A fully self-powered, ultra-stable cholesteric smart window triggered by instantaneous mechanical stimuli

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ABSTRACT

Smart windows (SWs), especially self-powered SWs, are desirable in a great variety of applications. Nowadays, nearly all SWs require continuous power supply enabled by batteries or energy harvesters such as solar cells, etc. However, batteries are usually with limited lifetime and potential environmental issues, while solar cells largely depend on the weather conditions. In this work, a fully self-powered, instantaneous-mechanical-stimuli-triggered, normally transparent smart window was developed based on an elaborately tailored cholesteric liquid crystal (LC) and a freestanding sliding triboelectric nanogenerator (FS-TENG). The transparency switching including transparency-to-haziness and haziness-to-transparency are facilely triggered by instantaneous TENG-charging and pressure-loading, respectively, with the high transparency contrast of 71.5% and the haze contrast of 61.8%. Both transparent and opaque modes can sustain for an extremely long time without continuous power supplies from energy harvesters. The smart window demonstrated in this work shows the capability of fully self-powered irradiation control for indoor temperature modulation and battery-free privacy information protection while the continuous power supply is no longer required, benefiting a wide variety of fields such as self-powered sunroofs, smart farming systems, motion-driven privacy protection systems, etc.

1. Introduction

As a key component in our daily life, windows bring indoor lighting and enable energy and information exchange between indoor and outdoor environments. Smart windows (SWs) were developed recently, where the transparency can be well-controlled [1–6]. The advent of SWs enables the room temperature adjustment without external cooler or heater under well regulations on irradiation flux through SWs [7,8], which potentially reduces 20% in building cooling and heating operation [2,9]. Beside the irradiation modulation, SWs also help to realize the selective visualization, which contributes to the privacy protection [15]. Liquid crystal SWs (LC-SWs) are regarded as the best candidate for SWs. Compared with other techniques such as electrochromic or thermochromic windows [10–13], LC-SWs have more facile and faster response to the electric field and cover broader solar spectrum [15,16]. LC-SWs exhibit plenty of appealing characteristics, but the operation of SWs has to rely on external electrical power which even multiplies as the window size scales up [17–19]. The need of uninterrupted power supply also raises the demands on the electrical circuit in order to meet the driving voltage as well as the frequency suited for LCs. As a result, conventional LC-SW modules suffer from relatively large space occupation as well as notoriously high facility cost. Moreover, SWs which run outdoors require batteries to power SWs, raising concerns on the limited lifetime and environmental pollution issues [20,21].

Over the past several years, people have paid great efforts to address this issue by combining LC films with energy harvesters. The photovoltaic assisted LC-SW was demonstrated by depositing an absorbing layer (a-Si) on the SW [22–24]. However, the generated electric power unavoidably depends on the weather, and an external circuit for direct to alternating current (DC-AC) conversion is needed, which consumes additional energy. Different from solar cells, triboelectric nanogenerators (TENGs), as firstly invented in 2012 [25,26], provide...
high-voltage outputs in AC form to power small electronic devices by harvesting ubiquitous mechanical energies from ambient environments [27–32]. Previous studies have demonstrated multiple TENG triggered smart windows [11,14,45]. However, it should be noticed that for both the photovoltaic assisted SW and the tribo-induced SW, to maintain the full functionality, continuous power supply from energy harvesters is normally required, which remains a huge challenge as the continuous energy supply may not be always available in the environment depending on the daytime and the weather. Therefore, an eco-friendly smart window capable of long-term sustaining both hazy and transparent states without continuous power supply required is particularly desirable. In this work, a self-powered bi-stable cholesteric LC-SW was developed. The transparency and opacity can be switched back and forth by tribo-charging and pressure-loading, respectively, both of which are triggered by instantaneous mechanical stimuli and maintained for a long time period, and thus continuous electrical power supply is not required anymore.

