Normally Transparent Tribo-Induced Smart Window

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ABSTRACT: Self-powered smart windows are desirable with the expectations of their energy-saving, weather-independent, user-controllable, and miniature performance. Recently developed solar- or thermal-powered smart windows largely depend on the weather conditions and have an extremely slow response, and only a certain portion of the saved energy can be utilized by the external circuit for mode conversion. In this work, a self-powered normally transparent smart window was developed by the conjunction of a rotary freestanding sliding triboelectric nanogenerator (RFS-TENG) and a polymer network liquid crystal (PNLC) cell. To fabricate the PNLC cell, the alignment layer with randomly distributed microdomains was constructed to encapsulate a mixture of LC polymers and nematic LCs. The opacity of the smart window exposed to an alternating electric field was considerably improved owing to the embedded microdomains and a dense web of LC polymers. The ultrahigh haziness greatly alleviates the charge density required for the LC actuation and thus enables the driving by the TENG where the charge amount is usually limited. The RFS-TENG was elaborately designed with six periodic bent triboelectric films and Ag electrodes, which presented an ultralow friction wear and met the frequency requirement to achieve the steady opacity. By harvesting the mechanical energies from ambient environments, the tribo-induced smart window can benefit a wide variety of fields, such as self-powered sunroofs, wind-driven smart farming systems etc.

KEYWORDS: self-powered smart windows, triboelectric nanogenerators, liquid crystals, polymer network liquid crystals, ultrahigh haziness

Windows in buildings not only enable daytime indoor lighting and facilitate the photosynthesis of room plants but also serve as a pathway to exchange information between the indoors and the outdoors. However, a window with controllable transmittance is preferred to enable modulation on the radiant energy entering the building, as well as information exchange for privacy protection purposes. Smart window technology has recently gained considerable attention owing to the ability to alter the window transmittance. A wide range of mechanisms was investigated including electrochromism,1−6 thermochromism,7−9 and liquid crystal (LC) rotations.2,5,10−14 However, electrochromic (EC) windows usually suffer from long switching time of up to hundreds of seconds and a light leakage issue, which limit their application on privacy protection. Thermoresponsive windows are also not ideal due to the lack of user control.15,16 As a comparison, the smart window based on LC rotations exhibits the advantage of significantly fast response (e.g., a few milliseconds) due to the rapid reaction of LCs to the electrical field.

It is estimated that an energy savings of 20% can be made through smart windows due to the reduced power for cooling and heating,17 but we also notice that the operation of smart windows still consumes unwanted electrical power, which increases as the window size scales up.18−21 In this case, a self-powered smart window or a window driven by green power is highly demanded to achieve genuine energy savings and environmental protection. Over the past several years, many efforts have been devoted to develop self-powered smart windows, where components with special functionality are incorporated. For example, an absorbing layer (a-Si) was deposited on a LC window to serve as a photovoltaic cell,22,23 but the generated electric power highly depended on the weather, and an external circuit is required to convert a DC signal into an AC signal.1,24 A smart window switched by thermal energy is another solution; however, the switching performance is seriously affected by environmental variations, and the response is notoriously slow.25,26 Triboelectric nanogenerators (TENGs), however, provide a different way...
to solve these issues. TENGs, first invented in 2012, can effectively harvest environmental mechanical energy, which is abundant and independent of weather. The operation of TENGs is based on the conjunction of triboelectricity and electrostatic induction mechanisms. As the output performance of TENGs has been greatly improved, the TENG is being widely employed to generate electrical power for small electronic devices.

