}_s}{\partial t}$. The coil is used as the wireless energy collector of EL-TENG and wireless sensor signal collector. The device can generate energy, which be stored in capacitors to power microelectronic devices. When the transmission distance is 5 cm, the single coil can maintain a stable voltage of 19 V and a current of 0.3 μA. And the surrounding environment, such as humidity, temperature, barrier material or "a low energy consumption", has little effect on output of EL-TENG. In addition, this work makes it sensing signal in combination with traditional wireless circuit modules to build a wireless self-powered sensor network based on Maxwell's displacement current and nanogenerators (WPSN-MDC). WPSN-MDC based on EL-TENG combines the wireless energy transmit and wireless sensor for the first time, and both are used as wireless self-powered sensor signals to realize the function of one source and multiple senses and the switch control of desk lamp, alarm system, etc. This is of great significance to the further research of artificial intelligence and the Internet of Things.

2. Results and discussions

Any two different materials that rub against each other will have a static charge. Most of TENGs conducts Maxwell's displacement current through metal electrodes and wires, by conjugation of triboelectrification and electrostatic induction. The construction of EL-TENG makes a qualitative leap from wire to wireless for Maxwell's displacement current transmission. Fig. S1 shows the assembly process of EL-TENG. It can be constructed by laser cutting and physical assembly. Fig. 1b and c shows the working principle and structure diagram of EL-TENG. It consists of a stator and a rotor, which are different materials, and both of them are polymer materials, but not metal. In this work, we choose acrylic (PMMA), a kind of cheap commercial material, as the rotor, and polytetrafluoroethylene (PTFE) is chosen to be the stator. Fig. 1d shows the picture of EL-TENG. When the rotor rubs against the stator, it generates triboelectric charges, which creates a three-dimensional Maxwell's displacement field in space. Maxwell's displacement currents can be collected by the collector which placed around EL-TENG.

Fig. 2a shows the potential distribution in the friction surface simulated by COMSOL, when the rotor and the stator are rubbed,