2. Results and discussion

2.1. Operation overview of the self-powered bi-stable smart window

As shown in Fig. 1(a), a self-powered bi-stable smart window was developed, the transparency switching of which was triggered by instantaneous mechanical stimuli. A cholesteric LC material was pre-engineered to be able to self-sustain its transparency or opaque state. The cholesteric LC was formed by elaborately adding a chiral dopant into a nematic LC (NLC) host medium, where the NLC spontaneously rotate and form a helical supra-structure in cholesteric LC film so as to switch the window from transparency to opacity. In our study, a free-standing sliding TENG (FS-TENG) was developed to charge the cholesteric LC film, with an electric field built through the coupling effect of triboelectricization and electrostatic induction. The FS-TENG consists of a stator and a slider. The stator was sandwiched by a 2.3 mm cardboard based substrate, two 60 µm copper electrodes and a 50 µm nylon film, the areas of which are 21.6 cm by 10.5 cm, 9.8 cm by 10.5 cm and 20 cm by 10 cm, respectively. The 9 cm by 8 cm slider still employs the 2.3 mm cardboard based substrate, beneath which a 200 µm fluorinated ethylene polymer (FEP) film was attached. The employment of the cardboard based substrate buffers the pressure loaded and enhances the contact triboelectricization area, thus promoting the output performance. Besides, the cardboard is both economically and environmentally friendly, which can be easily recycled. The developed FS-TENG is very compact and flexible, making it feasible attachment or detachment on different locations, triggered by environmental energies such as vibrations, wind and ocean waves [42–44]. The developed SW in this study can be widely employed in a great variety of application fields. The stator of the TENG can be mounted on the rear cover of the smartphone with the SW on the camera, to enable or disable the QR code scanning through the different hand motions for the privacy protection purpose. The FS-TENG can also be integrated with several mechanical structures, for examples, a spring-based oscillator in a ship, harvesting the vibration energy from the ocean wave and powering the SW for the irradiation controlling and privacy protection purpose. The developed FS-TENG can also be combined with a turbine located in buildings for harvesting the wind energy, powering the SW in the building for transparency modulation, etc.

![Operation mechanism of the developed fully self-powered, instantaneous mechanically-triggered smart window. (a) Transparency transition cycle of the developed smart window: the window initially features an ultra-high transparency caused by the orderly assembled helical structure in cholesteric LC film. By importing a sliding motion on the FS-TENG, the helical structure responds to the charging rapidly and transits to a randomly oriented texture leading to the highly opaque mode. The opacity even sustains for an extremely long time even the charge delivery is stopped. By gently touching the window, the scattering mode soon refresh back to initial transparent mode. (b) The cholesteric LC film is elaborately prepared by infiltrating an NLC mixture with a chiral dopant into the gap defined by two glass plates. The NLC molecules spontaneously rotate and form a helical supra-molecular structure given by the helical twisting power of the chiral dopant.]

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Upon the hand-sliding of the slider on the stator of the FS-TENG, the nylon film loses electrons and the FEP film gains electrons as the result of the triboelectric effect. To effectively charge the cholesteric LC, a rectifier was employed to convert the AC generated by the FS-TENG to the DC to boost the voltage drop on the cholesteric LC. When the voltage drop exceeded the threshold, the window became hazy. Even though the TENG was disconnected and the charge between the cholesteric LC film was quickly exhausted, the haziness can last for several days, benefiting from the bi-stable characteristic of the cholesteric LC as will be discussed in following sections. This means that the continuous power supply from the FS-TENG is no longer necessary for sustaining the hazy state. The charging time can be as short as a few seconds, which is several hundred times faster than the previously developed self-powered electrochromic smart window [11]. To resume the transparency back from the tribo-induced hazy state, a moderate pressing was enforced on the window. This pressing caused slight variation on the cell gap, by which LC molecules under the pressure point soon flowed and re-assembled their orientations to the initial transparent state, as an equilibrium state featuring a low system energy. Therefore, the developed smart window offers a fully self-powered irradiation modulation and information protection scheme merely relying on the instantaneous mechanical stimuli.

