Materials Today • Volume xx, Number xx • xxxx xxxx RESEARCH

ELSEVIER

Water wave energy harvesting and self-powered liquid-surface fluctuation sensing based on bionic-jellyfish triboelectric nanogenerator

RESEARCH: Original Research

Bao Dong Chen [1,2,†], Wei Tang [1,2,†], Chuan He [1,2], Chao Ran Deng [1,2], Lei Jing Yang [1,2], Lai Pan Zhu [1,2], Jian Chen [1,2], Jia Jia Shao [1,2], Long Liu [1,2], Zhong Lin Wang [1,2,3,*]

[1] Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, Beijing 100083, China
[2] CAS Center for Excellence in Nanoscience, National Center for Nanoscience and Technology (NCNST), Beijing 100190, China
[3] School of Material Science and Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA

Due to the natural working mechanism of triboelectric nanogenerators (TENGs), potential energy stored by elastic materials may not be effectively converted into electric power, post mechanical triggering. Here, we report a practical bionic-jellyfish triboelectric nanogenerator (bjTENG) with polymeric thin film as the triboelectric material, which is shape-adaptive, with a hermetic package and a unique elastic resilience structure, similar to the behavior of a jellyfish. The charge separation in the elastic resilience of this bionic-structure is based on the liquid pressure-induced contact-separation of the triboelectric layers. On the basis of the conjunction of the triboelectrification and the electrostatic induction, a sustainable and enhanced output performance of 143 V, 11.8 mA/m^2 and 22.1 μC/m^2 under a low frequency of 0.75 Hz and at a water depth of 60 cm is produced, which can be used to supply power for dozens of green LEDs or a temperature sensor directly. More significantly, bjTENG is believed to be a priority technology which is attributable to its highly sensitivity, portability, and suitability for continuous detection of water level and fluctuation. Furthermore, a wireless self-powered fluctuation sensor early-warning system, which provides exact and wireless monitoring of fluctuation of a liquid surface, is also successfully developed.

1. Introduction

Triboelectric nanogenerators (TENGs) based on triboelectrification and electrostatic induction have been extensively investigated for effectively converting arbitrary mechanical energy from ambient environment [1–3]. TENG is not only a new energy, but also an energy technology for the new era – the era of internet of things. Recently, various types of TENGs have been developed for harvesting ocean wave energy [4–10]. Compared to traditional electromagnetic generator, TENG has the incompatible efficiency for harvesting low-frequency (<3 Hz) wave energy [11–13], so that it has unique applications for exploration of blue energy, which has the potential of making a huge contribution to sustainable energy for the world.

To efficiently capture water wave energy, the TENG needs to be incorporated into a watertight and rigid float, so that the structural design is a key factor to meet the complexity of marine environment supply conditions and to improve its output power by the optimal structure of the TENG-NW [14–17]. Effort has been devoted in this direction in the past 3 years based on four basic modes of TENG, for example, mechanical amplifier-assisted [18], integrated [19], multi-layered disc [20], freestanding-triboelectric-layer based [21], multifunctional [22] and single-spring resonator based [23] etc. [24–28]. However, these TENG devices have limited structural design, confined hermetic package and restricted resilient ability which cannot satisfy the requirements imposed by the rapid growth of water wave energy

* Corresponding author at: School of Material Science and Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA.
E-mail address: zlwang@gatech.edu (Z.L. Wang).
† These authors contributed equally to this work.

1369-7021/© 2017 Published by Elsevier Ltd. https://doi.org/10.1016/j.mattod.2017.10.006

Please cite this article in press as: B.D. Chen et al., , (2017), https://doi.org/10.1016/j.mattod.2017.10.006

harvesting, particularly at the liquid-surface fluctuation sensing technology undersea.

Here, inspired by biology, we presented an innovative prototype of bionic-jellyfish triboelectric nanogenerator (bjTENG), composed of polydimethylsiloxane (PDMS) as the hermetic package, polymeric nanocomposite thin film as the tribomaterial and metal electrodes. bjTENG possesses the advantages of waterproof and adaptive shape. It outputs a sustainable and enhanced performance of 143 V, 11.8 mA/m^2 and 22.1 μC/m^2 under low frequency of 0.75 Hz and a depth of 60 cm is produced, which can be used to supply power for dozens of green LEDs or a temperature sensor directly. Based on the shape-adaptive, hermetic package and a unique elastic resilience structure, bjTENG is believed to be a priority technology which is attributable to its highly sensitivity, portability, and suitability for continuous detection of water level and fluctuation. Furthermore, a wireless self-powered fluctuation sensor early-warning system, which provides exact and wireless monitoring of fluctuation of liquid surface, is also successfully developed. This work opens up new opportunities for wave energy harvesters and self-powered sensors by mimicking the structural design, fluid dynamics and wave mechanics.

2. Material and methods

The hermetic package PDMS cover was molded by injection technology according to the unique structure of bionic design, and the connection was stuck through an elastic adhesive polymer. The PTFE thin films were prepared by spin-coating process, in this experiment; the PTFE aqueous emulsion (Teflon DISP40, DuPont) contained both the solid granule and the liquid dispersant with the weight ratio of 3:2. Scanning electron microscopy (SEM) images of the PTFE thin film's morphology and microstructure are shown in Fig. 1. Subsequently, we utilized the PTFE thin film to construct a bjTENG, where one part comprises of PTFE film, aluminum electrode, cuprum electrode, and the package of PDMS. The PTFE film serves as the tribomaterial, and the cuprum electrode serves as the electrode connected with the external load. bjTENG's counter parts are aluminum electrodes, which are also utilized to contact with PTFE films. The electrical output signals of bjTENGs were measured by a Keithley voltage preamplifier and a Data Acquisition Card.