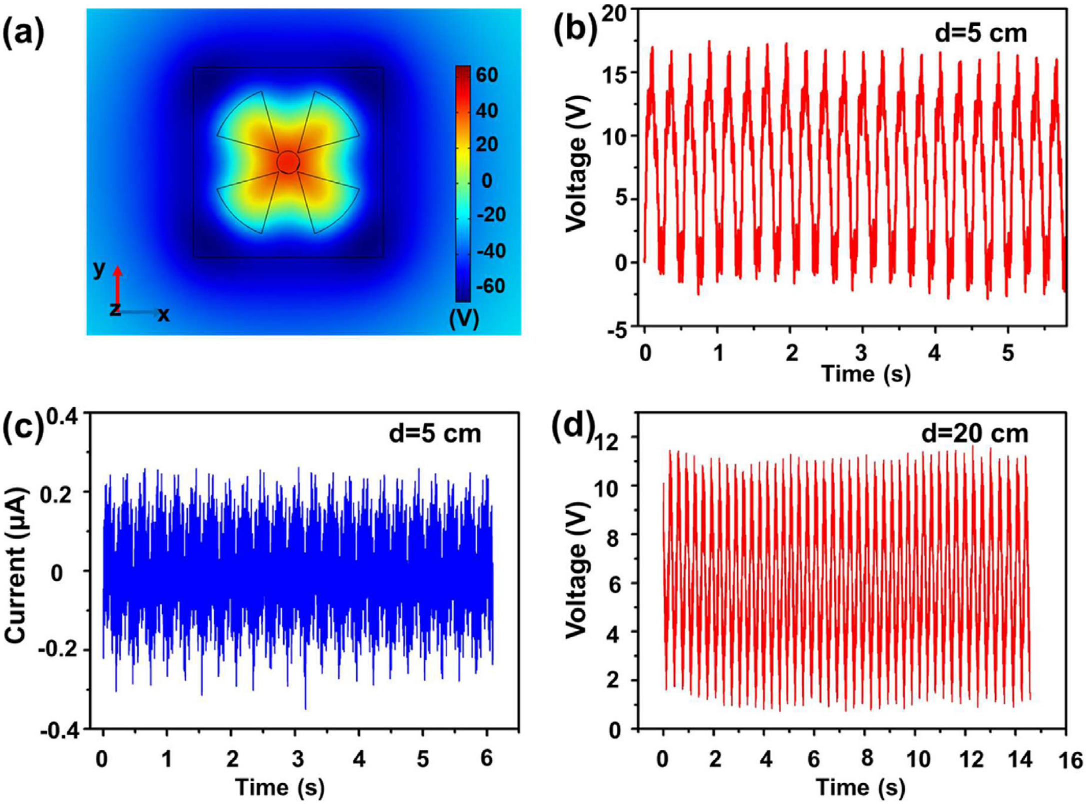


Fig. 2. (a) Simulation of the potential distribution in the rotational triboelectrication between PMMA and PTFE. The output performance of EL-TENG when the wireless transmission distance is 5 cm. (b) the output voltage of EL-TENG. (c) The output current of EL-TENG. (d) The output voltage of EL-TENG when the wireless transmission distance is 20 cm.

they will carry a large amount of triboelectric charge and form the induced potential. Here, we use a pair of collectors (two coils) to collect the Maxwell's displacement currents generated by EL-TENG wirelessly. Fig. 2b and c show the open circuit voltage and short current of the EL-TENG when the distance of Z-axis is 5 cm. As we can see, the voltage is 19 V while the current is 0.3 μA. To explore the performance of the collector over long distances, we tested the voltage performance of the collector when the transmission distance is 20 cm. Fig. 2d shows that the voltage received at the collector is about 10 V. The distance is quadrupled and the output is reduced by 47%.

For sensors, especially self-powered sensors, the stability of performance is extremely important. Therefore, several environmental factors were used as a single variable to investigate the influence of environmental factors on the stability of EL-TENG. First, the stator and the rotor are rubbed against each other for 10 s. Then, they are separated to make the rotor idle, the triboelectric charges accumulated on the surface of the rotor can still be collected wirelessly. What's more, the dependence of external mechanical energy is reduced to realizes a "low energy consumption" (LEC) working mode (Fig. 3a). Fig. 3b shows the voltage of LEC working mode is similarly to the previous one. And Fig. 3c shows the stability of the collector's voltage within 2 min. We can see that the voltage of the collector has basically remained unchanged and the stability is good. In addition, we also tested the effect of temperature on the output performance of EL-TENG. Set 25 °C as the initial temperature, and the collector voltage is V_0. When the temperature changes, the instantaneous voltage of the collector is V_t. As Shown in the Fig. 3d, when the temperature changes from 25 to 50 °C, V_t / V_0 is always stable between 0.9 and 1. Considering the error of the test instrument, the temperature actually has a very small effect on the output of the EL-TENG.

Similarly, the influence of humidity in the environment on the output performance of EL-TENG is also very important. We tested the voltage of the collector ($H = 10$ cm) of the transmission medium (air) under different humidity conditions. Fig. 3e shows that with the change of humidity, the value of V_t / V_0 shows an unstable trend. When the humidity increases to a certain value, the voltage shows a decreasing trend. In the external environment, when an interfering object passes through the transmission medium, it may also have an impact on the transmission performance (such as the traditional electromagnetic wireless transmission model). So, we have studied several different common objects for impact of transmission performance. Fig. 3f shows that when A4 paper is placed between EL-TENG and the collector, the value of V_t / V_0 does not change much, so the appearance of external objects has little effect on the output performance of EL-TENG. For FEP, PTFE, sandpaper and other objects, the conclusion is the same.