The preparation of the cholesteric LC film was described in Methods, involving a non-rubbing treatment method. The schematic diagram of the fabricated cholesteric LC film is illustrated in Fig. 1(b). In liquid crystal (LC) devices, the alignment layer determines how strong LC molecules can be anchored at the surface. Commonly, through a mechanical rubbing with the help of a velvet roller on the alignment layer, the LC molecules can align themselves along the rubbing direction with an enhanced interaction. In this work, we adopt a non-rubbing treatment on both substrates to weaken the interaction of the LC molecules and the surface. This is highly beneficial for the maintenance of the focal conic state to achieve the opaque state as triggered by the TENG. And it can switch to the planar state (transparent state) if the surface was rubbed by mechanical force.

2.2. Electrical characterization of TENG-charged cholesteric LC

The electric field that induced by the FS-TENG re-arranged the orientation of the cholesteric LC, and switched the smart window from the normally transparent state to the hazy state bearing an extremely long-term stability even when the electric field vanished. To effectively load the tribo-induced electric field across the cholesteric LC film, it is necessary to evaluate the electrical properties of each component of the window. We firstly evaluated the transferred charge of the FS-TENG under the short-circuit (SC) condition by an electrometer Keithley 6514 as shown in Fig. 2(a), indicating an AC mode output. The peak-to-peak transferred charge $Q_{\text{p-p}}$ is 250 nC. The output voltage of the FS-TENG under the open circuit (OC) condition was also measured by the same electrometer under the identical mechanical triggers, and the peak-to-peak value $V_{\text{p-p}}$ is 340 V as shown in Fig. 2(b). When the Keithley 6514 was employed to characterize the OC voltage of the TENG, the 300 pF capacitor embedded was also connected in the measurement circuit, as reported in our previous work [41]. This means that the measured OC voltage is attributed to both the inner capacitance of the TENG $C_T$ and the 300 pF capacitance of the Keithley 6514 $C_K$. $C_T$ can be calculated by the following equation.

$$Q_{\text{p-p}} = V_{\text{p-p}}(C_T + C_K)$$

Therefore, $C_T$ is evaluated to be 435 pF. The developed FS-TENG was repeatedly operated for over 5000 times, and the electrical output degradation is less than 1%, thanks to the buffer design for the TENG. Afterwards, the FS-TENG was electrically connected to the cholesteric LC to form a self-powered bi-stable smart window. The measurement circuit is shown in Fig. S1 in the Supporting Information, where the voltage drop $V$ and the transferred charge amount $Q$ was measured simultaneously. Two Keithley 6514 electrometers were employed, functioning as a coulometer and a voltmeter, respectively. As shown in Fig. 2(c), when the cholesteric LC was directly powered by the FS-TENG in AC mode, the $V$ and $Q$ was recorded simultaneously by the NI cDAQ data acquisition system and plotted through the LabVIEW program. The

