

Double-folding paper-based generator for mechanical energy harvesting

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Abstract Paper-based generators are essential elements for building all paper-based systems. To obtain robust paper-based generators with outstanding high power outputs, this paper introduced a new type of double-folding paper-based generator by folding two paper components together. The output performance levels of the double-folding generator were twice higher than that of the single-folding and parallel-plate generators. A peak power of ~3.24 mW was achieved under a stimulating frequency of 3 Hz. Furthermore, 47 light-emitting diodes (LEDs) were lit directly by a double-folding paper-based generator assembled to the crack of a door that opens and closes. This finding indicated the potential applications of the double-folding generator in the production of door ornaments or for security in places where doors frequently open and close.

Keywords paper-based generator, double-folding, electret, electrostatic induction

1 Introduction

The rapid development of electronics allowed conveniences and drastically changed social life [1–4]. However, the problem of electronic waste becomes increasingly prominent as electronic products are quickly upgraded [5]. To alleviate the electronic waste pollution, many scientists focused on paper-based electronics [6,7] such as sensors [8,9], micro-electromechanical system [10], and transistors [11,12], because of their superiority in terms of biodegradability, low cost, foldability, flexibility, and light weight. The power sources are a key factor which confines the development of paper-based electronics. Traditional bulky batteries and capacitors cannot support the concept of “green electronics”. Thus, paper-based power sources that

work independently and sustainably, such as lithium battery [13,14], supercapacitor [15–17], solar cell [18], piezoelectric generator [19–22], and electrostatic generator [23–26], are designed and proposed to build all paper-based systems. Paper-based electrostatic generators, including triboelectric generator [23,24] and electret generators [25,26], are a quite new alternative technology to convert mechanical energy in the ambient environment into electricity. This generator is easily fabricated and highly reliable. For example, Wang et al. developed origami triboelectric generators that can harvest ambient mechanical energy from various human motions and can also serve as self-powered pressure sensors [25]. Zhou et al. introduced a paper-based electret generator that can be attached onto movable objects to harvest energy [26]. These studies indicated the significant potential applications of a paper-based self-powered system as an energy source or as an active sensor. Although some low-power consumption electronics have been successfully driven by previous paper-based generators, their output ability still needs to be promoted as electricity demand of electronics escalates.

In this work, we introduced a new type of double-folding paper-based generator with high yielding output; this generator was folded with two paper components. The related fundamental working mechanism was based on electrostatic induction caused by the charges captured by the polytetrafluoroethylene (PTFE) electret on the paper component. A peak power of ~3.24 mW generated by the paper-based generator was obtained under a stimulating frequency of 3 Hz. The effective working area of the double-folding generator was twice larger than that of single-folding and parallel-plate generators because of the artful origami design, leading to outstanding output performance. A double-folding generator was assembled into a crack of a door to demonstrate the potential applications in harvesting irregular mechanical energy. The generator could light up 47 light-emitting diodes (LEDs) directly while the door was closing and opening.

This study showed a simple, distinctive, and efficient way to build robust paper-based generator with excellent outputs.

2 Experiment

2.1 Fabrication of the generator

The detailed fabrication processes of the double-folding paper-based generator are schematically indicated in Fig. 1(a). The raw materials were Carbon-Paper (Haoqi, China) and PTFE electret film (30 μm thickness). Both surfaces of the Carbon-Paper were coated with carbon nanoparticles. PTFE electret films were adhered to both surfaces of the Carbon-Paper to form the PTFE/Carbon-Paper/PTFE component, as indicated in Fig. 1(b). A double-folding paper-based generator was assembled by folding a Carbon-Paper component and a PTFE/Carbon-Paper/PTFE component together, where one PTFE/Carbon-Paper/PTFE component was inserted between two Carbon-Paper components. One folding number would form two working units.

2.2 Characterization equipment

The morphology of the samples was viewed by using a high-resolution field emission scanning electron microscope (FEI Nova NanoSEM 450). The surface potential of the samples was detected by an electrometer (EST102, Huajing Beijing, China). The output characteristics of the samples were measured using a NI PCI-6259 with a Stanford Low-noise Current Preamplifier (Model SR570) for current harvesting. A resonator (JZK, Sinocera, China) controlled by a signal generator (YE 1311-D, Sinocera, China) was utilized to periodically trigger the devices attached on a force meter (Model ZPS-DPU-50N). All the electrical measurements were carried out after the surface potential of the electret materials reached stability.