The Maxwell's displacement current collected by EL-TENG wirelessly can be used for two applications. The first is to use it as a power supply. The Maxwell's displacement current is collected wirelessly to directly power the microelectronic equipment or stored in an energy storage device to power the microelectronic equipment. In addition, Maxwell's displacement current can also be used as a sensing signal, which is set as a trigger signal and combined with traditional electronic modules to build a novel type of wireless sensor without external-power. As shown in the Fig. 4a, when the transmission distance is 5 cm and the rotor rotation speed is 100 r min^{-1} (unless otherwise specified, the data are measured under this condition), the voltage of the collector can light up 5 LEDs. (When the transmission distance is 20 cm, the voltage of collector can also light up 3 LEDs.) The collected Maxwell's displacement current can also be stored in capacitors to power microelectronic devices (Fig. 4b). In addition, the effect of

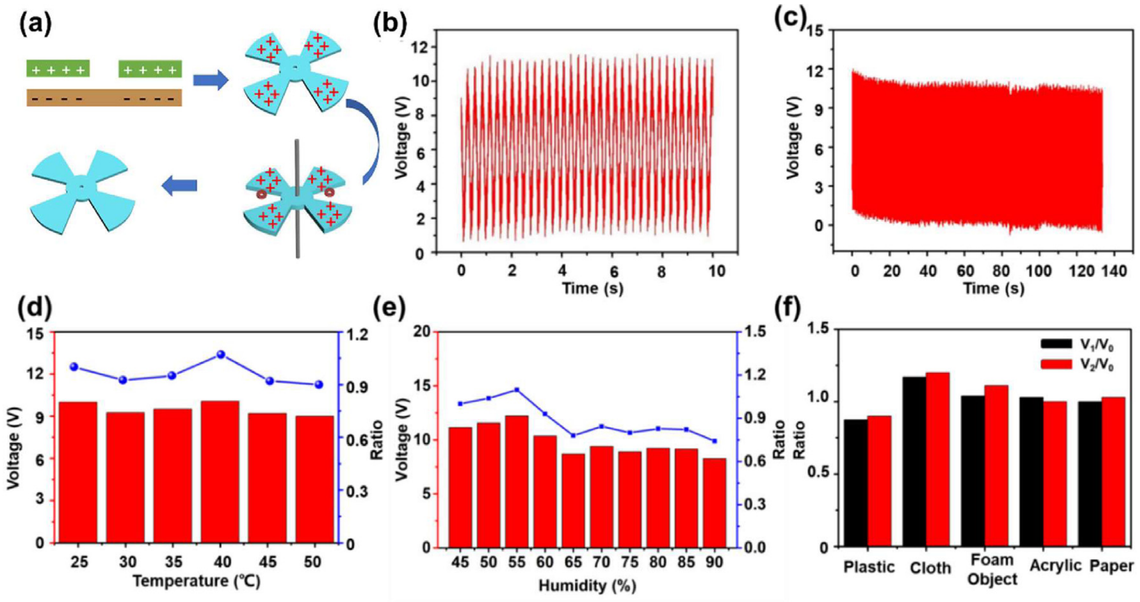


Fig. 3. The performance testing of EL-TENNG. (a) The stability output of EL-TENG in the “low energy consumption” working mode. (b) The output voltage of EL-TENG when the when the wireless transmission distance is 20 cm in the “low energy consumption” working mode. (c) The output voltage of EL-TENG within 2 min in the “low energy consumption” working mode. (d) The influence of temperature on the output performance of EL-TENG. (e) The influence of humidity on the output performance of EL-TENG. (f) The influence of interfering objects on the output performance of EL-TENG.