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Fig. 2. Electrical characterization of the FS-TENG and TENG-charged cholesteric LC. (a) Transferred charge amount of the FS-TENG under the SC condition. (b) Output voltage of the FS-TENG under the OC condition. (c) The relationship between the transferred charge amount and the voltage drop on the cholesteric LC powered by the FS-TENG. (d) Equivalent circuit model of the cholesteric LC, where the chiral dopant and NLC served as the resistor and capacitor, respectively. (e) Voltage drop on the cholesteric LC powered by the FS-TENG through a rectifier in DC mode.
characteristics of the cholesteric LC can be reflected by the measured $V-Q$ cycle. If the cholesteric LC is a capacitor, the $V-Q$ cycle should be two-overlapped lines. The circle shaped $V-Q$ cycle indicates the existence of the discharging channel in the LC with the resistive characteristic, which may come from the dopant of the LC during the preparation of cholesteric LC film. Since the dopant was spatially distributed in the cholesteric LC, the equivalent electrical circuit model can be represented as shown in Fig. 2(d), where an NLC-based capacitor was firstly connected with an equivalent chiral dopant resistor in series and then the serial connection was connected with another equivalent chiral dopant resistor in parallel connection. Based on a commercial capacitance meter, the capacitance of the fabricated cholesteric LC was measured to be 800 pF, which is much higher than the inner capacitance of the FS-TENG. If we assume that the discharging channel does not exist, the voltage drop on the cholesteric LC should be around 90 V, other than 2 V as indicated in Fig. 2(c). Thus, the resistance effect arose from the chiral dopant cannot be ignored in the equivalent circuit model. The 2 V voltage drop fails to induce an effective polarization over LC molecules for a re-assembly of the cholesteric LC orientations. To overcome the limitation of the TENG-charged cholesteric LC in AC mode, a rectifier was employed to convert the AC electrical output into DC form. By doing so, despite of the discharge, the cholesteric LC can continue accumulating the charge, and as a result, the voltage drop on the cholesteric LC is boosted to meet the actuation requirement to modulate the window transparency. Through this approach, the voltage drop on the cholesteric LC is above 14 V as shown in Fig. 2(e), which is sufficient enough to trigger the cholesteric LC from one stable transparent mode to another stable hazy mode as will be discussed in following sections. From Fig. 2 (e), the TENG-charged cholesteric LC through the rectifier performed a zigzag pattern when the hand-sliding was loaded on the FS-TENG. When the hand-sliding time increased, the peak voltage drop kept increasing. This phenomenon indicated that charging and discharging occurred simultaneously, once again confirming the discharge inside the cholesteric LC. The high output performance of the FS-TENG can compensate

![Image](image-url)
the charge loss in the LC quickly, and thus it can trigger the LC in only a few cycles. The LC based smart window can be scaled up as well, with multiple TENGs stacked together to enhance the transferred charge.

2.3. Operation mechanism description of mechanically triggered cholesteric LC

The transparency switching mechanism of the self-powered cholesteric LC is illustrated in Fig. 3. Owing to the helical twisting power (HTP) of the chiral dopant possessed in liquid crystal host, the chiral dopant can effectively transfer the chirality to the host LC medium leading to a helical supramolecular structure [35,36] as shown in Fig. 3 (a). The distance of 2°-rotation is called helical pitch $P_o$ (Fig. 3(a)), which is mutually determined by the HTP value and the concentration (%) of chiral dopant in liquid crystal and is expressed as:

$$P_o = \frac{1}{HTP \times C\%}$$

(2)

Given that the HTP of chiral dopant used is about 10 μm$^{-1}$, by properly tuning the chiral dopant’s concentration, a helical pitch of 0.9 μm beyond the visible regime was constructed. Thus, when a broad spectrum is launched onto the cholesteric LC film, the entire visible light can transmit, giving the window an ultra-high transparency. The correlated helical structure is called planar texture, presenting a very uniform microscopic texture (Fig. 3(f)) under two crossed polarizers.

When the FS-TENG started to trigger the LC, an electric field began to be loaded across the cholesteric LC film. The LC molecules rapidly responded to the electric field and aligned themselves parallel to the electric field owing to the positive electric anisotropy [37]. The electric field varied slightly across the cholesteric LC film due to the non-uniformity of the cell gap and impurities inside the film. The variation of the electric field induced an undulation among the helical structure, where the helical pitch stretched in some regions while suppressed in the other regions [38,39], as illustrated in Fig. 3(b). When the voltage drop on the cholesteric LC film continued increasing to 12 V, the cholesteric LC film gradually evolved into a focal conic texture leading to an intense scattering of the input light beam. The mechanism behind the transition from the transparent planar texture to the opaque focal conic texture is explained as follows. In an NLC system with positive dielectric anisotropy, the electric energy induced by the electrical field is given by [40]:

$$\frac{1}{2} \Delta \varepsilon \varepsilon_o (E \cdot n)^2$$

(3)