3. Results and discussion

3.1. The structure and fabrication process of bjTENG

The bjTENG is schematically illustrated in Fig. 1a, the basic unit consists of a multilayered TENG inside and a hermetic package outside, which is made of PDMS (Fig. 1b). The detailed fabrication process presented in Fig. 1c, d shows an optical picture of the bjTENG (length, 50 mm; width, 40 mm; height, 10 mm). The hydrophobicity and resilient ability of bjTENG were characterized, as shown in Fig. 1e and f. The static contact angle of the PDMS package surface was measured by a sessile droplet method with 1 ml water droplet. Fig. 1e is the contour of the droplet, which indicates a contact angle of 127° by the Young–Laplace fitting. The hydrophobicity of the PDMS package surface assures its self-cleaning property, which can effectively keep the device from water. Fig. 1f shows a combo photograph of bjTENG pressed under a finger; the fabricated bjTENG shows great resilient ability, making it possible to detect water level and fluctuation with high sensitivity, not just from press but also from a slight deformation. Fig. 1g and h shows SEM images of the prepared PTFE thin film, as the triboelectric-layer of bjTENG has a thickness of about 20 μm.

3.2. Workplace scenario, working condition and operating mechanism of bjTENG

The use of bjTENG is extensive, e.g. attaching it to various positions of hulls harvests water wave energy and senses liquid-surface fluctuation from the vast oceans, as indicated in Fig. 2a. Fig. 2b–d presents the working condition across and under the sea. The operating mechanism and numerically calculated electrical potential distribution of bjTENG are presented in Fig. 2e. The operating mechanism is based on the contact-separation model in which four typical states are involved. At the initial state i, both sides of PTFE film and aluminum electrode are in contact and there is no current flow or electrical potentials. Due to different surface electron affinities, the charges will be transferred from the aluminum electrode surface to the PTFE film surface, leaving net positive charges on the aluminum electrode surface and net negative charges on the PTFE film surface. When PTFE film/aluminum electrode is close to the copper electrode (state ii) and contact (state iii), the resulting charge separation will induce positive potential on the copper electrode, positive charges will be driven from aluminum electrode to copper electrode. At the maximum contact area (state iii), the open-circuit potential on the electrode will reach its maximum value. When the contact area decreases as the PTFE film/aluminum electrode moves in the direction opposite to the copper electrode (state iv), the positive open-circuit potential on the electrode will decrease while positive charges will flow from the copper electrode to the aluminum electrode under short-circuit condition, forming a reverse current in the load. To theoretically predict the distribution of the electrical potential from both sides of aluminum electrode and between they for the copper electrode, COMSOL software that employs the finite element method was implemented. At the starting point as shown in Fig. 2e (i), the calculated electrical potential difference between the two electrodes is zero (state i). Then, a potential is generated to keep the charge balance (state ii), state iii and state iv, as shown in Fig. 2e (ii–iv) according to simulation.

3.3. Interfacing bjTENG and self-powered fluctuation sensor

When bjTENG is worked in an air–water interface, it senses the liquid-surface fluctuation by the pressure changes on an air–water interface; this working process is shown in Fig. 3a. Fig. 3b and c is the output performance of the interface bjTENG. The output current at different frequencies is shown in Fig. 3b. The output current of the interface bjTENG steadily increased from 0.7 to 2.3 μA with the increasing of the frequency from 0.25 to 2.25 Hz. The open-circuit voltage, short-circuit current and transfer charge quantity of interface bjTENG are shown in Fig. 3c. They all show an approximately linearly increasing trend, with the increase in frequency the output electrical signals increased up to 5.8 V, 1.7 μA and 6 nC at a frequency of 2.25 Hz (Fig. S1). As shown in Fig. 3d, the bjTENG was constructed

Please cite this article in press as: B.D. Chen et al., , (2017), https://doi.org/10.1016/j.mattod.2017.10.006

