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Triboelectrification induced UV emission from plasmon discharge

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ABSTRACT

UV is a high-energy electromagnetic radiation that has been widely used in industrial production and the scientific research domain. In this work, a deep UV light emission was obtained using triboelectrification induced plasma discharge without any extra power supply. By a mechanical friction between polymer and quartz glass, the triboelectric charges cause a changing electric field, which may bring plasma discharge of low pressure gas (Ar–Hg) and give out 253.7 nm irradiation. The UV light caused by continuous friction can excite a trichromatic phosphor and afford a bright white light emission. A UV sterilization experiment shows that ~98% of *Escherichia coli* can be killed in 30 min by UV irradiation, which reveals that a self-powered sterilization apparatus with good sterilization effect was fabricated. This work provides a novel design to fabricate a self-powered UV light emitting device using low-frequency mechanical friction and realizes the coupling of triboelectrification and plasma luminescence, which may further expand the application of UV light in special circumstances.

1 Introduction

Deep ultraviolet (UV) light with wavelength ranging from 200 to 350 nm has high photon energy and thereby has been widely used in different fields, such as medical care [1, 2], biological detection [3, 4] and lithography [5–7]. Generally, a controllable UV source is obtained by means of a light emitting diode using transition irradiation of photons in wide-bandgap III–V nitride semiconductor materials (GaN, AlGaN or AlN) [8, 9]. Another method of UV light emission involves low-pressure gas discharge, in which a high-frequency voltage is necessary to cause a changing electric field for plasma discharge and result in UV light emission [10, 11]. The UV light produced by plasma discharge has the merits of large irradiation areas, high output power and low cost, but the need for a high-frequency power supply restricts its application in portable devices. Therefore, harvesting mechanical energy to create high-energy UV irradiation will be of great significance. Previously, triboelectrification has been used to emit X-rays from the

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interface of separating surfaces by contact friction in insulating materials, and a possible explanation is the localization or accumulation of tribocharges and discharge [12–14]. Since X-rays can be induced by triboelectrification this suggests that other forms of high energy photon irradiation can be obtained using mechanical energy.

Recently, an innovative technology—a triboelectric nanogenerator (TENG)—has been extensively studied and the mechanism of charge generation, distribution, as well as transfer between the two materials had been clarified [15–17]. A continuous contact or friction can yield a high charge density [18–20] and form a strong potential around the friction surface, which may provide a new way to design voltage tuned/controlled devices using tribocharges [21]. In this work, a deep UV light emission was obtained using a triboelectrification induced plasma discharge. By means of a low-frequency mechanical friction between polymer and quartz glass, the changing electric field caused by tribocharges can bring about plasma discharge of low pressure gas (Ar–Hg) and gives out 253.7 nm irradiation. The strong UV light not only can kill 98% of bacteria in 30 min, but also excites a trichromatic phosphor to give white light emission. This work realizes the coupling of triboelectrification and plasma luminescence, and provides a novel approach to a mechanically driven UV source for imaging, detection, sterilization and other applications without the need for a power source.

2 Results and discussion

2.1 Theoretical and experimental analysis

According to the free-standing-triboelectric-layer based TENG [22], when there is friction between two different dielectric materials, such as polymer polytetrafluoroethylene (PTFE) and quartz galss, negative tribocharges will be injected from the glass to the PTFE surface while the positive tribocharges are left on the surface of the glass according to electrostatic induction. If the effective friction areas for PTFE are far less than glass, the tribocharge density on PTFE is much larger than on glass, as shown schematically in Fig. 1(a). In consequence, this is equivalent to a charged plate with net negative charge sliding along a plane. In electrodynamics, a moving charge will induce electromagnetic radiation in space, which means that it can form a changing potential and electric field for a fixed position. The changing electric field generated by the friction of PTFE on glass can be exploited to excite the plasma discharge for a low-pressure gas. Schematics in Figs. 1(a) and 1(b) reveal the principle underlying the discharge of UV light from the device. A sealed quartz glass cavity filled with low-pressure Ar–Hg was fixed and a relative friction was produced between the PTFE film and the surface of glass cavity. Here, the moving PTFE is regarded as a charged plate for triboelectrification. When the PTFE slides, the potential and electric field at a fixed point p beneath the PTFE is heterogeneous and changes with time, which is analogous to a changing electric field generated by changing current. Based on the principle of plasma discharge [23–26] the mercury atoms can be excited by the changing electric field from the ground state 6^1S_0 to the higher energy states $6^3P_{0,1,2}$ and 6^1P_1 generating the resonance emission at 184.9 and 253.7 nm. Therefore, a mechanical rubbing of the PTFE may yield a continuous plasma UV luminescence in the glass cavity.