where $\Delta \varepsilon$ is the dielectric anisotropy of the NLC host, $\varepsilon_o$ is the dielectric constant, and $E$ and $n$ refer to the electric field and the LC director, respectively. Eq. 2 reveals that the electric energy is zero in the planar mode since the LC director $n$ is perpendicular to the electric field $E$ everywhere. While the electric energy becomes negative, the LC director is along the electric field. Especially, the helical structures adjacent to the cell surface tilt differently due to the weak anchoring strength of the non-rubbing confining substrates. Therefore, the increasing electric field triggered by FS-TENG can cause the helical structure re-assemble and eventually form a randomized focal conic texture as depicted in Fig. 3 (c). In the focal conic texture, the disordered multi-domain distribution as shown in the microphotograph in Fig. 3(g) causes dramatical scattering of the light beam. Here the instantaneous output from TENG is highly preferred to trigger the LC, since the continuous DC output may induce the potential hazards of changing chemical properties or even damages of the LC.

As FS-TENG stopped triggering the LC, the focal conic texture stably sustained for a tremendously long duration. The maintenance of the focal conic texture is jointly attributed to the chirality granted by the chiral dopant, the balance between the elastic and electric energies, as well as the weak anchoring force from the non-rubbing confining substrates as illustrated in Fig. 3(d). First, it is known that when the elastic free energy of a LC system is minimized, the LC system can stabilize at its equilibrium state [40]. The elastic free energy of a cholesteric LC system is given by:

$$f = \frac{1}{2} K_{11}(\nabla \cdot n)^2 + \frac{1}{2} K_{22}(n \times \nabla \times n - \frac{2\pi}{P_o})^2 + \frac{1}{2} K_{33}(n \times \nabla \times n)^2$$

(4)

where $K_{11}$, $K_{22}$ and $K_{33}$ represent the Frank elastic constants for splay, twist and bend director deformations, respectively. The factor of $-\frac{2\pi}{P_o}$ in the second term is due to the introduction of the chiral dopant S811, where the negative sign represents the left-handed twist of the chiral dopant. We assume the LC molecules are ideally oriented at the focal conic texture with the helical axis parallel to the cell surface as shown in the dashed black box of Fig. 3(d). Thus, $\varphi$ is a constant and equals to 0 and the components of $n$ projected to $x, y$ and $z$ axis can be written as:

$$n_x = \sin \varphi = 0$$

(5)

$$n_y = -\sin \theta \times \cos \varphi = -\sin \left(\frac{2\pi}{P_o} \times y\right)$$

(6)

$$n_z = \cos \theta \times \cos \varphi = \cos \left(\frac{2\pi}{P_o} \times y\right)$$

(7)

Thus, $\nabla \cdot n = 0, n \times \nabla \times n = 0$ and $n \times \nabla \times n = \frac{2\pi}{P_o} \neq 0$. It is noticed that without the factor of $-\frac{2\pi}{P_o}$ due to the chiral dopant, the elastic free energy of the LC system is not minimal and the focal conic texture cannot be stabilized.

The balance between the elastic and electric energies also accounts for the stability of the focal conic texture. When the charge starts to load and induces a relatively low voltage drop, an undulation across the cell occurs as illustrated in Fig. 3(b). On one hand, as the voltage drop increases, the amplitude of the undulation increases, by which the helical pitch dilates in some regions while contracts in the other regions. The deformation on the helical pitch accordingly causes an increase of the elastic energy. On the other hand, the electrical energy reduces as the voltage drop increases. When the voltage drop reaches a threshold value, the decrease of the electrical energy is able to compensate the increase of the elastic energy to maintain the cholesteric LC system at its equilibrium state.

Besides, the anchoring strength of the confining substrates also matters. After the focal conic texture is formed, the anchoring strength granted by the confining substrate can enforce the LC molecule back to its pre-defined direction. The non-rubbing treatment adapted is an efficient way to greatly weaken the anchoring strength of the surface. Therefore, a stabilized focal conic texture is freely sustained with little constriction from the confining substrates.