Compared with other energy-harvesting technologies, the energy required by smart windows can be easily met by TENGs with extremely miniature structures, which can be flexibly embedded in a moving mechanical component for triboelectricity. Most importantly, the output signal of TENGs is in an AC form, which is particularly suitable to actuate the LC-based window. Also, a LC-based window is a capacitive device powered by ultralow current, which exactly matches the output feature of TENGs. In LCs, the polymer-dispersed LC (PDLC) suffers from high charge density of 220 nC/cm², and its normally opaque state causes difficulties and reliability challenges to be driven by TENGs. As a comparison, a polymer network LC (PNLC), possessing a normally transparent mode and much lower switching power, is extremely suitable for TENG actuation. In this work, a self-powered tribo-induced smart window was developed by the integration of a rotary freestanding sliding (RFS) TENG with a normally transparent PNLC window. A microdomain structure on the LC alignment surface provides the PNLC window with an ultrahazy state with a low charge density of 60 nC/cm².

RESULTS AND DISCUSSION

As shown in Figure 1a, the tribo-induced self-powered smart window consists of a RFS-TENG and a PNLC. The RFS-TENG was utilized to collect rotational mechanical energies from the ambient environment, such as windmills, wheels, and electric fans, from which the harvested electrical energy was employed to charge the PNLC in the AC mode. To achieve excellent triboelectricity performance, a pair of triboelectric materials with a large electron affinity difference should be selected. In this work, polyvinyl chloride (PVC) and nylon were chosen for the triboelectricity, where the PVC loses electrons and the nylon gains electrons. In the proposed RFS-TENG, nylon and PVC films function as the stator and rotator, respectively. For practical applications, the PVC film should be attached to the moving mechanical components such as wheels in a vehicle, indoor electric fans, and windmills, serving as a freestanding slider. In this work, an acrylic plate with a high rotating speed imitated those mentioned mechanical components, providing ambient rotation mechanical energies. When the RFS-TENG operates, the rotating PVC sweeps on the nylon. In this process, low friction wear is needed for the durability and reliability considerations of a mechanical system. To minimize the friction wear during the operation of RFS-TENG, the PVC film was bent to contact the nylon film, instead of directly pressing the whole acrylic-based rotator on the stator, which not only induces greater friction wear but also becomes easily damaged upon unbalanced loading. When the triboelectricity occurs, the effective contact between the PVC and nylon films can be ensured owing to the electrostatic attraction effect. The bent PVC film can be self-adjusted when the unbalanced pressure is loaded to minimize the impact on the sliding process. The bending-induced elastic force, which is determined by the PVC stiffness, should be kept high enough to ensure the desired contact area. The PVC stiffness increases with respect to the thickness, and in this work, 100 μm thickness was selected. The contact area between the PVC and nylon was determined by the distance between the acrylic plate and the nylon film, where the shorter distance corresponded to the larger contact area. Electrodes are placed beneath the nylon film. The fabrication of electrodes was based on printed circuit board (PCB) technologies, where Ag was deposited on the flame retardant 4 (FR4) substrate. The whole Ag-coated FR4 is rectangle-shaped, which was separated into two electrodes. Six uniformly distributed Ag-deposited sectors on the FR4, which are electrically connected, served as one electrode, and the remaining Ag area functioned as the other electrode. To enhance the frequency of the TENG output to fit the driving requirement of the PNLC, six bent PVC films were attached to the acrylic, each of which corresponded to one sector in the electrode. Such a periodic structure enables the 6-fold frequency. The rotation speed of 16 in. vehicle wheels at 70 km/h and electric fans in normal operations are 914 and 900
rpm, respectively. If such a RFS-TENG is applied on such wheels or electric fans, the frequency of the output should be around 90 Hz, which is much higher than the 24 Hz limit required by the smart window. A PNLC was electrically connected with the RFS-TENG, the crystal alignment of which was randomized upon charging by the RFS-TENG, resulting in the multiple-scattering effect. The transparency can be controlled through the voltage drop on the PNLC. The proposed PNLC, as an optical modulation device, has great potential for various applications where conventional windows such as indoor windows, vehicle sunroofs, green-house farming sunroofs, as well as an aircraft porthole can be replaced for controllable cooling and privacy protection applications. The fabrication details and switching mechanism will be introduced in following sections. The conjunction of the RFS-TENG and PNLC, as a whole, enables a fully self-powered transparency-tunable smart window, where the external power supply can be eliminated. A photograph of the landscape on the campus imaged through the PNLC with and without RFS-TENG driving is shown in the bottom left corner of Figure 1a. The landscape can be faithfully revealed when RFS-TENG was not triggered, which looks like the PNLC did not exist. When the PNLC was driven by the RFS-TENG, the landscape image through the PNLC was fully blocked and is attributed to the multiple-scattering effect.