To analyze the variation in potential, a charged plate and slider (PTFE) with a triboelectric charge density of σ sliding along the x direction on a plane was fabricated and is shown in Fig. 2(a). The size of the charged plate is $l \times l_0$ ($l > l_0$) and it is moving with a

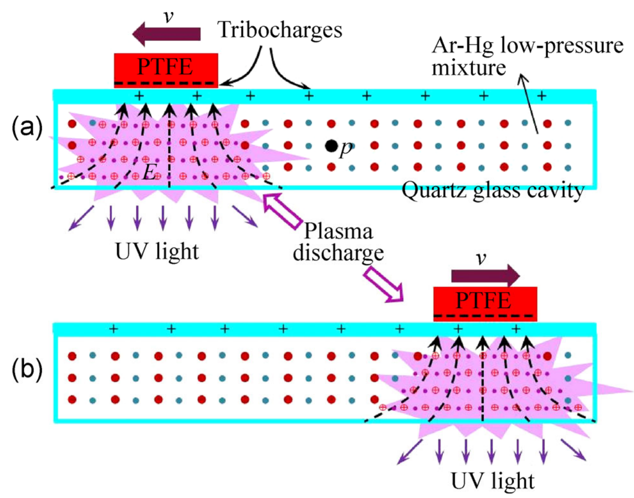

Figure 1 The principle of the UV light emitting device based on triboelectrification and plasma discharge luminescence.