Nonetheless, to break the equilibrium and resume the focal conic texture back to initial planar texture, there is a rather flexible route. As illustrated in Fig. 3(e), when a moderate pressure was exerted to the window surface, the window quickly responded and resumed back to its transparent mode. From a microscopic perspective, the cell gap decreased as a sufficient pressure was loaded. The LC molecules flowed radially away from the hitting point, due to its high fluidity. And as facilitated by a slightly lower elastic free energy in the planar mode than that of the focal conic mode, the LC molecule soon aligned parallel to the cell surface once the flow stopped. The microscopic image showing a uniform morphology also indicates the eventual planar texture due to cholesteric LC re-assembly (Fig. 3(h)).

2.4. Optical characterisation of the mechanically triggered cholesteric LC

As discussed above, the instantaneous voltage pulse can switch the cholesteric LC from one stable state to another one, thus leading to the transparency switching. It is of necessity to identify the threshold voltage allowing the cholesteric LC to reach the stable hazy state. To
reveal the dependence of the voltage drop on the optical performance of the cholesteric LC, a two-channel synchronous data acquisition system was established. As shown in Fig. S2 in the Supporting Information, the experimental setup includes an optical table, a laser diode with a peak emission wavelength of 650 nm, the cholesteric LC connected with the FS-TENG through the rectifier, a silicon photodetector (PD), a Keithley 6514 electrometer, a NI-cDAQ multi-channel synchronous data acquisition system, and a computer installed with a LabVIEW program. The collimated beam from the laser diode passed through the cholesteric LC, of which the transmitted power was characterized by the photodetector. The radiant power received by the PD has a linear relationship with the output voltage of the PD. The Keithley 6514 electrometer functioned as a voltmeter to measure the voltage drop on the cholesteric LC. Both the PD and electrometer provided voltage signal outputs to the two synchronous channels of the NI-cDAQ system, with the sampling rate of 1000 Hz. Using the identical hand-sliding motion pattern and various sliding duration, different peak pulse voltages are achieved, which allows us to evaluate the influence of the pulse voltage on the optical property of the cholesteric LC.

The synchronous measurement results under various loading conditions are illustrated in Fig. S3 in the Supporting Information. It is observed that when the voltage drop on the cholesteric LC is above 7 V, the PD output voltage indicating the detected radiant power decreased. This means that the electric field induced the cholesteric LC re-orientations and the optical transparency was changed. Besides, it is clearly shown that the higher voltage drop on the LC corresponds to lower PD output voltage. However, it should be noticed that the hazy state triggered by the voltage drop below 12 V cannot sustain as the minimum elastic free energy has not been reached, as illustrated in Fig. 3(b). When the instantaneous voltage drop was above 12 V, a stable hazy state was achieved, as shown in Fig. 4(a). This means that even though the voltage loading is withdrawn, the hazy state can last for an extremely long time as demonstrated in the Video-S1 in the supporting information. From Fig. 4(a), it can be observed that when the instantaneous voltage drop is above 12 V, the transmitted light intensity quickly drops to one-quarter of its original value within 1 s. The stability of the hazy state after removing the electric field was also evaluated in this study. As shown in Fig. 4(b), the detected voltage by the PD after 24 h is still below ~4.5 V, which is 10% of that under the normally transparent state. To recover the transparent performance from the stabilized hazy state, directly pressing the developed self-powered smart window is enough. As shown in Video-S1 in the supporting information, after pressing the opaque cholesteric LC film for a few seconds, the window quickly returned to its original transparent state. As a result, the PD output voltage quickly arose to its original high value, which is also identified in Fig. 4(a).