Figure 1b illustrates a schematic diagram of the charge transfer process in one electric cycle with four stages. The contact between the nylon and the PVC results in the triboelectric charge separation, followed by the electrostatic induction resulting from the displacement between the two triboelectric layers. The surface charge amounts of two triboelectric layers continue accumulating until saturation, and as a result, the RFS-TENG delivers periodic electrical output after a few cycles. The RFS-TENG is electrically connected with the proposed PNLC. The PNLC can be electrically treated as a capacitor, where the induced electric field inside polarized the PNLCs. Charging and discharging of the PNLC occurred when the RFS-TENG was triggered. The PNLC was normally transparent when no voltage was applied because, at this state, the PNLC molecules are well-aligned. When the voltage applied on the PNLC was above the actuation threshold voltage, the PNLC became opaque immediately, resulting from the randomization induced multiscattering. Therefore, as indicated in Figure 1b, each of the hazy and transparent statuses are presented alternatively twice in each electric cycle of the TENG.

As a self-powered voltage supplier for the smart window, it is necessary to electrically characterize the performance of the developed RFS-TENG. The measurement setup is shown in Figure 2a. Two Keithley 6514 electrometers were employed to measure the current and the charge transfer amount. The proposed RFS-TENG operated at 900 rpm, which approaches the rotation speed of the vehicle wheel at 70 km/h and an electric fan at the normal operation. The aforementioned 6-fold frequency enhancement featured by the RFS-TENG enables a 90 Hz output frequency. RFS-TENGs usually provide an open-circuit (OC) voltage of over 1000 V, which exceeds the measurement range of the majority of voltmeters, making it challenging to directly characterize it. Alternatively, the OC voltage can be revealed through the measured current passing through a resistor with an ultrahigh resistance serially connected with the RFS-TENG. The switch was connected to position 2 to measure the current passing through the 2000 MΩ resistor, and the OC voltage was obtained by the product of the measured current and the 2000 MΩ resistance. From the measured result, as shown in Figure 2b, it can be observed that the peak OC voltage of the RFS-TENG can be as high as 2000 V due to the ultralow inner capacitance of the proposed RFS-TENG. In addition to the OC voltage measurements, the electrical performance of the RFS-TENG was characterized...
under the short-circuit (SC) condition, where the SC transferred charge and the SC current were measured, as illustrated in Figure 2c,d. The switch was connected to positions 1 and 3 to measure the current and the amount of transferred charge in the SC conditions. The maximal transferred charge amount of the proposed RFS-TENG can be 350 nC, which is high enough to drive the proposed PNLC window as will be discussed. The SC current is the time derivative of the SC transferred charge number, and this value linearly increases with respect to the rotating speed, and at 900 rpm, the SC current is greater than 150 μA.

The electricity harvested by the RFS-TENG was employed to drive an electrically responsive optical switching device. The optical transparency modulation in this study was enabled by a PNLC window, where the alignment layer surface is treated to be a randomly embedded microdomain structure. Compared with conventional LC-based switching devices, such as PDLCs, the proposed PNLC features normally transparent performance. Due to the inhomogeneity on the alignment surface, greatly enhanced multiple-scattering capability was achieved by a small amount of charge required, making it extremely suitable to be driven by the TENG.