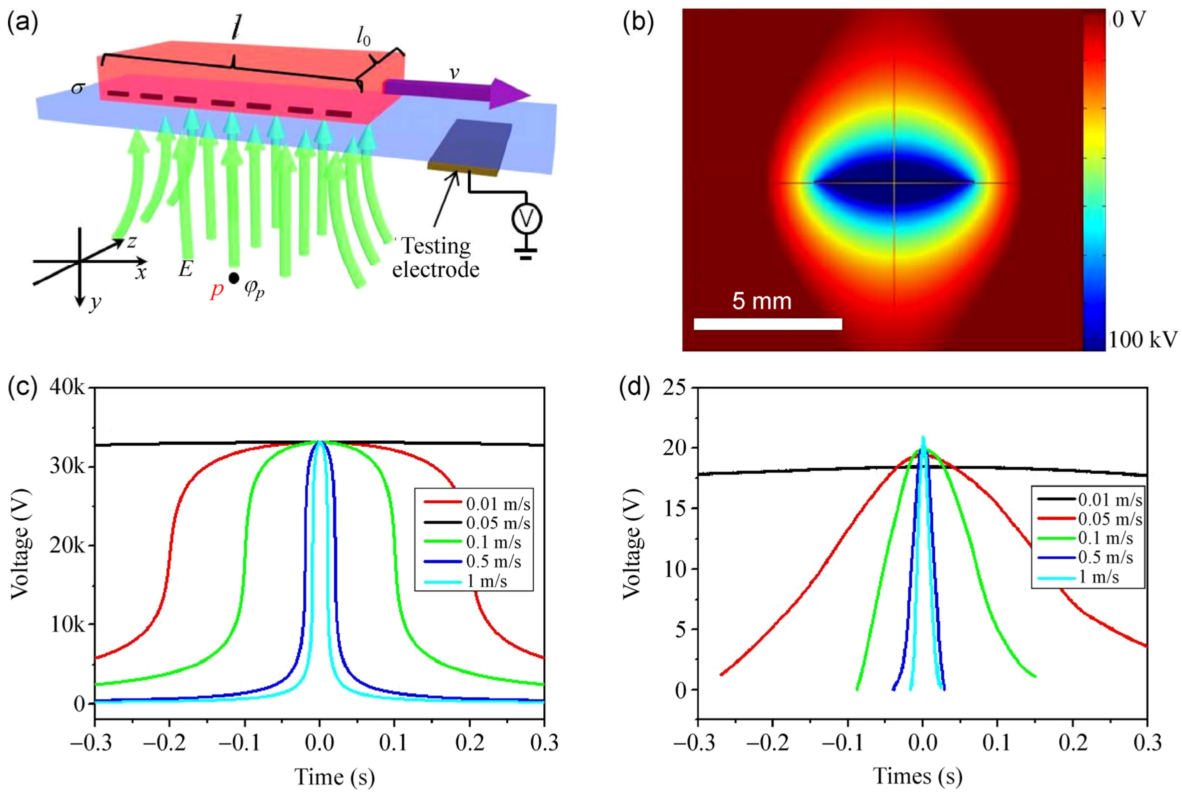

Figure 2 (a) Schematic diagram of the electric-field and potential distribution for a charged slider (PTFE) moving along the surface of a glass plane. (b) Finite element simulation of the potential distribution for the charged slider. (c) The calculated and (d) the measured voltage changes as a function of different sliding speed. The testing electrode was attached on the other side of the glass plane (as shown in (a)).

uniform speed of v along the x direction. The electric potential φ_p at the point p at time t ($t > 0$) can be obtained using electrostatics principled (see the Electronic Supplementary Material (ESM) for a detailed derivation) [27]

$$\varphi_p = \frac{\sigma l_0}{4\pi\varepsilon_0}\left[\ln\left(vt + \frac{l}{2} + \sqrt{d^2 + \left(vt + \frac{l}{2}\right)^2}\right) - \ln\left(vt - \frac{l}{2} + \sqrt{d^2 + \left(vt - \frac{l}{2}\right)^2}\right)\right] \quad (1)$$

where ε_0 is the vacuum dielectric constant, d is the vertical distance of p point away from the moving direction, corresponding to the time $t = t_0 = 0$ (Fig. 2(a)). Therefore, the potential generated by the moving charged plate in space changes with time t and the speed v. The potential distribution for the charged plate can be verified through numerical simulation using COMSOL. The σ on the frictional interface of PTFE was assumed to be 100 μC/m^2. As displayed in Fig. 2(b), the potential gradually decreased in space far away from the charged plate, which forms a potential gradient around the centre. When the charged plate slides at different speeds, the induced potential at the point p can be calculated by Eq. (1) as shown in Fig. 2(c). All the curves have same maximum voltage at $t = 0$, corresponding to the minimum distance d between the plate and the point p. When the plate is far away from the center ($t = 0$), the voltage curve exponentially decreases as an approximate Gaussian function, and the voltage gradient increases with the speed. For comparison with the theoretical curves, experimental data were measured and are shown in Fig. 2(d). A testing electrode was attached on the other side of the glass plane and the distance between the PTFE and electrode was 0.5 mm. The results illustrate that the speed of voltage drop is proportional to the speed of the plate, which is consistent with the theoretical analysis. Due to the changing potential, a varying electric field can be generated and used for plasma discharge.

2.2 UV light emitting device

Using the variable electric field, a self-powered UV light emitting device based on triboelectrification was fabricated. A low-pressure Ar–Hg mixture was sealed in a quartz glass discharge cavity and a PTFE film was attached on the surface of the glass cavity and slid with different speeds along the surface of the cavity. When friction appears, a violet plasma radiation was found under the friction interface (Fig. 3(a)). The emission spectra, shown in Fig. 3(b), reveal that the main peak is located at 253.7 nm, and has a full width at half maximum of ~0.14 nm. According to the model of low-pressure plasma discharge, a strong 253.7 nm UV emission originates from the radiative transitions of Hg atoms from the excited state of 6^3P_1 to the ground state of 6^1S_0 [26]. Another peak (313 nm) is also ascribed to the transitions to the resonance level $^3P_1$ of Hg atoms. Other emission peaks, such as 750, 763 and 811 nm, are typical discharge from Ar [28].