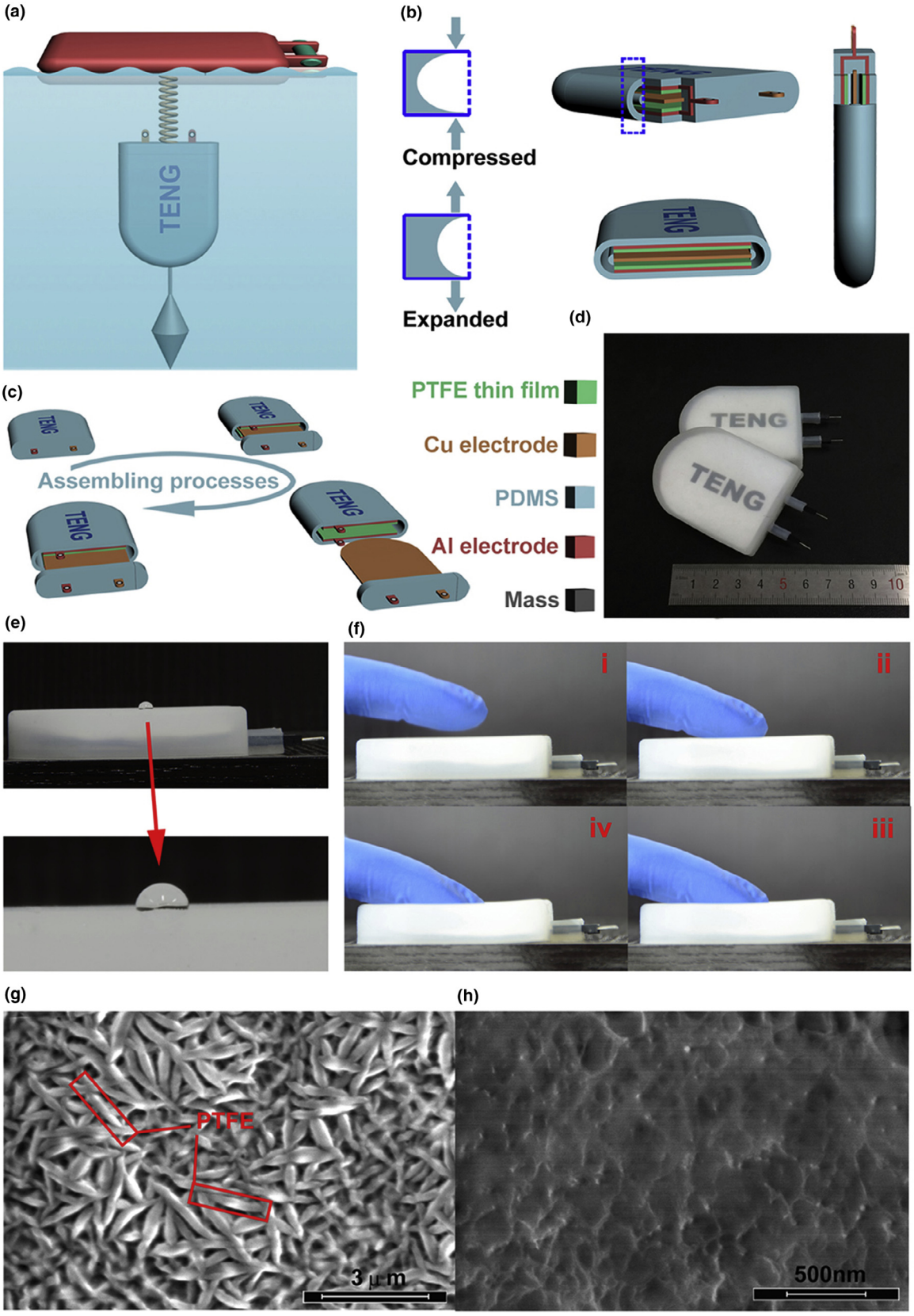


FIGURE 1

The structure and fabrication process of the bionic-jellyfish triboelectric nanogenerator (bjTENG). (a) Illustration of an application. (b) Schematic diagram showing the structure, (c) assembling process of bjTENG, (d) digital image of bjTENG and (e) the high hydrophobicity testing of bjTENG. (f) Digital images showing the high flexibility of bjTENG. (g) SEM images of the tribo-material PTFE thin film, and (h) magnified view.

Please cite this article in press as: B.D. Chen et al., , (2017), https://doi.org/10.1016/j.mattod.2017.10.006

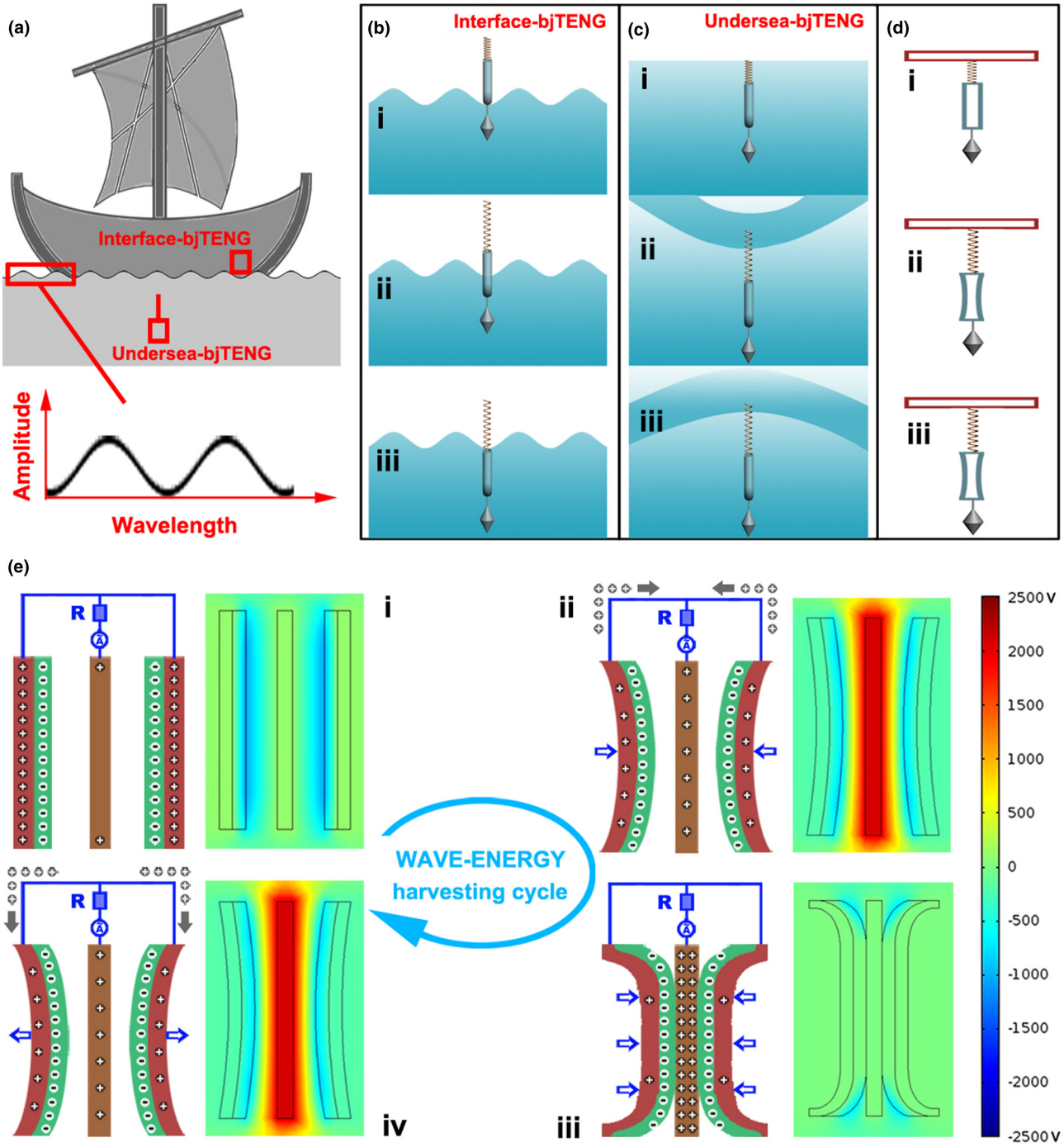


FIGURE 2

Workplace scenario, working condition and operating mechanism of bjTENG. (a) Workplace scenario, (b) working condition of the interface bjTENG, (c) working condition of the undersea bjTENG and (d) diagrammatic drawing of the state. (e) Operating mechanism of bjTENG by pressure-induced.