The fabrication process of the proposed PNLC window is shown in Figure 3a. The alignment layer preparation process is stated in the Methods section. In fact, the alignment layer plays a significant role in most of the LC-based devices, where the alignment layer is aimed to control the orientation of liquid crystal molecules with a satisfactory anchoring energy. By properly choosing the alignment materials, different LC orientations can be achieved, such as planar alignment, homeotropic alignment, as well as tilted alignment. The alignment material used in our PNLC window is a vertical alignment polyimide material from the Nissan company, which can provide LCs with a very good and uniform homeotropic alignment. The vertically aligned configuration accordingly offers a transparent state to the PNLC cell owing to a matched refractive index of short-axis for both LC and the LC monomer. During the cooling treatment of the alignment layer, as shown in Figure S1 in the Supporting Information, the LC monomer is gradually isolated from the polyimide due to its reduced interaction with polyimide. The phenomenon is called phase separation, and its occurrence leads to an evolution on the film from a smooth surface to an inhomogeneous surface. The surface morphologies after the cooling treatment were characterized by atomic force microscopy (AFM), the result of which is presented in Figure 3b. It is observed that, after the temperature treatment, the surface appeared with a puddle-like morphology, the domain size of which is around 10 μm and the average depth of which is around 100 nm, which is much higher than that without the surface treatment, as indicated in Figure S2 in the Supporting Information. Afterward, the film was illuminated with a UV lamp with an intensity of 20 mW/cm² for 2 min so that the LC monomer was partially polymerized and the alignment surface was strengthened.

After that, two indium tin oxide (ITO) coated glasses with treated inhomogeneous alignment layers were placed to face each other, between which the distance of 8 μm was uniformly controlled by silicon dioxide spacers. The empty cell was then filled with a mixture consisting of a fluidic nematic LC and the LC monomer. Here, it is worthy to mention that the nematic LC cannot be polymerized, whereas the LC monomer doped by the photoinitiator can be polymerized when exposed to UV light. Due to the vertically aligned polyimide material, both LC and LC monomer are aligned homeotropically to the ITO glass. The mechanism behind the homeotropic alignment at the LC/LC monomer alignment layer interface is due to the structure of polyimide, which possesses a long alkyl side chain that promotes vertical alignment of the LC and the LC monomer. In order to construct a polymer network inside the LC cell, UV light was used again to shine on the LC cell for 10 min. During the UV irradiation, the LC monomers start to cross-link with each other either inside the LC bulk or near the surface due to the embedded LC monomer on the surface. As a result, a polymer network was formed in the fluidic LC continuum. The fabricated PNLC device in this work has a 2.3 cm by 2.3 cm LC encapsulation area.

The fabricated PNLC window exhibits ultrahigh transparency at the power-off state so that it is quite challenging to distinguish two stacked glasses and the PNLC window, as shown in Figure 3c. In fact, without the application of the electrical field, both nematic LC and the LC polymer network aligned vertically in the cavity of the cell. LC is a birefringence material and has two different refractive indices along its short axis and long axis. The refractive indices along the short axis and the long axis are called ordinary refractive index, n₀, and extraordinary index, nₑ, respectively. For the nematic LC, these two refractive indices are 1.5 in the short axis and 1.67 in the long axis. The short-axis refractive index of the LC polymer is identical to that of the nematic LC, and its long-axis refractive index is 1.7. As the incident light passes through the window,
the ordinary refractive indices of nematic LC and LC polymer apply, abbreviated as \( n_{\text{el}} \) and \( n_{\text{op}} \) respectively. Because \( n_{\text{el}} \) equals \( n_{\text{op}} \), the light will not be scattered and a transparent window will be present. However, if a voltage is loaded, the network monomer LC remains unchanged and only the nematic LC molecules will realign as a response to the electrical field. At this moment, what the incident light meets is an effective refractive index of nematic LC, \( n_{\text{eff}} \), and the unchanged \( n_{\text{op}} \) of the polymer.\(^{38,39}\) The effective refractive index of the nematic LC, \( n_{\text{eff}} \), is expressed as

\[
n_{\text{eff}} = \sqrt{n_{\text{el}}^2 \sin^2 \theta + n_{\text{op}}^2 \cos^2 \theta}
\]

where \( n_{\text{el}} \) is the refractive index of the nematic LC in the long axis and \( \theta \) is the angle between the polarization of incident light and the long axis of the LC molecule. Therefore, in this case, if \( n_{\text{el}} \) is not equal to or largely differs from \( n_{\text{op}} \) then the incident light will be randomly diverged inside, empowering a multiple-scattering effect accordingly, the details of which are explained in Figure S3 in the Supporting Information.