3 Results and discussion

The carbon paper exhibited good flexibility and foldability, as indicated in Fig. S1. Figure 1(c) shows the scanning electron microscope (SEM) images of the surfaces of Carbon-Paper coated with carbon nanoparticles. Carbon

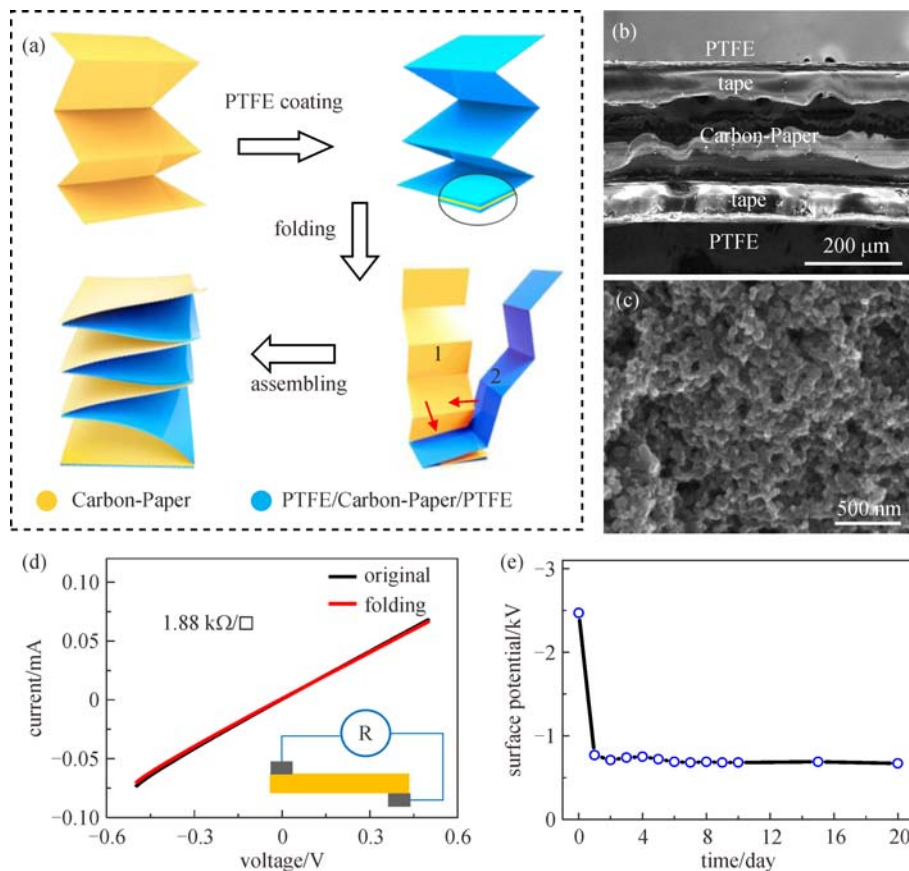


Fig. 1 Fabrication of the double-folding paper-based generator. (a) Schematic diagram indicating the fabrication process of the generator; (b) cross-section view SEM image of the PTFE/Carbon-Paper/PTFE component; (c) SEM image of the surface morphology of the Carbon-Paper; (d) I - V scanning curves for the conductive Carbon-Paper in straight and folding states, insert shows the schematic diagram for I - V scanning; and (e) surface potential decay curve versus time for the PTFE electret film

nanoparticles permeated inside the paper served as the conductive path between upper and lower surfaces of the Carbon-Paper (Fig. S2). Two external electrodes were covered on two respective surfaces of a Carbon-Paper with an area of 2 cm×2 cm during the I - V scanning measurement (insert in Fig. 1(d)). The results in Fig. 1(d) clearly displayed that the I - V scanning curves for the Carbon-Paper in straight and folding states overlapped closely (Fig. 1(d)), and the sheet resistance was 1.88 k Ω /□.