using a self-powered fluctuation sensor system and connected to a computer to monitor the pressure changes from air–water interface. It proves that the interface bjTENG is sensitive to changing interface of air–water and rapidly respond. It can be applied in a flood disaster or the fluctuation of liquid surface monitoring.

3.4. The optimized structure of the undersea bjTENG

The device structure of the undersea bjTENG is schematically depicted in Fig. 4a. This optimized of elastic resilient structure is composed of magnet, L shape panel of PMMA and mass. A five-step working process of undersea bjTENG is presented in Fig. 4b. This system of force assistance resembling breaststroke is targeting to realize effective contact and separation and increases the contact area of triboelectric surface, thus enhancing the electrical output properties of undersea bjTENG making it more suitable to detect water level or fluctuation of liquid-surface. The typical electrical signals of the undersea bjTENG are presented in Fig. S2. The long-term stability/reliability of

Please cite this article in press as: B.D. Chen et al., , (2017), https://doi.org/10.1016/j.mattod.2017.10.006

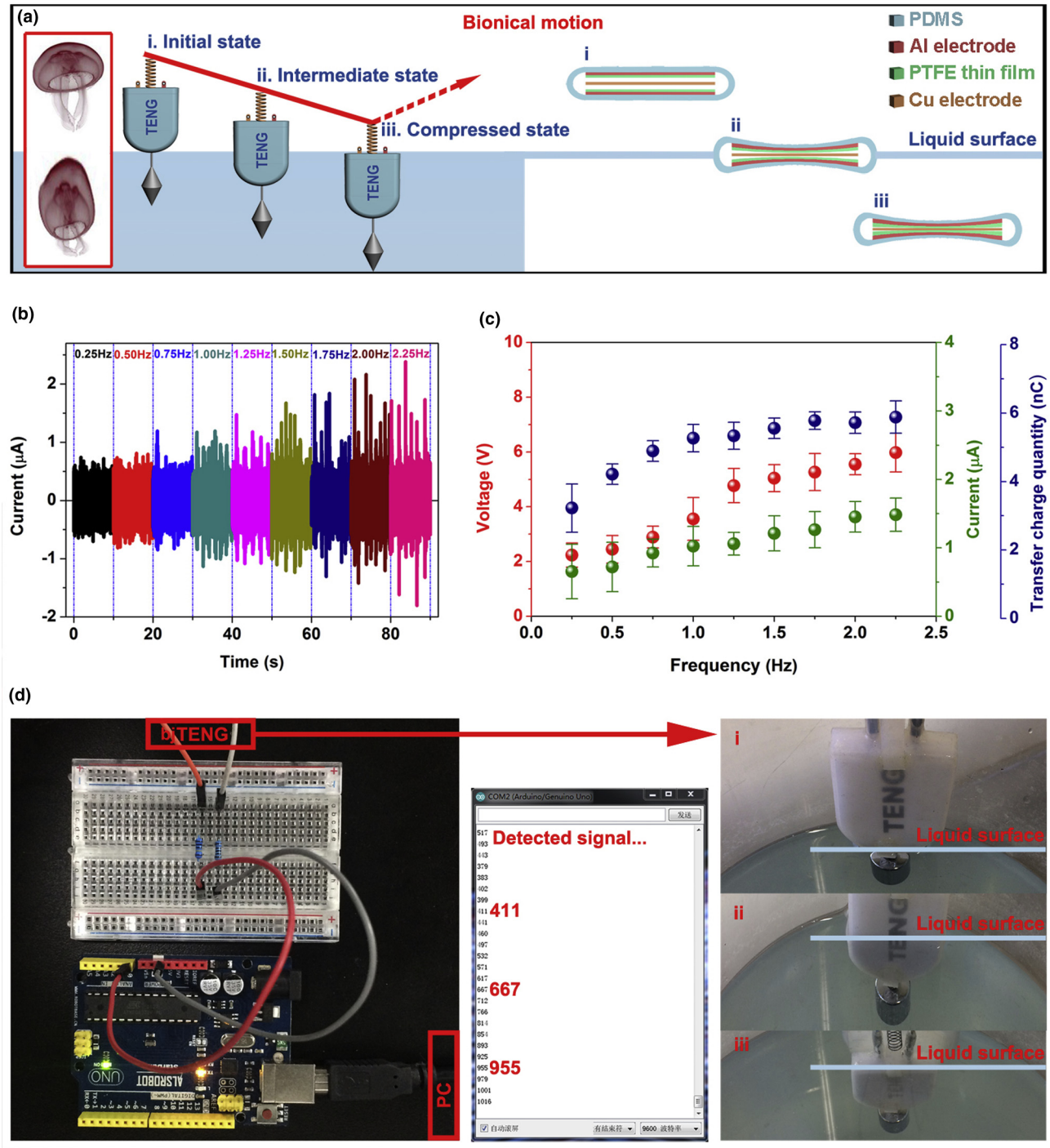


FIGURE 3

Demonstration of the interface bjTENG as a self-powered fluctuation sensor. (a) Working process of the interface self-powered fluctuation sensor (sizes of 5 cm × 4 cm × 1 cm). (b) and (c) Electrical output performances of the interface self-powered fluctuation sensor with working frequencies form 0.25 to 2.25 Hz. (d) Digital images of the self-powered fluctuation sensor system, and its response to liquid surface.