Therefore, as shown in Figure 3d, when the RFS-TENG was not triggered, the PNLC was not charged and performed a transparent appearance attributed to the matched refractive index of nematic LC and the LC monomer. The transparent smart window is denoted as the OFF state. When the RFS-TENG was triggered, the PNLC was charged with the electric field across the encapsulation, as shown in Figure 3e. The LC monomer, however, was cross-linked as the polymer networks so that they could not rotate. Instead, the fluidic nematic LC molecules can respond to the electrical field. The rotation of nematic LC, on one side, was driven by the electrical field, whereas on the other side, it was hindered by the surrounding polymer network. Nevertheless, with a proper voltage or charge loaded, the nematic LC molecules will anchor at their desired positions. The refractive index contrast between the randomly oriented LC and the well-aligned LC polymer network led to the multiscattering of the incident light, and as a result, the smart window became significantly opaque. In this moment, the opaque smart window is referred to as the ON state.

Another contributor to the haziness enhancement is the inhomogeneous alignment surface. It should be mentioned that the LC monomer embedded on the alignment surface can prominently enrich the polymer strands near the surface. As a result, these increasing polymer strands as well as the inhomogeneous morphology mutually promote the randomness of LC molecule distribution. Therefore, the power-on haziness was considerably enhanced. In addition, it should be noticed that the electric field loaded on the LC must be in the AC mode. If the DC mode electrical input is applied, the LC, as a dielectric medium, will stay at a polarization state. Whereas a long-term polarization state of the LC molecule will cause a change or even damage on the chemical characteristic of LC itself.\(^{30–42}\) As a consequence, the response of LC molecules to the electric field will be less sensitive and effective. Therefore, compared with DC output energy harvesters such as solar cells, pyroelectric nanogenerators, a TENG with a natural AC electrical output is more suitable for the actuation of LC-based smart windows.

The fabricated PNLC was electrically connected with the RFS-TENG, serving as a self-powered smart window. The PNLC can be electrically treated as a capacitor. When the RFS-TENG was triggered, the PNLC was charged and the induced electric field caused the smart window to be hazy. During the operation of the RFS-TENG, the PNLC window quickly switched between the ON and OFF status. Considering that the 6-fold frequency was enabled by the RFS-TENG and the two hazy stages of the PNLC in one electric cycle, the switching frequency of the proposed smart window is 12 times of the rotation frequency. This means that the required rotation frequency to achieve the stable haziness can be as low
as 2 Hz, which can be easily attainable for the majority of ambient mechanical energies. The electrical performance of the tribo-charged PNLC window was evaluated. A measurement setup was constructed, as shown in Figure S4, where two Keithley 6514 electrometers functioned as a voltmeter and a charge meter. Such a measurement circuit enabled the characterization of the voltage drop on the tribo-charged PNLC and the amount of the charge transferred. The voltage drop on the PNLC is illustrated in Figure 4a. The peak voltage drop of the PNLC is around 68 V, much lower than the OC voltage of the RFS-TENG. The reason is that the capacitance of the PNLC is much higher than that of the inner capacitance of the RFS-TENG. The electrical frequency measured from the PNLC is 90 Hz, identical to the output frequency of the RFS-TENG. Figure 4b indicates the relationship between the voltage drop \( V \) on the PNLC charged by the RFS-TENG and the amount of transferred charge \( Q \). It is observed that the \( V-Q \) profile is two nearly overlapped lines, further demonstrating the capacitive nature of the developed PNLC. The extremely low power loss, as indicated by the narrow area surrounded by two lines, might arise from the unexpected discharging effect in some electrical contact points. Upon charging by the RFS-TENG, the rotation of the nematic LC led to the permittivity variation, thus the capacitance of the PNLC was affected. However, such a capacitance variation of the PNLC is so small that it cannot be revealed in the \( V-Q \) profile. As shown in Figure 4b, the transferred charge amount \( Q \) linearly increased with respect to the voltage drop \( V \) on the PNLC, and \( Q \) had its maximal value of greater than 300 nC when the voltage drop reached 68 V.