In this device, the voltage and current between the inductive electrode attached on the opposite surface of the discharge cavity and ground were measured. A discontinuous friction between PTFE and quartz glass leads to a pulsed voltage and discharge current, which are shown in Fig. 3(c). As depicted there, a discharge current pulse and phase difference of ~π/2 between current and voltage were formed during the plasma discharge. Because the discharge occurs between the glass dielectrics, the glass can be viewed as a dielectric barrier discharge (DBD) [25, 26]. In the DBD model, the discharge circuit is equivalent to a parallel connection of a gas gap capacitance and a resistance, in series with a dielectric capacitance [23, 29]. The current peaks are derived from the displacement current in the cavity. When discharge occurs, the movement of ions from the plasma towards the dielectric layer (quartz glass) results in a displacement current, which is asynchronous but superimposed with a capacitive current with a phase difference between the current and voltage. When the sliding speed increases, the discharge current and the corresponding UV light intensity also increased

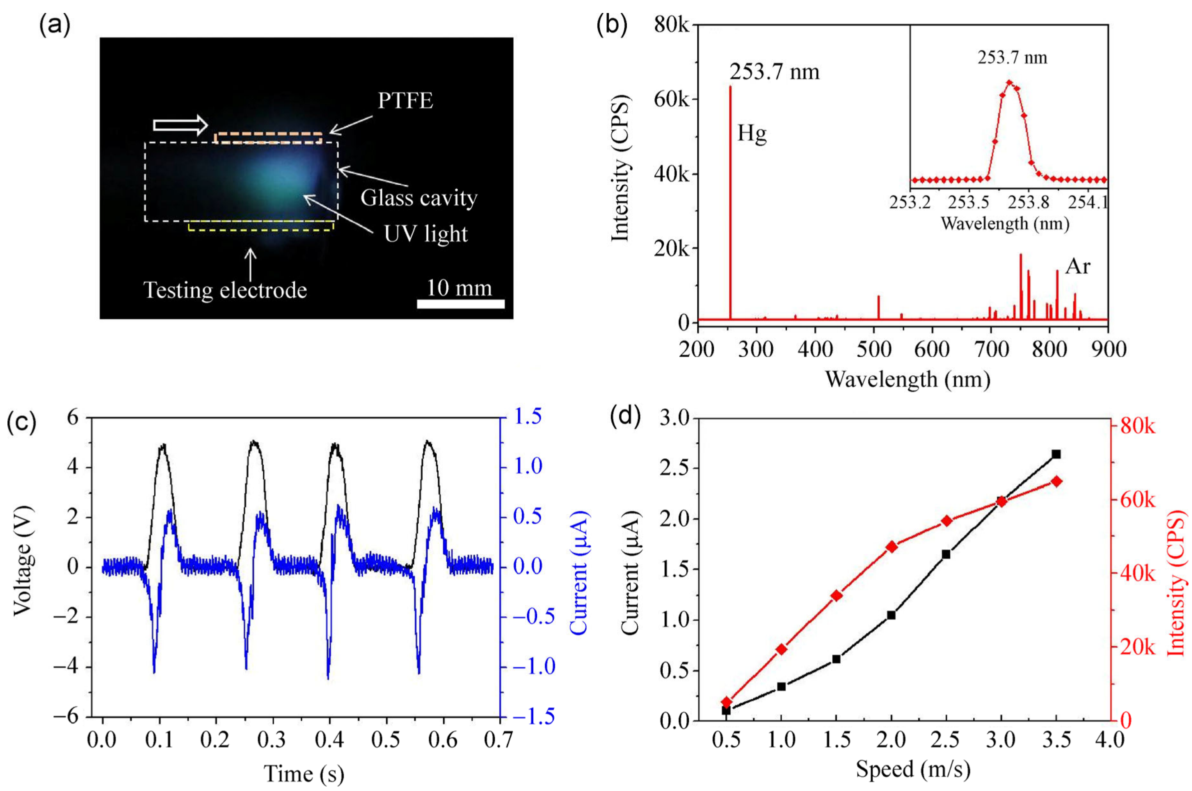

Figure 3 (a) A photograph of UV emission caused by friction between PTFE and the quartz cavity. (b) The corresponding UV emission spectra. (c) Measured voltage and discharge current curves. (d) The discharge current and UV luminescence intensity as a function of different rubbing speeds.

as shown in Fig. 3(d). This result indicates that the coupling between triboelectrification and plasma discharge is an effective way to obtain a strong UV emission.