undersea bjTENG device was examined for over 2500 cycles (frequency, 0.75 Hz; depth, 60 cm; amplitude, 10 cm), as exhibited in Fig. 4c. It was found that there was no decrease in its current response after 2500 cycles. Fig. 4d shows the relationships between the electrical output performances of the undersea bjTENG with the depth from interface to 70 cm. The undersea bjTENG produces a voltage of 12 V, a current of 2.4 μA and transfer charge quantity of 6.2 nC, which is higher than those of the interface bjTENG measured at an applied frequency of 0.75 Hz. The output electrical signals increased up to 36 V, 7.5 μA and 23 nC at a depth of 70 cm and amplitude of 10 cm. Fig. 4e shows the relationships between the electrical output performances of the undersea bjTENG with the amplitude from 1 to 20 cm (frequency, 0.75 Hz; depth, 60 cm). The output electrical signals all

Please cite this article in press as: B.D. Chen et al., , (2017), https://doi.org/10.1016/j.mattod.2017.10.006

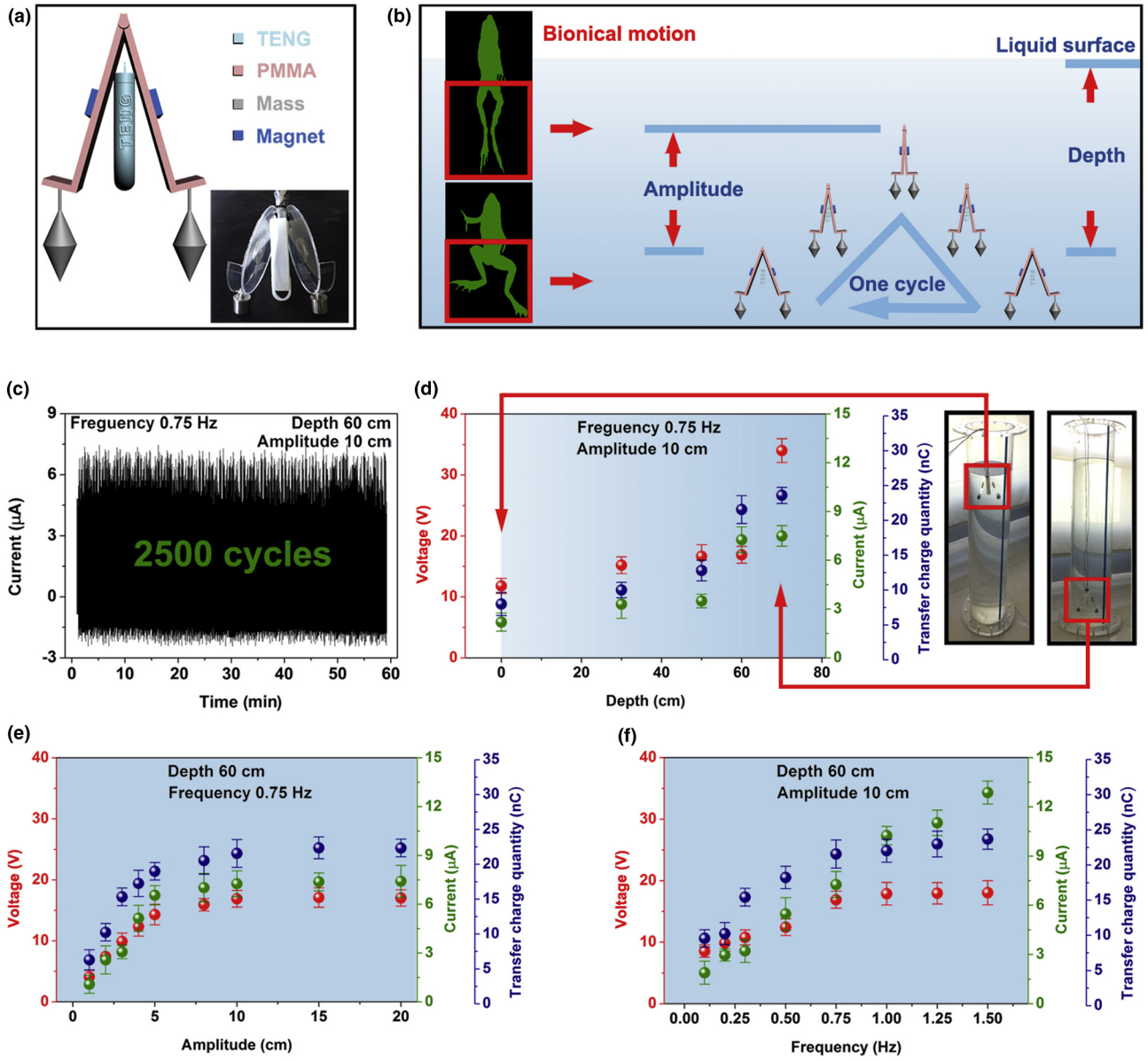


FIGURE 4

The optimized structure, working process and electrical output performances of the undersea bjTENG. (a) Schematic diagrams of the optimized structure (sizes of 5 cm × 4 cm × 1 cm) and (b) five steps working process of the undersea bjTENG. (c) Stability and durability test of the undersea bjTENG. (d) Outputs open-circuit voltage, short-circuit currents and transfer charge quantity of the optimized undersea bjTENG with different depth, (e) different amplitude and (f) different frequency.

show a similar nonlinear increase trend with the increase in amplitude, and reaches the maximum value when the depth is 10 cm, and gradually reached stability after ~10 cm. Fig. 4f shows the relationships between the electrical output performances of the undersea bjTENG with the frequency of wave from 0.1 to 1.5 Hz (depth, 60 cm; amplitude, 10 cm). The output electrical signals showed a significantly increased trend with the increase in frequency, and reached the maximum value when the frequency is 1.5 Hz at 18 V, 13 μA and 24 nC.