The tribo-induced electric field on the PNLC led to the variation of its optical properties. Therefore, it is necessary to characterize the optical performance of the developed self-powered PNLC via the RFS-TENG. A UV–vis spectrophotometer was first employed to evaluate the transmittance of the PNLC with and without tribo-charging. A Lambda 20 spectrophotometer from PerkinElmer was utilized in this study. The transmittance of the PNLC was obtained by the radiant power ratio of the transmitted light from the PNLC and the incident light. In the measurement setup, the monochromatic light was perpendicularly pumped to the PNLC window, and the transmitted light was collected by an integrating sphere embedded with a photodetector inside. The integrating sphere guaranteed that the diffused light after the multiple-scattering process was able to be fully collected. The transmittance measurement was undertaken through a wide range of the light wavelength from 300 to 1000 nm, ranging from UV to infrared (IR) regions. From the measured results, as shown in Figure 4c, it is observed that when the PNLC was not connected with the RFS-TENG, the PNLC presented a normally transparent mode with extremely high transmittance. At the 350 to 1000 nm wavelength range, the transmittance is greater than 87%. A transmittance fluctuation was observed in the range from 350 to 750 nm, which resulted from the interference effect of the monochromatic light in a high transparent medium. For the low transmittance ranging from 300 to 350 nm, it is possible that the doped photoinitiator presented the absorption effect on the UV light. Afterward, the PNLC was powered by the RFS-TENG operating at 900 rpm as set above. The measured transmittance result indicates that a significant transmittance decrease was achieved when tribo-charging in the AC mode was performed, resulting from the backscattering of the tribo-charged PNLC window. The measured transmittance increases with the increase of the incident light wavelength and peaks around 17%. At least 65% transmittance contrast can be attainable in the range from 780 to 1000 nm, which means greater than 65% infrared radiance from sunlight can be blocked using the proposed self-powered PNLC. This demonstrates the feasibility of the proposed self-powered smart window serving as a sunroof. It is interesting to find that the tribo-charged PNLC performed no transmittance fluctuation as did by the uncharged PNLC. The underlying mechanism is that the randomized PNLC induced the multiple-scattering effect, where the light path length was greatly enlarged and randomized, and as a result, the interference effect inside the PNLC was eliminated. Compared to the PNLC status with and without tribo-charging, the maximal transmittance contrast can be as high as 97%. Another important optical property to evaluate the smart window performance of the smart window is the haze ratio. Different from the transmittance, the haze ratio evaluates the radiant power ratio between the diverged transmitted light and the direction-unchanged transmitted light after the multiple-scattering process. The operation mechanism to measure the haze ratio and the corresponding calculation principle can be found in Figure S5 in the Supporting Information.\(^{43}\) To reveal the overall haze performance through a broadband wavelength range, the filament-based lighting source was employed for measurement, which performed a blackbody-like emission spectrum. The measured haze ratio of the PNLC with and without charging by the RFS-TENG is compared, as shown in Figure 4d. The haze ratio contrast is calculated to be as high as 78%. The measurement of the haze ratio of the stacked two glasses without PNLC encapsulation was also carried out. This ratio was measured to be 0.4%, smaller than that of the power-off PNLC of 2.28%. The reason for the higher power-off haze ratio of the PNLC over the stacked two glasses is that even though the alignment layer was present in two types of LCs, such alignments cannot be as perfect as all LCs were perpendicular to the ITO layers. Such less perfect alignments therefore led to a weak scattering effect and slightly increased the haze ratio. However, it should be noticed that the above-mentioned increasing haziness is extremely trivial and difficult to distinguish, as indicated in Figure 3c.