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To evaluate the diffused transmittance performance of the developed smart window, a spectrophotometer, Lambda 20 from Perkin Elmer was employed for the characterization. In the measurement setup, after the collimation, the monochromatic light with the chosen wavelength was perpendicularly pumped to the developed smart window, and the diffusely transmitted light went to an integrating sphere embedded with a PD. The transmitted light with and without loading the developed smart window were measured by the PD, the ratio of which served as the transmittance. The transmittance measurement scanned from the 400–800 nm wavelength, covering the full visible light wavelength region. The measured transmittance of the normally transparent state, the stabilized hazy state as well as the recovered transparent state after pressing are plotted in Fig. 4(c). Ultrahigh transparency is observed at the normally transparent state, with around 10% transmittance loss mainly due to the Fresnel’s power loss, indicating that the cholesteric LC molecules were well aligned. Afterwards, the developed window was tribo-charged through a rectifier to reach the hazy state, and the transmittance measurement was undertaken after the FS-TENG was detached. At the stabilized hazy state, the transmittance of the developed window become only around 1/4–1/3 of that in the normally transparent state, which is around 10%–20% lower than that under the normally transparent state.
transmitance, which means that the information covering is effective for multi-color objects. Transmittance characterization was also undertaken after pressing the stabilized hazy window for a few seconds, which is almost identical to that of the normally transparent state as indicated in Fig. 4(c), indicating that the window transparency was fully recovered. The haze ratio is another important parameter to evaluate the optical performance of the smart window, which is defined by the power ratio of the diverged light to the unidirectional transmitted light after passing through the window. The haze ratio measurement facility and the calculation principle are illustrated in Fig. S4 in the Supporting Information. A filament-based lighting source, which performed a black-body-like emission spectrum, was employed for the haze ratio measurement for providing the incident light with a broadband wavelength region. For the above-mentioned windows with three states, the haze ratios were measured and compared as shown in Fig. 4(d). The measured haze ratios of the normally transparent and stabilized hazy states are 1.2% and 62%, respectively. Upon pressing the window for a few seconds, the haze ratio returned to 1.2% at the recovered transparent state, achieving the transparent mode once again.

2.5. Applications of the developed smart window

The developed self-powered smart window can be effectively applied for the visualization control of the secure information, where the covering and retrieval of the information are enabled by the mechanically triggered tribo-charging and pressure-loading. In this work, we selected a fruit group photograph as the secure information to evaluate the information covering and retrieval performances of our developed self-powered smart window, which contained multiple colors corresponding to a broadband wavelength regime. As shown in Fig. 5(a), the fruit group photograph was imaged by a camera through the developed smart window, and the distances from the photograph to the window and from the window to the camera were 35 cm and 10 cm, respectively. As indicated in the left-bottom panel of the Fig. 5(a), the fruit in the photo is clearly revealed by the camera when the window was at the normally transparent state. The imaged photograph after the pulsed charging from the FS-TENG is shown in the right-top panel of the Fig. 5(a). It is observed that the fruit image is fully blocked by the LC film, resulting from the multi-scattering effect of the randomly distributed helical structure. Besides, the image blurriness through the window is very uniform, demonstrating the privacy protection capability of the self-powered smart window, which has a great potential to be widely utilized for secure commercial applications while batteries and general electrical supply is no longer necessary and such a privacy protection device has a theoretically infinite lifetime. To enable the target user to retrieval the covered information, the smart window was touched by the finger, and the details of the fruit group are clearly revealed once again, demonstrating the effectiveness of the pressure induced information retrieval approach. The whole process was recorded as Video S2 in the supporting information. In large-area window applications, the actuation region of the CLC can be scaled up if the several FS-TENGs were vertically stacked for enhancing the electrical output.

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Another exampled demo for the information protection and retrieval is the QR code scanning, which is very commonly used in our modern daily life. The demo system was kept identical, where the fruit photograph was replaced by the QR code for the recognition of the WeChat official account of our lab. As recorded in the Video-S3 in the supporting information, the QR code scanning was performed three times for the above-mentioned three states of the window. At the normally transparent state, the recognition can be quickly finished once scanned. The QR code was blocked from recognition after the window was instantaneously triggered by the FS-TENG. At last, the window was pressed by fingers and the QR code quickly appeared again, enabling the recognition. This QR code scanning demo demonstrates the self-powered information protection and retrieval capability of the developed smart window once again.

Supplementary material related to this article can be found online at doi:10.1016/j.nanoen.2021.105976.