3.5. Self-powered LED lighting system

To further explore the possible applications for the developed undersea bjTENG, a practical demonstration in the stimulant scenes of water wave and flow energy had been conducted. Fig. 5 shows the demo of the developed undersea bjTENG for harvesting in the water wave and flow energy. The digital photographs of the whole testing apparatus are shown in Fig. 5a (length, 70 mm; width, 60 mm; height, 20 mm). The voltage, current and transferred charge quantity of the undersea bjTENGs are measured under a fixed contact frequency of 0.75 Hz, depth of 60 cm and amplitude of 10 cm, as shown in Fig. 5b and d, it produces an open-circuit voltage of 143 V, a short-circuit current density (J) of 11.8 μA/m^2 and short-circuit charge density (σ) of 22.1 μC/m^2, which can be used to supply power for about dozens of green LEDs (Fig. 5e), and Supplementary Movie 1 (Video S1). This kind of self-powered LED lighting system based on the

Please cite this article in press as: B.D. Chen et al., , (2017), https://doi.org/10.1016/j.mattod.2017.10.006

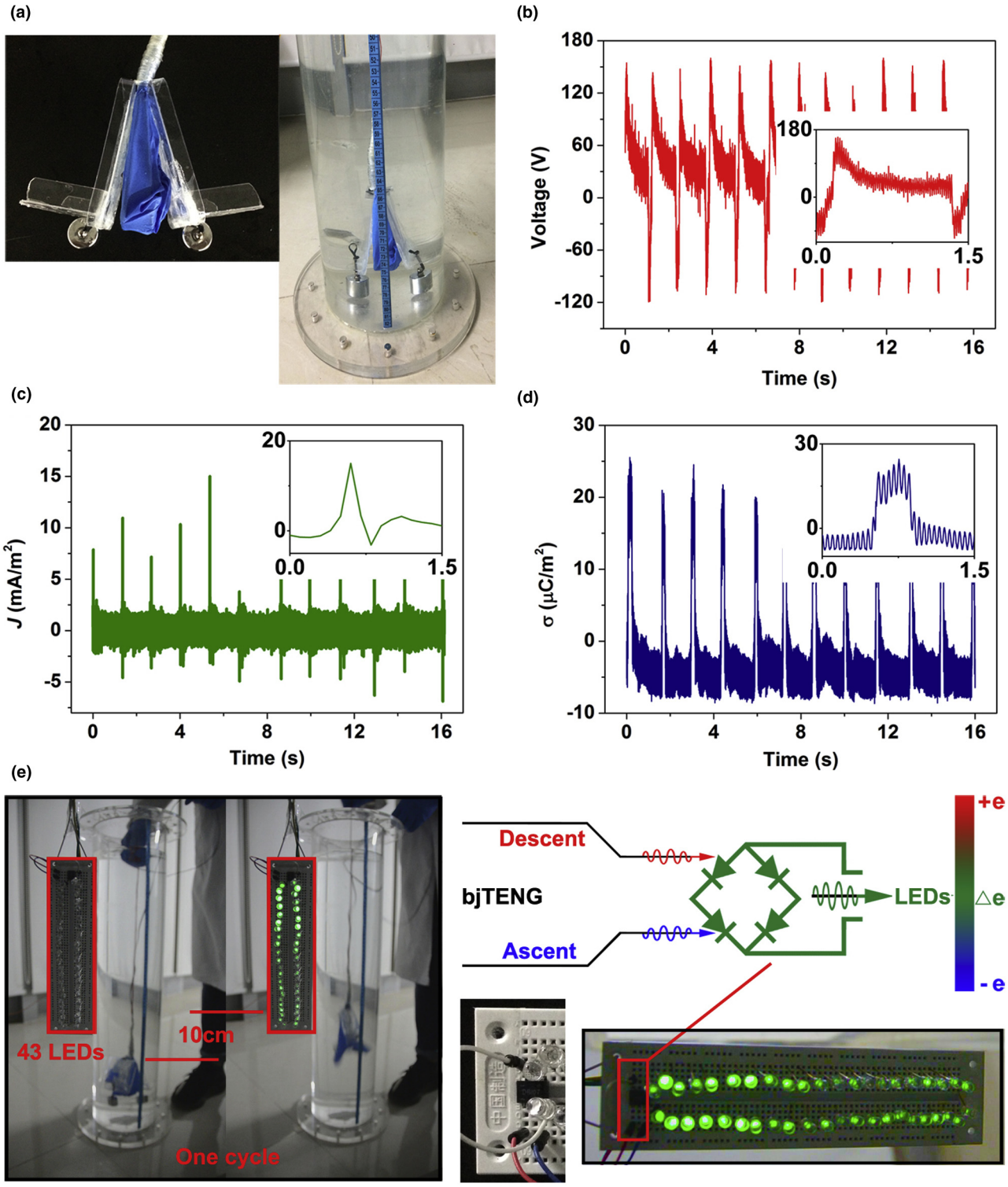


FIGURE 5

Demonstration of the undersea bjTENG as a wave energy harvester. (a) Digital photographs of the undersea bjTENG (sizes of 7 cm × 6 cm × 2 cm). (b) Output open-circuit voltages, (c) short-circuit current density (*J*) and (d) short-circuit charge density (*s*) of the undersea bjTENG. (e) Demonstration of the undersea bjTENG as a self-powered LED lighting system (digital photographs and wave energy harvesting circuit).