The developed tribo-induced self-powered smart window was also evaluated in terms of its privacy protection performance. The logo of the Chinese University of Hong Kong (CUHK) was employed for the image observation to validate the privacy protection effectiveness of the self-powered smart window. The logo was imaged by a camera through the developed smart window. A Huawei Mate 20 smart phone served as the camera for recording. The logo-to-window and window-to-camera distances were 36 and 17 cm, respectively. The photographs of the self-powered smart window before and after powered by the RFS-TENG are illustrated in Figure 4e,f. It can be observed that when the PNLC was powered by the RFS-TENG, the logo image was fully blocked and nothing could be observed through the window, demonstrating its privacy protection capability. It can also be found that the haziness of the smart window is extremely uniform, indicating that the strength of the multiple-scattering effect is very high. When the RFS-TENG is not triggered, the self-powered smart window was very transparent and the logo could be clearly observed. Switching the self-powered smart window ON and OFF was also performed repetitively, the video of which is shown in Video S1. From Video S1, it can be observed that the
response of the self-powered smart window was very fast, and the image changed immediately upon the electrical switching. The switching ON and OFF times of the developed PNLC were measured to be 0.5 and 6.5 ms, the details of which are introduced in Figure S6 in the Supporting Information.44−46

An application demo using the developed tribo-induced smart window was performed for the QR code protection, as shown in Video S2 in the Supporting Information. The logo was replaced by a QR code for the recognition of the WeChat official account of the Zi Lab of CUHK, and the distance for imaging remained the same. When the smart window was actuated by the RFS-TENG, the QR code behind was blocked and the smart phone was not able to recognize the QR image. Once the RFS-TENG was disconnected, the QR code appeared and was recognized immediately, enabling the access of the official account. This demo demonstrates the privacy protection capability of the developed self-powered smart window, and a great number of applications can be expected.

In real applications, the transparency of smart windows should be tunable to fit various situations. Through connecting an external capacitor in parallel, the voltage drop on the PNLC will be decreased and various external capacitances correspond to different voltage drops. In this work, various external capacitors were electrically connected with the PNLC in parallel, and one Keithley 6514 electrometer was employed to measure the voltage drop on the PNLC, the schematic diagram of which is shown in the inset in Figure 5a. The capacitances of the external capacitors employed were 4.7, 6.9, 9.9, 13.8, and 16.3 nF. The voltage drop measurement results are shown in Figure 5a. It can be observed that with the increase of the external capacitance, the voltage drop decreased. As the inner capacitance of the RFS-TENG is extremely low compared with that of the PNLC and external parallel capacitors, the voltage drop on the PNLC presented a nearly linear relationship with the external capacitance. When the 16.3 nF external capacitor was loaded, the voltage drop on the PNLC can be as low as 20.5 V. The voltage drop measurement result varies with different measurement approaches. When a voltmeter was employed, the voltage drop measured was 3−5 V lower than the one using the electrometer. The possible reason is that the sampling rate of the commercial voltmeter is lower than that of the Keithley 6514 electrometer.

The transmittance dependence on the voltage drop of the PNLC was also measured using the aforementioned spectrophotometer, the measurement setting of which was kept unchanged. The measured results are illustrated in Figure 5b. It can be observed that the measured transmittance decreased with the increase of the voltage drop on the tribo-charged PNLC. The spectral transmittance profile under 26.5, 29.5, and 35.7 V voltage drop of the PNLC with the external capacitor connected is very similar to that without the external capacitor, and with further decrease of the voltage drop, the transmittance profile is much more similar to that of the PNLC without charging. It is interesting to find that the zigzag waveform transmittance variation from 350 to 750 nm is gradually alleviated with the increase of the voltage drop applied, once again demonstrating that the interference was destroyed by the multiple-scattering effect, as discussed above, where the extent of destruction was associated with the strength of the multiple-scattering effect.