2.3 White light emission

UV irradiation can be used as an excitation source to realize visible light emission because of the high UV photon energy. One of the most extensive applications of UV irradiation is the fluorescent lamp [30]. A high-frequency alternating current electric field can bring about a discharge of low-pressure mercury vapor leading to emission of UV light, which can excite a fluorescent powder and give white light emission. In our experiment, the UV device was introducused as an excitation source to realize self-powered white light emission. The glass cavity was filled with a low pressure Ar–Hg mixture and a tricolour phosphor coating was coated on the inner surface forming fluorescent cavity. The triboelectric field is generated by the friction beween a PTFE plate and the surface of the fluorescent cavity resulting in triboluminescence. Figure 4(a) shows the variation in luminescence intensity as a function of the friction and sliding speeds. At a low speed of 0.05 m/s, a marked luminescence can be observed. When the sliding speed increases, the luminescence intensity increases almost linearly. Meanwhile, a fast reciprocating-friction with bare hands can generate a bright and continuous white emission (see the Movie in the ESM), which means that a high frictional frequency contributes leads to increased luminescence intensity by increasing the frequency of the changing current electric field. According to plasma discharge theory [23], the plasma power is proportional to the discharge frequency and determines the luminescence intensity; this is in accordance with the experimental results. Figure 4(b) shows the luminescent spectra of a commercial fluorescent lamp (220 V, 50 Hz) compared with the fluorescent cavity. The similar peak positions shows that they have the same luminescence nature. The notable luminescence demonstrates the feasibility of our voltage tuned/controlled light-emitting device and self-powered device.

2.4 UV sterilization

Ultraviolet rays have been used as a reliable and environmentally-friendly sterilization method for medical equipment or packaging of food for a long time [31–34]. Due to the high energy, the chemical bonds of deoxyribonucleic acid and chemical sub-stances in cells can be broken or decomposed resulting in bacteria death [33, 35, 36]. Compared with traditional sterilization methods, such as heat, chemical solutions or gases, UV sterilization have the advantages of low temperatures, high efficiency and leaving no residues on objects. In general, a power supply is necessary for the generation of UV source. Herein, a self-powered UV sterilization system, which can be operated by consuming mechanical energy was fabricated. A reciprocating friction at a frequency of 5 Hz was employed to generate approximately continuous UV

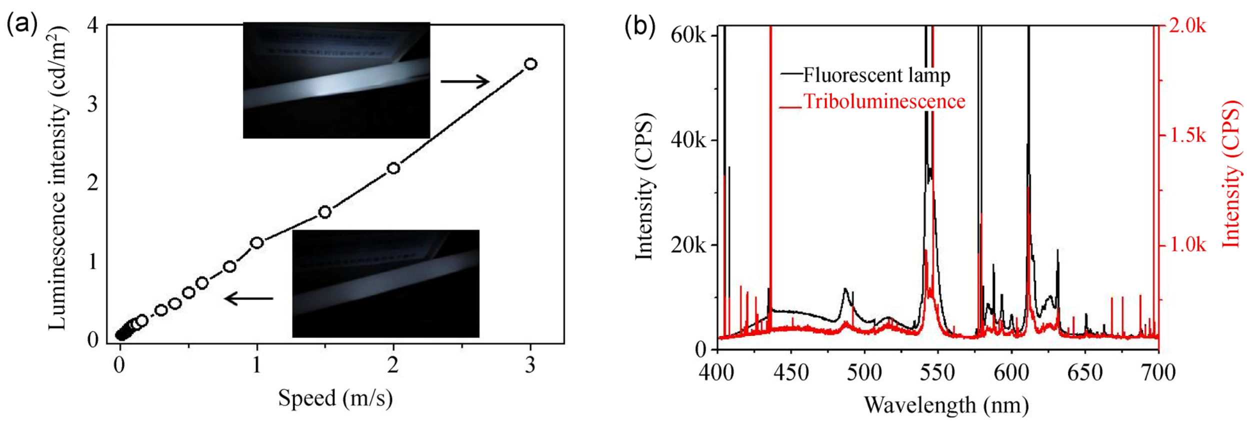

Figure 4 (a) The luminescence intensity changes at different sliding speeds. The insets are photographs of the luminescence cavity at different speeds. (b) Comparison of the emission spectra for a fluorescent powder excited by triboelectrification induced UV light and a fluorescent lamp.

irradiation. To test the sterilization properties, *Escherichia coli* (*E. coli*) CICC 23657 were chosen as the experimental targets and treated for 0–30 min by UV irradiation. The results of sterilizing *E. coli* under various conditions are shown in Fig. 5(a). It is obvious that thousands of colonies can be observed in the Petri dishes without UV radiation (Fig. 5(a), 0 min). With the increase of radiation time, the colony counts decrease markedly. The survival curve at different UV irradiation times is shown in Fig. 5(b). The curve approximates to an exponential decay and about 80% of *E. coli* were eliminated after 10 min UV irradiation. On average, a sterilization rate of ~98% can be reached after 30 min treatment. This confirms the effective sterilization obtained using our UV device driven by mechanical movement rather than the consumption of electrical power or chemical agents.