The PTFE films were injected with negative charges via corona charging process. The surface charge density σ can be calculated by measuring the surface potential V according to the following equation [27–29]:

$$\sigma = V\varepsilon_r\varepsilon_0/d_m, \quad (1)$$

where ε_r and ε_0 are dielectric constants of electret and air, and d_m is the thickness of the electret material. After corona charging, the surface potential of PTFE reached ~2.47 kV, dropped to ~0.70 kV after 2 days, and remained at such constant for the following 20 days (Fig. 1(e)).

Figures 2(a) and 2(b) schematically indicate the simplified equivalent generation mechanism of the double-folding paper-based generator. Generally, a generator is the number of ideal parallel plate capacitors connected and does not consider the edge effect. In the original state (Fig. 2(a)), both PTFE sides of the PTFE/Carbon-Paper/PTFE component were negatively charged with a total

charge density of σ . According to electrostatic induction effect, the corresponding positive charges were generated in the Carbon-Paper of the PTFE/Carbon-Paper/PTFE component (σ_1) and in the Carbon-Paper component (σ_2), where $-\sigma = \sigma_1 + \sigma_2$. Assuming the charges were distributed uniformly in PTFE and both electrodes, we can obtain the following [27–29]:

$$\sigma_2 = -\frac{\sigma d_1}{d_2\varepsilon_{rp} + d_1}, \quad (2)$$

where d_1 is the thickness of the PTFE, ε_{rp} is the relative permittivity of the PTFE, d_2 denotes the distance between the PTFE and the Carbon Paper component, and d_1 and ε_{rp} are constants in this case, which are 30 μm and 1.93, respectively.

d_2 decreased in size when the double-folding paper-based generator was pressed (Fig. 2(b)). Increased σ_2 and reduced σ_1 damaged the electrical potential equilibrium. As a result, current flowed from the Carbon-Paper of the PTFE/Carbon-Paper/PTFE component to the Carbon-Paper component, generating a positive current peak until the electrical potential balanced again (left in Fig. 2(c)). In the releasing process, the generator reverted back to original shape because of resilience, and d_2 increased in size. Therefore, the electrical potential variation was the opposite of the pressing process, and a negative current peak was generated (left curve in Fig. 2(c)). In general, continuously pressing and releasing

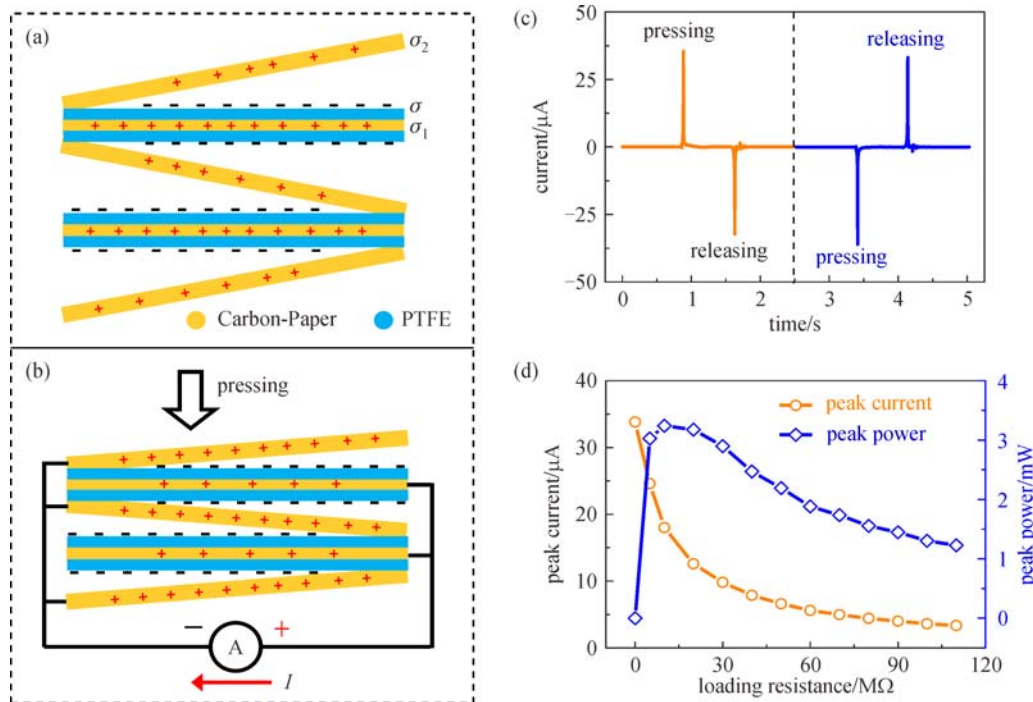


Fig. 2 Working mechanism and output performances of a double-folding paper-based generator. Equivalent circuit diagram for the generator when in (a) the original state and (b) pressing process. Left current curves in (c) indicated the corresponding current signal for pressing and releasing the generator. Right current curves in (c) indicated corresponding current signal for the switching polarity test; (d) load peak currents and power curves for a generator as a function of the load resistances under a given frequency of 3 Hz