The dependence of the haze ratio on the voltage drop was also characterized using the aforementioned setup. Alleviated haze performance was observed when the external capacitor was connected. When the external capacitance decreased so that the voltage drop on the smart window increased, the haze ratio also increased accordingly owing to the enhanced scattering capability. This tendency can be clearly observed in the measured haze ratio of the smart window driven in...
various voltages, as shown in Figure 5c. It can be observed that the haze ratio is very sensitive to the voltage drop of the PNLC ranging from 20 to 40 V.

The logo images observed through the self-powered smart window when various external capacitors were loaded are illustrated in Figure 5d. The measurement setup and imaging distance were kept unchanged, as introduced above. The variation of the imaged logo when various external capacitors were loaded can be found in Video S3 in the Supporting Information. It can be observed that when the external capacitor was loaded, the transparency of the smart window became greater, and the larger external capacitance corresponded to the higher clarity of the logo image. When the 4.7 nF external capacitor was loaded, the voltage drop on the smart window decreased by 31 V, and in this moment, even though the logo image is still very blurry, the uniformity of the window is not as high as that without an external capacitor loaded, as shown in the first photograph in Figure 5d, where the subtle color variation can be observed outlining the logo profile. When the external capacitor loaded was 6.9, 9.9, or 13.8 nF, the transparency became much greater, where the profile of the logo image could be clearly observed. However, it is interesting to find that the observed color of the logo is quite different from that of the PNLC without power. The reason is that the multiple-scattering capacity among different wavelengths is different and each color consists of a combination of various wavelengths; therefore, the true color cannot be revealed through the smart window. This feature enables several self-powered camouflage applications. When a 16.3 nF capacitor was loaded, the pattern of the logo was much clearer and the logo color was more true, demonstrating that the incident light from the logo photo was weakly scattered by the smart window. However, it should be noticed that the 20.5 V tribo-induced PNLC still cannot present a logo image as clear as that without voltage. Through tuning the external capacitance, a great number of applications can be anticipated, where the desired transparencies, camouflaged colors, as well as the incident radiance can be well-controlled.

CONCLUSIONS

In summary, a tribo-induced smart window was presented by conjunction of a RFS-TENG and a PNLC, which is normally transparent and becomes opaque immediately upon tribo-charging. The randomly distributed microdomains embedded in the alignment layer and a dense web of liquid crystal polymers give the PNLC an ultraopaque state when charged by polymers (SE-4811, Nissan Chem.) were first blended and a mass ratio of 1:50 in N-methyl-2-pyrrolidone solvent and then spin-coated on an ITO substrate. The polyimide was used to provide a LC with a vertical alignment on the substrate. Afterward, the coated substrate was soft-baked at 80 °C for 60 s to evaporate most of the solvent and then slowly cooled for 30 s at a cooling rate of 1 °C/s, as shown in Figure S1 in the Supporting Information.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsnano.0c00107.

Temperature profile of the alignment layer treatment; comparison between inhomogeneous and smooth surfaces; mechanism of light scattering; distributions of nematic LC and LC polymer from the top view at power-off and power-on states; electrical characterization of the tribo-induced PNLC; haze measurement; response time measurement (PDF)

Video S1: Switching performance of the tribo-induced smart window (MP4)

Video S2: Information protection application for QR coding scanning using the tribo-induced smart window (MP4)

Video S3: Transparency variation of the tribo-induced smart window connected with different external capacitors (MP4)

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METHODS

Preparation of the PNLC Alignment Layer. A LC monomer (UCL017, DIC Corp.) and polyimide (SE-4811, Nissan Chem.) were first blended with a mass ratio of 1:50 in N-methyl-2-pyrrolidone solvent and then spin-coated on an ITO substrate. The polyimide was
Notes
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