Fig. 5. Fully self-powered information covering and retrieval applications of the developed mechanically-triggered smart window. (a) Self-powered information covering and retrieval cycle for a photograph of fruit group. (b) An application of the QR code scanning protection system, where the QR code covering and extraction were enabled by the hand-sliding and finger pressing, respectively.
3. Methods

3.1. Fabrication of the FS-TENG

A 2.3 mm thick cardboard was used as the soft substrate. To fabricate the stator of the FS-TENG, two copper tapes were attached to the substrate as electrodes, and two copper wires were introduced for connecting external components. Afterwards, a double-faced Kapton film with identical size with the substrate was attached to the top of copper tapes. A 50 µm nylon film was attached at the top of Kapton film. Similarly, to fabricate the slider, a 9 cm by 8 cm FEP film was attached to the cardboard with the identical size through the Kapton tape.

3.2. Fabrication of the cholesteric LC film

We firstly washed indium-tin-oxide-coated (ITO) glass substrate, and then broke them into 20 mm × 20 mm sections, using a pneumatic glass-scribing tool. We applied a weak planar alignment anchoring atop the ITO layer via a non-removing procedure. We then sandwiched two substrates with a gap of 6 ± 0.2 µm controlled by silica spacer spheres (Thermo Fisher) as shown in Fig. 1(b). The bonding of the two glass substrates is by placing epoxy on the margin of the cell volume. After the epoxy is fully solidified at room temperature, a LC mixture was infiltrated into the empty cell by capillary force. The LC mixture is composed of a nematic liquid crystal E7 from HCCH (n_e = 1.7429, n_o = 1.507) and a chiral dopant (S811, Fusol Material), with a helical twisting power (HTP) about 10 µm⁻¹ for E7. By tuning the concentration of S811 as 11%, we can obtain a cholesteric LC with a 0.9 µm helical pitch P, which is governed by

\[
P = \frac{\pi n_1 d}{m} = \frac{\pi n_1 L}{m}
\]

where \( n_1 \) is the average index of the presented LC layer, the illustrated characteristic of cholesteric LC window can be guaranteed.

4. Conclusion

To sum up, a self-powered cholesteric LC-based smart window was developed, where the transparency switching is enabled by the instantaneous mechanical triggering. Compared with previous studies, the developed smart window is totally free of batteries, and continuous power supply is no longer necessary. The transmittance and haze ratio contrasts between the normally transparent and stabilized hazy states enabled by the short-time tribo-charging can be as high as 71.5% and 61.8%, respectively. The transparency recovery is triggered by the pressure loading. The motion-driven, self-powered information protection and retrieval using the developed smart window is proven to be effective for the recognition of the colored photograph and QR code. Various self-powered applications can be anticipated, such as selective visualization display systems, secure information exchange systems for commercial transactions, radiation controlling systems including smart farming, etc.

CRediT authorship contribution statement

Jiaqi Wang: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Software; Validation; Visualization; Roles/Writing - original draft; Cuiling Meng: Conceptualization; Formal analysis; Investigation; Methodology; Roles/Writing - original draft; Chun-Ta Wang: Conceptualization; Funding acquisition; Investigation; Methodology; Resources; Visualization; Chia-Hua Liu: Investigation; Yong-Hsiang Chang: Investigation; Cheng-Chang Li: Investigation; Heng-Yi Teng: Investigation; Hoi-Sing Kwok: Resources; Yunlong Zi: Conceptualization; Funding acquisition; Methodology; Project administration; Resources; Supervision; Writing - review & editing.

Declaration of Competing Interest

In the DoCi form, we declared that there is NO known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Author contributions

J.W., C.M. and C.W. contributed equally to this work. J.W., C.M., C. W. and Y.Z. conceived the idea, discussed the results, and prepared the manuscript. J.W. designed the whole experiment, fabricated the FS-TENG, undertook the opto-electrical characterization and finished the demonstration. C.M. and H.K. analyzed the operation mechanism of the tribo-induced cholesteric LC. C.W., C.C., and H.Y. designed the cholesteric LC mixtures. C.H. and Y.H. fabricated and characterized the cholesteric LC.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.nanoen.2021.105976.

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