Please cite this article in press as: B.D. Chen et al., , (2017), https://doi.org/10.1016/j.mattod.2017.10.006

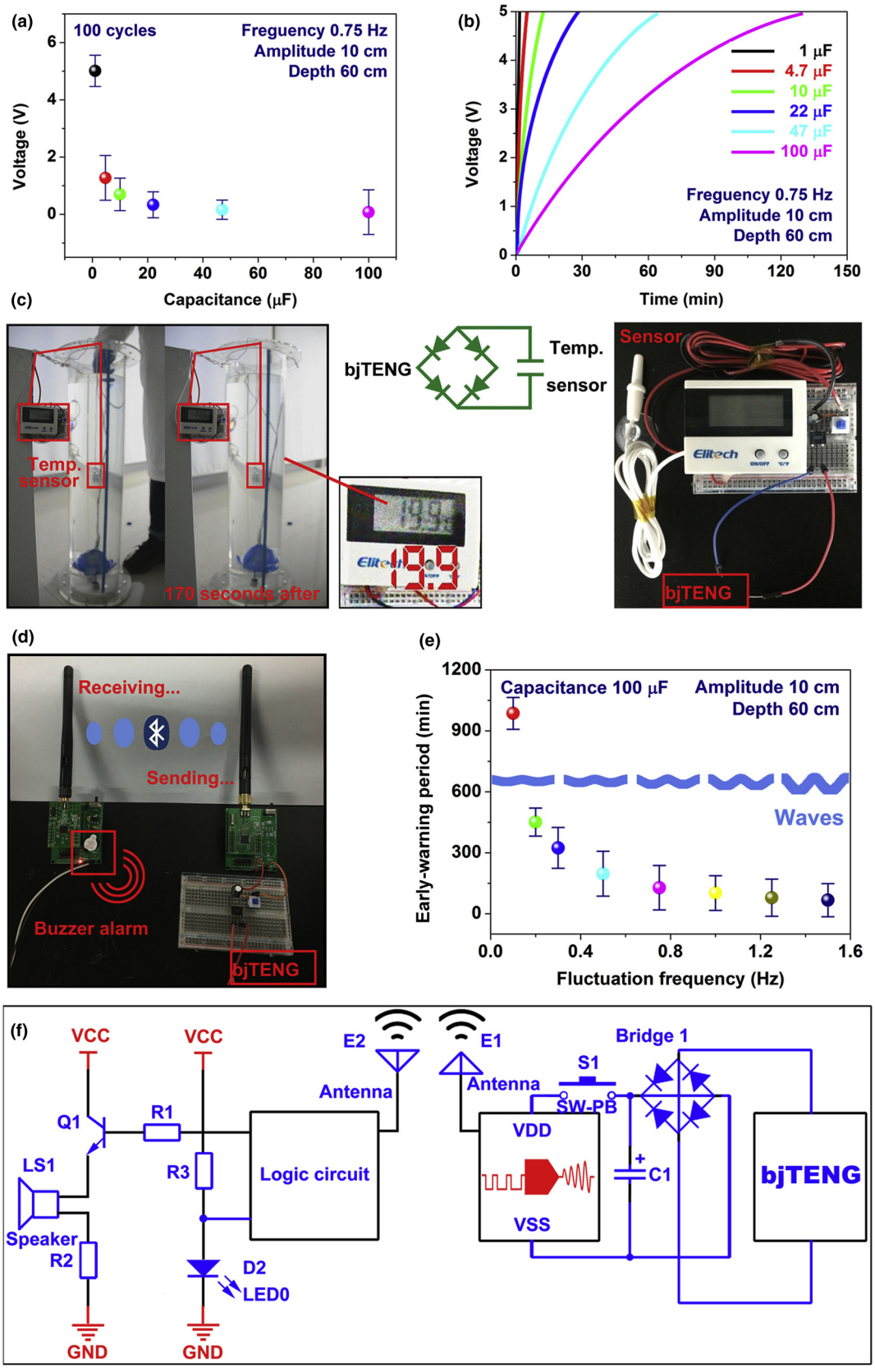


FIGURE 6

Demonstration of the undersea bjTENG as a self-powered temperature sensor system and wireless self-powered fluctuation early-warning system. (a) The relationship between charging voltage and load capacitance at 100 working cycles. (b) The voltage–time relationship at different load capacitances. (c) Digital photographs and wave energy harvesting circuit of the self-powered temperature sensor system. (d) Digital photograph of the wireless self-powered fluctuation sensor system, (e) the relationship between early-warning period and fluctuation frequency, and (f) the circuit principle and designing in detail.

Please cite this article in press as: B.D. Chen et al., , (2017), https://doi.org/10.1016/j.mattod.2017.10.006

undersea bjTENG can be applied as illumination on the water and coastal navigation warnings.

3.6. Self-powered temperature sensor and wireless self-powered liquid surface fluctuation early-warning system

To demonstrate the capability of the undersea bjTENG as practical energy harvesters and self-powered sensors, self-powered temperature sensor and wireless self-powered fluctuation early-warning system were developed by integrating bjTENG with a signal-processing circuit, as shown in Fig. 6. Fig. 6a shows the relationships between the charged voltage and load capacitance (1, 4.7, 10, 22, 47, 100 μF) at 100 working cycles of the undersea bjTENG. And Fig. 6b shows different capacitors charging curves (1, 4.7, 10, 22, 47, 100 μF). It is found that bjTENG could be a promising power source for electronic devices on the water or as a self-powered fluctuation sensor. A self-powered temperature sensor system was developed by integrating bjTENG with a wave energy harvesting circuit, as shown in Fig. 6c, and Supplementary Movie 2 (Video S2). The output signal of self-powered temperature sensor system was 19.9 degree Centigrade (°C) from water temperature after ~170 s. The wireless self-powered fluctuation early-warning system can be easily operated by a gate voltage of 3 V using a wave energy harvesting generated from the undersea bjTENG to trigger a remote controller that controls a wireless transmitter for remotely switching a siren between an emergency and a normal state, as shown in Fig. 6d. When undersea bjTENG is driven by water wave, on condition that the charged voltage in the capacitor (100 μF) reached a certain level (gate voltage of 3 V), it triggered the remote controller in the transmitting circuit, and wirelessly sends commands, as illustrated in the right-hand schematic of Fig. 6f will be timely response from receiving circuit, resulting in the triggered buzzer sounding sharp buzzing alarm, as shown in the left-hand schematic of Fig. 6 f. Fig. 6e shows the relationships between the warning period and fluctuation frequency of water. It indicated that the warning time shortened with the increase in the fluctuation frequency, which implies the bjTENG can be used to forecast the tidal changes and the fluctuation of sea.