the double-folding paper-based generator will generate alternating currents. Furthermore, switching polarity test was also carried out to confirm that the measured output signals are produced by the generator rather than the measurement system (right curve in Fig. 2(c)).

The electrical output performances of a double-folding paper-based generator with total device area of 36 cm^2 and folding numbers of 6 were studied by periodically pressing and releasing the generator at controlled external stimulation provided by a linear motor. Figure 2(d) displays the load peak currents and power curves as a function of the load resistances under a given frequency of 3 Hz. With the increasing load resistances, the load peak currents decreased step by step, from $\sim 33.8 \mu\text{A}$ at a short circuit state to $\sim 3.3 \mu\text{A}$ under $110 \text{ M}\Omega$. Accordingly, maximum load peak power of $\sim 3.24 \text{ mW}$ was obtained when the load resistance was $10 \text{ M}\Omega$.

Single-folding (Fig. 3(a)) and parallel-plate (Fig. 3(b)) paper-based generators with the same total device areas (36 cm^2) of double-folding paper-based generator (Fig. 3(c)) were fabricated for comparison. Specifically, PTFE/Carbon-Paper component and Carbon-Paper component were folded together to form the single-folding generator, in which one folding number forms one working unit (Fig. 3(d)). Oblong PTFE/Carbon-Paper component and Carbon-Paper component ($3 \text{ cm} \times 12 \text{ cm}$) were adhered together, with carbon side of the Carbon-Paper component facing the PTFE side of the PTFE/Carbon-

Paper component; thereby forming the parallel-plate generator (Fig. 3(e)).

Single-folding and double-folding generators have higher space utilization efficiency compared with the parallel-plate generator. More importantly, the total effective working area of double-folding generator was twice larger than other two types of generators. In consequence, the levels of peak short-circuit currents (Figs. 3(f) and S3) and corresponding transferred charges (ΔQ) (Fig. 3(g)) of double-folding generator were twice higher than that of other two types of generators under the same external stimulation conditions. Under a stimulating frequency of 5 Hz, the peak short-circuit currents for the parallel-plate, single-folding, and double-folding were ~ 31.1 , ~ 30.7 , and $\sim 66.1 \mu\text{A}$, with corresponding transferred charges of ~ 0.23 , ~ 0.26 , and $\sim 0.49 \mu\text{C}$, respectively. In addition, the peak short-circuit currents of all three types of generators increased with increasing stimulating frequencies, whereas the transferred charges remained the same.

Most of the mechanical energy in human's ambient environments are irregular and at a low frequency. A generator was fastened on a hinged door junction and connected with 47 blue LEDs in series (Fig. 4(a)) to extend the potential applications of the double-folding paper-based generator by harvesting irregular mechanical energy. When the door was closing or opening, the generator was compressed and released, generating electricity that could