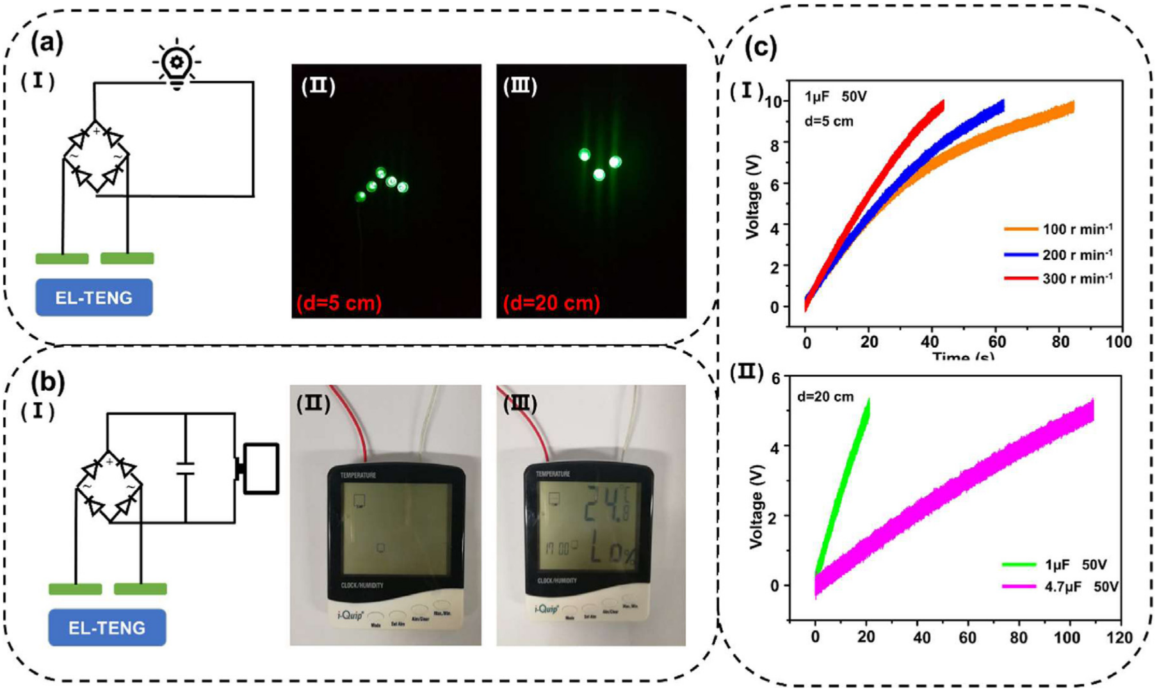
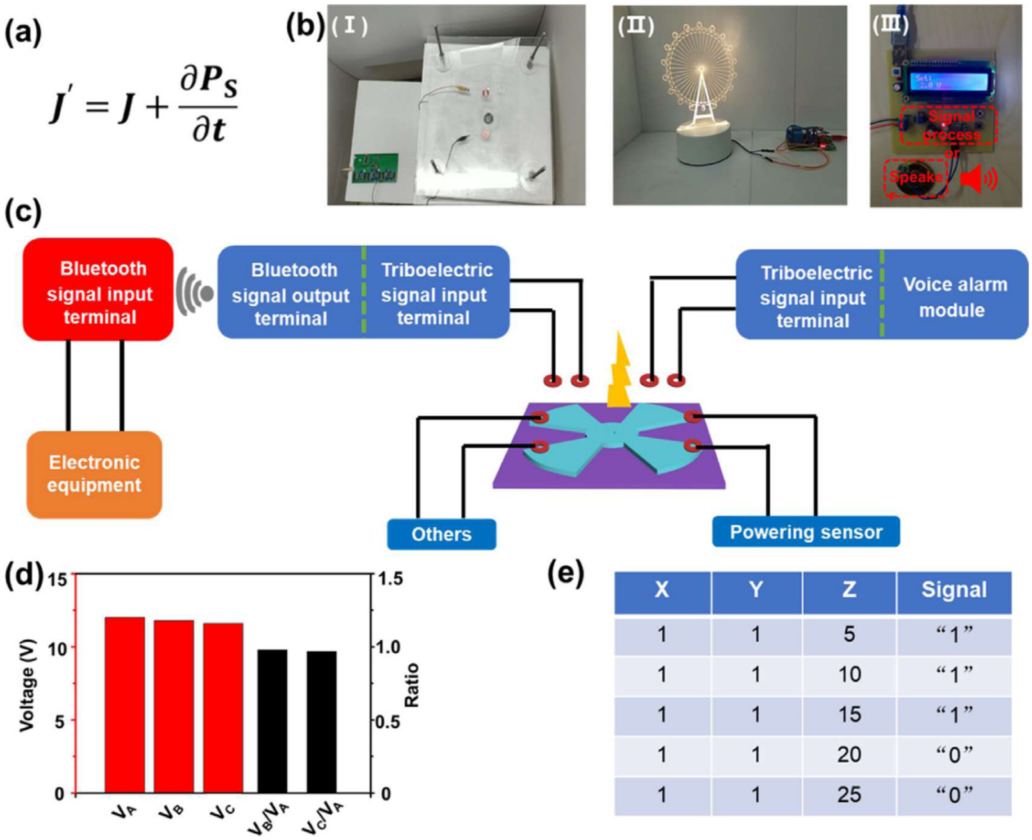