4. Conclusions

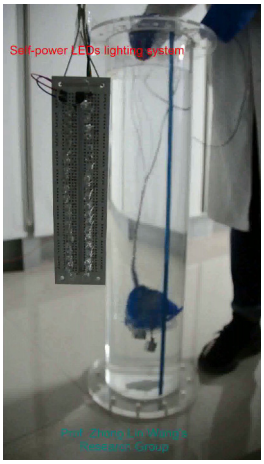
In summary, we reported here a practical bjTENG by a bionic structural design. The concept presented here enables a water wave energy harvester and a self-powered liquid-surface fluctuation sensor undersea. The hermetic package manufacturing is feasible and suitable for large-scale applications. The interface bjTENG can serve as a sensitive self-powered sensor to monitor flood disaster and measure the fluctuation of liquid surface.

In addition, the appended magnetic elastic resilient has an effect of force assistance, resembling that of breaststroke that can enhance the electrical output properties of the undersea bjTENG and its depth sinking into water. The results indicate output voltage, current density and charge density enhancement of ~24, ~13 and ~7.3 times, respectively, which considerably broaden the range of its applications in undersea. The undersea bjTENG can serve as a power source for self-powered LED lighting system, applied on illumination and coastal navigation warnings and so on. More importantly, a complete self-powered temperature sensor system, and the other wireless self-powered fluctuation early-warning system are built through integrating energy management circuit with the undersea bjTENG, which shows undersea continuous self-powered detection, with high sensitivity, portability, and feasibility.

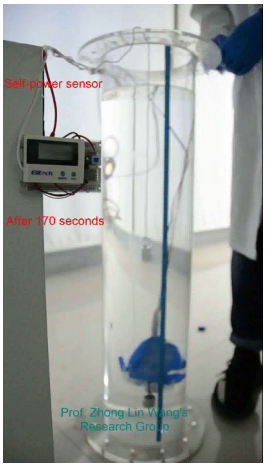
In most cases, this may not require the exact imitation of biological motion, but the fusion of biological and TENG technological construction principles. Hence, there is plenty of room for new structural designs of TENG inspired by the diverse propulsion modes of living creatures.

Acknowledgements

Thanks for the support from National Natural Science Foundation of China (Grant No. 61405131, 51432005, 5151101243, 51561145021), the National Key R & D Project from Minister of Science and Technology (2016YFA0202704), Beijing Municipal Science & Technology Commission (Y3993113DF), the "thousands talents" program for pioneer researcher and his innovation team, China.



Video S1. Self-power LEDs lighting system.



Video S2. Self-power temperature sensor system.

Please cite this article in press as: B.D. Chen et al., , (2017), https://doi.org/10.1016/j.mattod.2017.10.006

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.mattod.2017.10.006.

References

[1] F.-R. Fan, Z.-Q. Tian, Z.L. Wang, Nano Energy 1 (2012) 328–334.
[2] Z.L. Wang et al., Mater. Today 15 (2012) 532–543.
[3] Z.L. Wang, Mater. Today 20 (2017) 74–82.
[4] Z.L. Wang, ACS Nano 7 (2013) 9533–9557.
[5] Z.H. Lin et al., Adv. Mater. 26 (2014) 4690–4698.
[6] S. Niu et al., Energy Environ. Sci. 7 (2014) 2339–2349.
[7] Z.L. Wang, J. Chen, L. Lin, Energy Environ. Sci. 8 (2015) 2250–2282.
[8] Y. Zi et al., ACS Nano 10 (2016) 4797–4805.
[9] Z.L. Wang, Nature 542 (2017) 159–160.
[10] Y. Xi et al., Nano Energy 38 (2017) 101–108.
[11] G. Zhu et al., Adv. Mater. 26 (2014) 3788–3796.
[12] J. Yang et al., ACS Nano 8 (2014) 2649–2657.
[13] J.S. Chun et al., Nat. Commun. 7 (2016) 12985.
[14] G. Zhu et al., Nat. Commun. 5 (2014) 3426.
[15] J. Chen et al., ACS Nano 9 (2015) 3324–3331.
[16] S. Niu et al., Nat. Commun. 6 (2015) 8975.
[17] F.-B. Xi et al., Nano Energy 37 (2017) 168–176.
[18] G. Zhu et al., Nano Lett. 13 (2013) 847–853.
[19] X.-H. Li et al., ACS Nano 8 (2014) 10674–10681.
[20] Y.-N. Xie et al., Nano Energy 6 (2014) 129–136.
[21] S.-H. Wang et al., ACS Nano 8 (2014) 12004–12013.
[22] J. Yang et al., Adv. Mater. 27 (2015) 1316–1326.
[23] C.-S. Wu et al., Nano Energy 32 (2017) 287–293.
[24] Y. Xie et al., Adv. Mater. 26 (2014) 6599–6607.
[25] S. Wang et al., Adv. Mater. 26 (2014) 2818–2824.
[26] S. Niu et al., Nano Energy 12 (2015) 760–774.
[27] S. Wang, L. Lin, Z.L. Wang, Nano Energy 11 (2015) 436–462.
[28] J. Wang et al., Nat. Commun. 7 (2016) 12744.

Please cite this article in press as: B.D. Chen et al., , (2017), https://doi.org/10.1016/j.mattod.2017.10.006