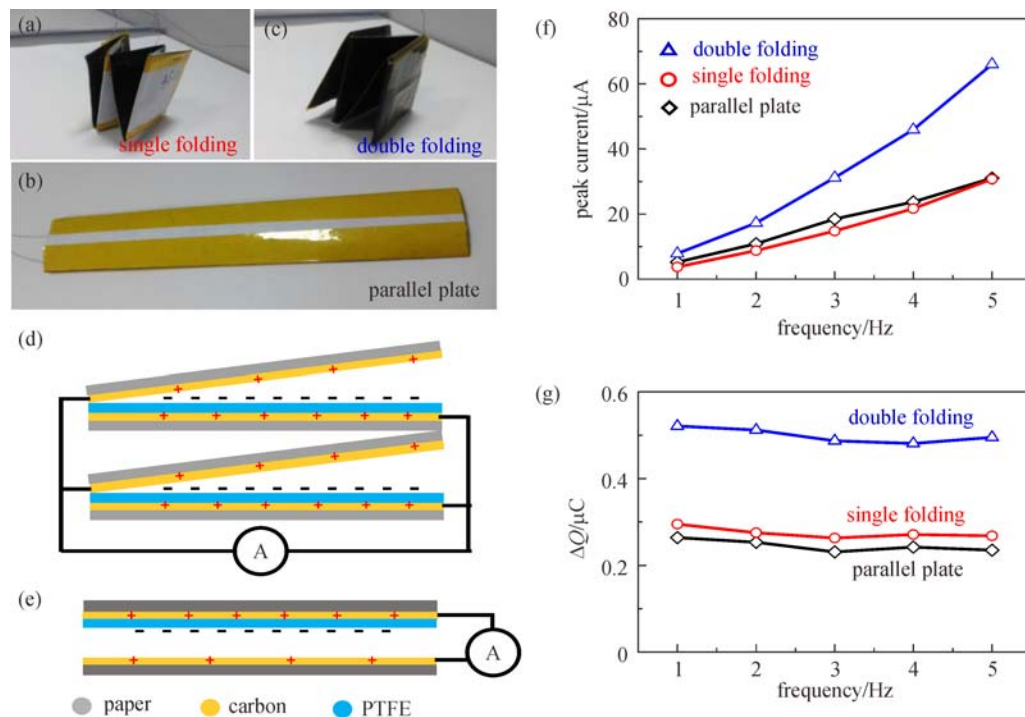


Fig. 3 Output performance comparisons for the single-folding, parallel-plate, and double-folding paper-based generators with same total areas. Digital pictures of (a) single-folding, (b) parallel-plate, and (c) double-folding paper-based generators. Equivalent circuit diagram for (d) single-folding and (e) parallel-plate paper-based generators; (f) peak short-circuit current; and (g) corresponding transferred charges (ΔQ) for three kinds of paper-based generators under given stimulating amplitude and different stimulating frequencies

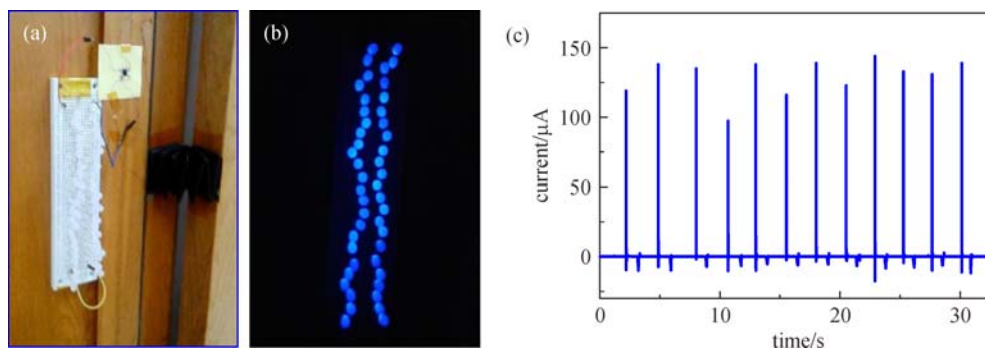


Fig. 4 Double-folding paper-based generator for harvesting irregular mechanical energy. Digital pictures indicating (a) a generator fastened on a hinge door junction; (b) 47 blue LEDs connected in series lit up by the door closing and opening action; and (c) the currents went through the LEDs when they were lit up

power the LEDs and showing the fantasy ornament for the door (Fig. 4(b)). When the LEDs were lit up, the maximum peak current was $\sim 120 \mu\text{A}$ (Fig. 4(c)). This study also indicated that generator is an active sensor for providing an alert when the door closes and opens. This finding showed potential applications for security in places where the doors frequently open and close, such as shopping malls and banks.

4 Conclusions

In summary, double-folding paper-based generator was fabricated by simply folding the PTFE/Carbon-Paper/PTFE component and Carbon-Paper. The output performance levels for the double-folding generator were twice higher than that of the single-folding and parallel-plate generators, as the effective working area of the double-folding generator increased in size. Under the stimulating frequency of 3 Hz, a maximum peak power of $\sim 3.24 \text{ mW}$ was achieved for the double-folding generator. In addition, 47 blue LEDs were lit by a generator stimulated by the door's closing and opening, thereby indicating the potential applications in door ornaments or for security in places where the doors frequently open and close.