Fig. 4. The direct power supply application of EL-TENG. (a) The direct power supply circuit diagram of EL-TENG (I). EL-TENG lights LEDs at a wireless transmission distance of 5 cm (II) and 20 cm (III). (b) The collected Maxwell’s displacement current can also be stored in capacitors to power microelectronic devices. (c) Characterization of the charging behavior of EL-TENG. (I) Charging curve of EL-TENG to a 1 μF 50 V capacitor with different rotation speeds at a wireless transmission distance of 5 cm. (II) The charging curve of EL-TENG with 300 r min^{-1} for 1 μF 50 V at a wireless transmission distance of 20 cm.

different rotation speeds on the charging curve has also been studied. (See Fig. S2 in the supporting information.) When the speed increases, the voltage increases slightly, and then maintains a relatively stable state. Figs. 4c and S3 shows that as the rotor rotation speed increases, the charging speed of the capacitor by EL-TENG gradually increases. In fact, the effect of the rotation speed on the voltage of the EL-TENG collector is very small, especially when the number of collectors is small. Therefore, the effect of the rotation speed on the charging speed mainly lies in the frequency of collecting voltage. According to the traditional rotary TENG structure model, it can be known that the higher the rotation speed, the higher the frequency of the voltage. So, in a fixed time, the higher the voltage frequency, the faster the charging speed. The electrical energy stored in capacitors can be used to power microelectronic devices, such as thermometers, hygrometers, microelectronic watches and so on.

Connecting the collector to traditional wireless sensors can combine two items in Eq. (1.8) to form a self-powered wireless



X	Y	Z	Signal
1	1	5	“1”
1	1	10	“1”
1	1	15	“1”
1	1	20	“0”
1	1	25	“0”

Fig. 5. (a) The current observed in TENG. The ***J*** is the conduction current that is observed at the external circuit of TENG, and $\frac{\partial \mathbf{P}_s}{\partial t}$ is the displacement current observed at the inner circuit of TENG. Both of them meet at the electrodes to form a complete loop for current transport. (b) Schematic diagram of wireless control system based on EL-TENG. (c) (I) Bluetooth control switch based on El-TENG, (II) signal receiving device and working desk lamp, (III) wireless voice alarm module based on EL-TENG. (d) The voltage and the ratio of EL-TENG with three sets of collectors working simultaneously. (e) The wireless logic signal of device based on Maxwell's displacement current.