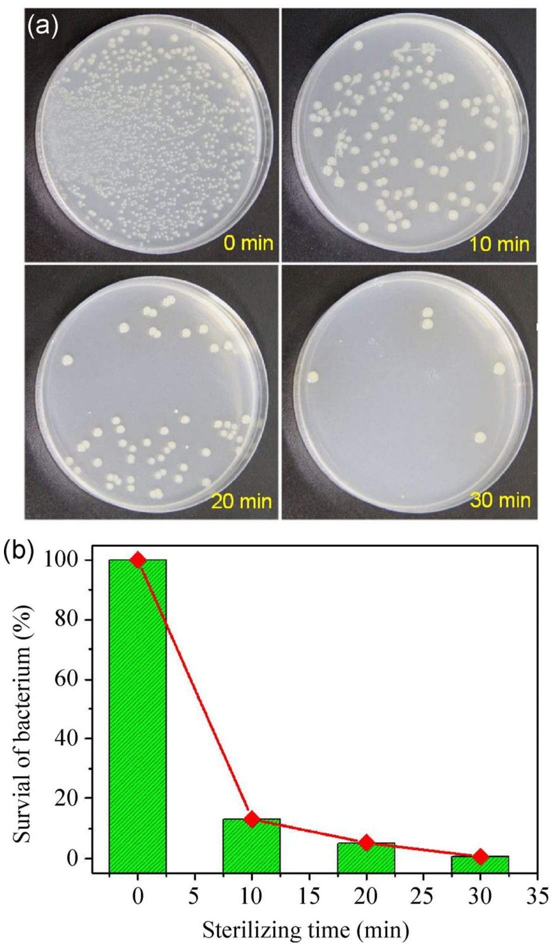

Figure 5 (a) Photographs of *E. coli* colonies under various radiation times. (b) Surviving rates of *E. coli* at different treatment times.

3 Conclusion

A simple UV light emitting device has been fabricated based on triboelectrification and plasma discharge luminescence. Continuous friction between PTFE and quartz glass was proven to generate a changing electric field in space and fast rubbing increases the potential gradient, which can bring a low-pressure plasma discharge and emit 253.7 nm UV light. Using the UV irradiation, a trichromatic phosphor can be excited and gives out white light, which is comparable to a fluorescent lamp. The UV irradiation from the reciprocating mechanical friction at a low frequency was also an effective sterilization agent, and ~98% of *E. coli* can be killed. By coupling triboelectrification and plasma luminescence, this work has expanded the application of TENG as a voltage tuned/controlled device. The result may provide a brand-new approach to obtain deep UV light emission using low-frequency mechanical friction in situations where there is no power source, which opens a new applications of our self-powered UV light emitting device.

4 Experimental section

4.1 Fabrication and characterization of the UV emitting device

A quartz glass discharge cavity, filled with argon and mercury vapor at a pressure of ~300 Pa was constructed to generate a plasma discharge. The vessel wall of the cavity was 0.5 mm. A PTFE film (100 μm thickness) was attached on the surface of the cavity to produce a direct friction with the surface of the quartz glass cavity. The electrical properties in the sliding mode were measured by a Stanford Research Systems SR570 current pre-amp to record current and a Keithley 6514 electrometer to record voltage. The spectrum distribution was detected by a spectrograph (HORIBA, iHR550).

4.2 Preparation of sterilization device

E. coli CICC 23657 was diluted (10^{-6}) by sterilized 0.9 wt.% NaCl solution and coated on sterilized LB agar plates in Petri dishes, which were then separately irradiated by the self-powed UV emission devices for 0, 10, 20 and 30 min, The distance between UV discharge cavity and Petri dish was 5 mm. Then it was incubated at 37 ℃ for 24 h to form bacterial colonies. The slider (PTFE) was rubbed with the cavity by a reciprocating motion at a frequency of 5 Hz.

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