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Supporting Information Available

A digital picture of the carbon paper (folded). Low and high magnification cross-section view SEM images for the conductive Carbon-Paper. Short-circuit current curves for the parallel-plate, single-folding, and double-folding paper-based generators. This information is available below.

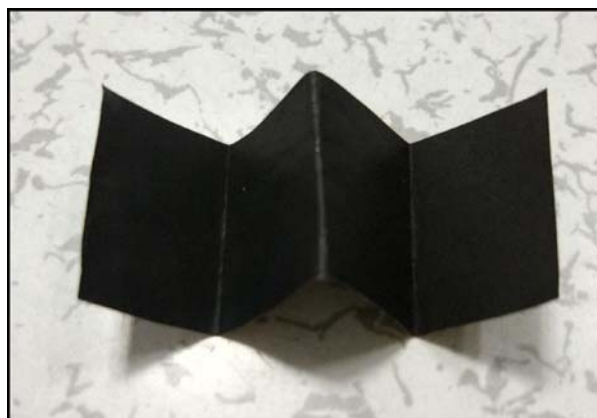


Fig. S1 Digital picture for the carbon paper in folding shape

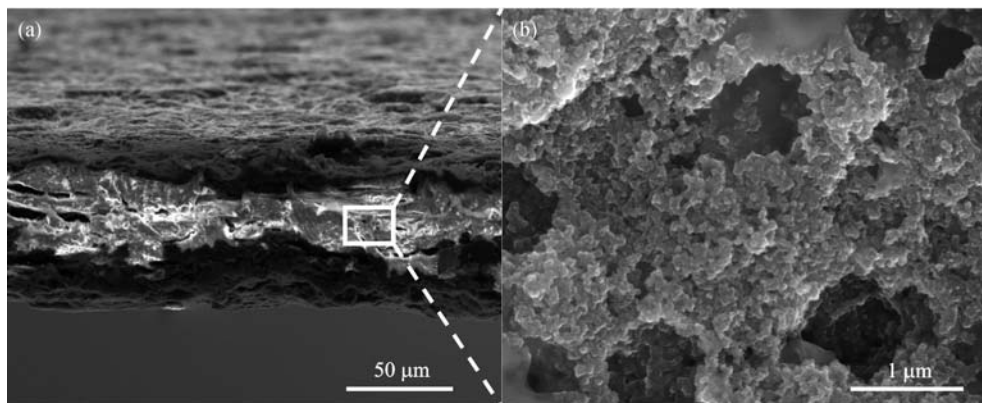


Fig. S2 (a) Low and (b) high magnification cross-section view SEM images for the conductive Carbon-Paper

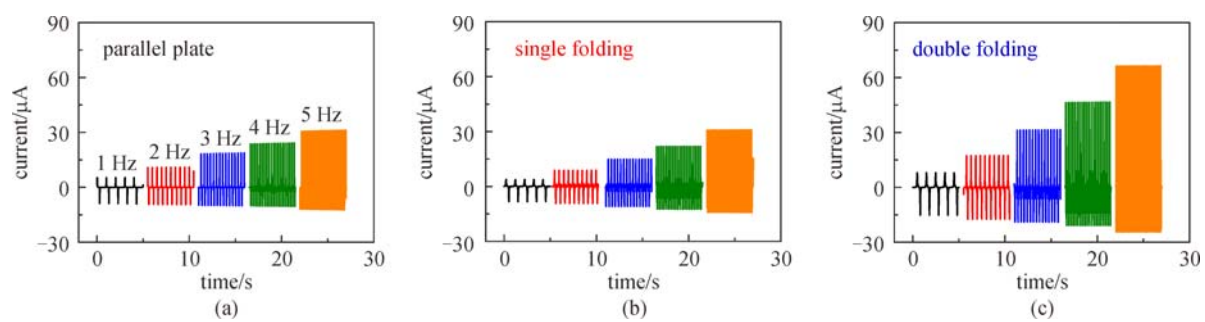


Fig. S3 Short-circuit current curves for the (a) parallel-plate, (b) single-folding and (c) double-folding paper-based generators, respectively