sensor (Fig. 5a and b). When EL-TENG works, the Maxwell's displacement current generated can be wirelessly transmitted to the collector, and then entered into the electrical signal receiver for signal judgment. When the input signal doesn't reach the threshold, there will be no next operation. When the signal exceeds the threshold, the Bluetooth transmission module will be triggered to perform the wireless sensing work in the next stage. Fig. 5c (I and II) shows the wireless switch control based on EL-TENG. The wireless transmission distance of EL-TENG is 20 cm, and let it combine with the Bluetooth control system, the remote console light can be switched on and off. When the voltage reaches the threshold voltage, it will trigger the Bluetooth control switch and light up the lamp. Turn off the EL-TENG and turn on it again, the voltage reaches the threshold voltage, it will trigger the Bluetooth control switch and close the lamp. (The video S1 shows the work process of wireless Bluetooth control switch in supporting information.) The same as the temperature and humidity meter in the Fig. S4. In addition, we also designed a wireless voice alarm based on Maxwell displacement current (Fig. 5b). It is a special voice alarm module, which is mainly composed of signal receiver and voice alarm trigger device. As shown in Fig. 5c (III), when the Maxwell displacement current generated by EL-TENG is wirelessly transmitted to the voice alarm module as triboelectric signal, the alarm behavior will be generated. The signal receiver can set a threshold value V_t according to the requirements of application scenarios. When the collector collects voltage $V \geq V_t$, it can trigger the voice alarm device, but when $V < V_t$, it will not trigger the voice alarm device. (The video S2 shows the work process of wireless voice alarm module in supporting information.)

Based on the working mode of EL-TENG and the structure principle of the collector, we tested the collection ability of the collector at different coordinate points on the same plane in three-dimensional space. When a certain XY plane in the Z-axis direction is set as a fixed plane, new collectors are gradually added to different coordinate points to affect the wireless collection capability of the initial collector. Taking EL-TENG's rotor center as the coordinate origin, three sets of wireless collectors are set at A:(1, 1, 20), (−1, −1, 20), B: (2, 2, 20), (−2, −2, 20) and C: (3, 3, 20), (−3, −3, 20). Fig. 5d shows that when the number of collectors increases, V_A, V_B and V_C are about 12 V, 11.8 V and 11.6 V respectively. With the increase of the number of collector groups, the voltage of wireless collector does not change much, V_B / V_A and V_C / V_A are 0.98 and 0.97, respectively. We can use this feature of EL-TENG to build a WPSN-MDC. Set up multiple sets of collectors in the EL-TENG based wireless transmission system, and connect it to different sensor devices, including single sensors, multi-function sensors, wired sensors, and wireless sensors, it also contains energy storage device and microelectronics (Fig. 5b).

Using this special property of WPSN-MDC, a novel logic device was designed. Multiple sets of signal receivers are set simultaneously in the Z-axis direction of EL-TENG, and each one of them is set to the same threshold. Here, two coils are set at a single coordinate point as a group of collectors. When EL-TENG works, the voltage collected by collectors at different coordinate positions is different. Here, we define the logic signal of the signal receiver as “1” when the voltage signal is greater than or equal to the threshold, otherwise it is “0”. As shown in Fig. 5e, different logic symbols will appear on different three-dimensional coordinate points, so that a novel logic device based on WPSN-MDC is be constructed. This logic device will open a new direction for the integration of multi-functional self-powered sensors and self-powered logic devices in the field of Internet of Things.

3. Conclusion

In this work, a wireless transmission system based on EL-TENG has been established. It does not require a specially designed collector, and only requires a commercial coil to collect the Maxwell's displacement current wirelessly. EL-TENG still has a good output performance and stability when the wireless transmission distance is at 20 cm, and its voltage reaches 10 V. It can stably power low-power devices, such as LED lights, commercial capacitors, thermometers. After the rotor is rubbed for 10 s and then idling, it can produce a stable output. What's more, the impact of ambient temperature and foreign objects on its output performance is relatively small. In addition, the application of wireless self-powered sensors based on Maxwell's displacement current is studied. One is a wireless control switch and the other is a voice alarm device. At a distance of 20 cm, the coil can effectively receive the Maxwell's displacement current signal and realize remote control of desk lamp by combining the Bluetooth module. In this study, both of the Maxwell displacement current expressions are used as wireless sensing means, and the two are coupled for wireless sensing. The research results show that EL-TENG can be designed and constructed into a stable wireless self-powered sensor network, which has broad application prospects in AI, Internet of Things and big data.

4. Experimental section

4.1. Preparation of EL-TENG

PMMA (thickness: 0.5 cm) and PTFE (thickness: 0.5 cm) were cut into fan shape and square shape with a laser cutter, a circular hole with a diameter of 1 cm and a diameter of 3 cm was cut at the center of them. The stator and rotor were assembled by a cylindrical acrylic rod with a diameter of 1 cm. Finally, two commercial coils were placed above the rotor as the two collecting electrodes of the collector.

4.2. Measurement and characterizations

The electrical outputs of the EL-TENG were measured, collected and analyzed by an electrometer (Keithley 6514, TEKTRONIX, INC) with computer measurement software written by LabVIEW.

Supporting Information

Supporting Information is available from the online library or from the author.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Yuanming Zeng: Data curation, Formal analysis, Writing – original draft, Investigation. **Yu Cheng:** Data curation, Formal analysis, Visualization, Investigation. **Jiaqing Zhu:** Data curation, Formal analysis, Visualization, Investigation. **Yang Jie:** Visualization, Investigation. **Ping Ma:** Visualization, Investigation. **Hao Lu:** Visualization, Investigation. **Xia Cao:** Conceptualization, Supervision, Resources, Writing – review & editing. **Zhong Lin Wang:** Supervision, Writing – review & editing.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.apmt.2022.101375.

References

[1] N. Nitta, F.X. Wu, J.T. Lee, G. Yushin, Li-ion battery materials: present and future, Mater. Today 18 (2015) 252–264.

[2] H.Y. Chen, M. Armand, M. Courty, M. Jiang, C.P. Grey, F. Dolhem, J.M. Tarascon, P. Poizot, Lithium salt of tetrahydroxybenzoquinone: toward the development of a sustainable Li-ion battery, J. Am. Chem. Soc. 131 (2009) 8984–8988.

[3] B.E. Conway, Transition from supercapacitor to battery behavior in electrochemical energy-storage, J. Electrochem. Soc. 138 (1991) 1539–1548.

[4] J.J. Shao, M. Willatzen, T. Jiang, W. Tang, X.Y. Chen, J. Wang, Z.L. Wang, Quantifying the power output and structural figure-of-merits of triboelectric nanogenerators in a charging system starting from the Maxwell's displacement current, Nano Energy 59 (2019) 380–389.

[5] J.J. Shao, M. Willatzen, Z.L. Wang, Theoretical modeling of triboelectric nanogenerators (TENGs), J. Appl. Phys. 128 (2020) 111101.

[6] Z.L. Wang, Entropy theory of distributed energy for internet of things, Nano Energy 58 (2019) 669–672.

[7] H.X. He, T.M. Zhao, H.Y. Guan, T.Y. Zhong, H. Zeng, L.L. Xing, Y. Zhang, X.Y. Xue, A water-evaporation-induced self-charging hybrid power unit for application in the Internet of Things, Sci. Bull. 64 (2019) 1409–1417.

[8] X. Zhao, Z. Kang, Q.L. Liao, Z. Zhang, M.Y. Ma, Q. Zhang, Y. Zhang, Ultralight, self-powered and self-adaptive motion sensor based on triboelectric nanogenerator for perceptual layer application in Internet of things, Nano Energy 48 (2018) 312–319.

[9] C.K. Qiu, F. Wu, Q.F. Shi, C.K. Lee, M.R. Yuce, Sensors and control interface methods based on triboelectric nanogenerator in IoT applications, IEEE Access 7 (2019) 92745–92757.

[10] F.R. Fan, Z.Q. Tian, Z.L. Wang, Flexible triboelectric generator!, Nano Energy 1 (2012) 328–334.

[11] Z.L. Wang, Self-powered nanosensors and nanosystems, Adv. Mater. 24 (2012) 280–285.

[12] F.R. Fan, L. Lin, G. Zhu, W.Z. Wu, R. Zhang, Z.L. Wang, Transparent triboelectric nanogenerators and self-powered pressure sensors based on micropatterned plastic films, Nano Lett. 12 (2012) 3109–3114.

[13] J.Y. Chang, H. Meng, C.S. Li, J.M. Gao, S.Q. Chen, Q. Hu, H. Li, L. Feng, A wearable toxic gas-monitoring device based on triboelectric nanogenerator for self-powered aniline early warning, Adv. Mater. Technol. 5 (2020) 1901087.

[14] H.L. Zhang, J. Wang, Y.H. Xie, G. Yao, Z.C. Yan, L. Huang, S.H. Chen, T.S. Pan, L.P. Wang, Y.J. Su, W.Q. Yang, Y. Lin, Self-powered, wireless, remote meteorologic monitoring based on triboelectric nanogenerator operated by scavenging wind Energy, ACS Appl. Mater. Interfaces 8 (2016) 32649–32654.

[15] L. Liu, W. Tang, C.R. Deng, B.D. Chen, K. Han, W. Zhong, Z.L. Wang, Self-powered versatile shoes based on hybrid nanogenerators, Nano Res. 11 (2018) 3972–3978.

[16] H.M. Chen, C. Xing, Y.L. Li, J. Wang, Y. Xu, Triboelectric nanogenerators for a macro-scale blue energy harvesting and self-powered marine environmental monitoring system, Sustain. Energy Fuels 4 (2020) 1063–1077.

[17] Y. Yang, H.L. Zhang, Z.H. Lin, Y.S. Zhou, Q.S. Jing, Y.J. Su, J. Yang, J. Chen, C.G. Hu, Z.L. Wang, Human skin based triboelectric nanogenerators for harvesting biomechanical energy and as self-powered active tactile sensor system, ACS Nano 7 (2013) 9213–9222.

[18] S.Y. Zhang, S.B. Li, Z.Z.L. Xia, K.Y. Cai, A review of electronic skin: soft electronics and sensors for human health, J. Mater. Chem. B 8 (2020) 852–862.

[19] Y.M. Liu, L. Zhao, L.Y. Wang, H.X. Zheng, D.F. Li, R. Avila, K.W.C. Lai, Z.K. Wang, Z.Q. Xie, Y.L. Zi, X.E. Yu, Skin-integrated graphene-embedded lead zirconate titanate rubber for energy harvesting and mechanical sensing, Adv. Mater. Technol. 4 (2019) 1900744.

[20] S.F. Hao, J.Y. Jiao, Y.D. Chen, Z.L. Wang, X. Cao, Natural wood-based triboelectric nanogenerator as self-powered sensing for smart homes and floors, Nano Energy 75 (2020) 104957.

[21] Z.L. Wang, On Maxwell's displacement current for energy and sensors: the origin of nanogenerators, Mater. Today 20 (2017) 74–82.

[22] Z.L. Wang, On the first principle theory of nanogenerators from Maxwell's equations, Nano Energy 68 (2020) 104272.

[23] Y.D. Chen, Y. Jie, N. Wang, Z.L. Wang, X. Cao, Novel wireless power transmission based on Maxwell displacement current, Nano Energy 76 (2020) 105051.

[24] X. Cao, M. Zhang, J.R. Huang, T. Jiang, J.D. Zou, N. Wang, Z.L. Wang, Inductor-free wireless energy delivery via maxwell's displacement current from an electrodeless triboelectric nanogenerator, Adv. Mater. 30 (2018) 1704077.