A fully self-powered, natural-light-enabled fiber-optic vibration sensing solution

Jiaqi Wang1,2 | Ho-Yin Man2 | Cuiling Meng3 | Pengcheng Liu3 | Shaoxin Li4 | Hoi-Sing Kwok3 | Yunlong Zi2

1 School of Marine Sciences, Sun Yat-Sen University, Zhuhai, Guangdong, P. R. China
2 Department of Mechanical and Automation Engineering, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong, P. R. China
3 State Key Laboratory on Advanced Displays and Optoelectronics Technologies, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, P. R. China
4 Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, Beijing, P. R. China

Abstract
Fiber-optic sensors have been developed to monitor the structural vibration with advantages of high sensitivity, immunity to electromagnetic interference (EMI), flexibility, and capability to achieve multiplexed or distributed sensing. However, the current fiber-optic sensors require precisely polarized coherent lasers as the lighting sources, which are expensive in cost and suffer from the power supply issues while operating at outdoor environments. This work aims at solving these issues, through developing a fully self-powered, natural-light-enabled approach. To achieve that, a spring oscillator-based triboelectric nanogenerator (TENG), a polymer network liquid crystal (PNLC), and an optical fiber were integrated. The external vibration drove the PNLC to switch its transparency, allowing the variation of the incident natural light in the optical fiber. Compared with the majority of conventional TENG-based active vibration sensors, the developed paradigm does not suffer from the EMI, without requirements of the signal preamplification which consumes additional energy. The vibration displacement monitoring was performed to validate the sensing effectiveness of the developed paradigm.

KEYWORDS
fiber-optics, liquid crystal, self-powered sensing, triboelectric nanogenerators, vibration sensing

1 | INTRODUCTION
For current structural engineering practice in our modern society, the structural sensing and corresponding structural health monitoring play significant roles, which benefits the structural safety via the failure warning, optimizes the utilization efficiency of maintenance resources, and facilitates the rational decision-making.1–6 Among various measurands for the structural evaluation, the structural vibration is an important influential factor, which reveals the structural health conditions through the diagnosis.4,7–10 Over the past couple of decades,
great efforts have been paid to monitor the structural vibrations.

Conventional electrical sensors, such as accelerometers, have been widely employed for the structural vibration sensing applications.\textsuperscript{11–16} In those sensors, the electrical signals, such as voltage, current, frequency, or phase variations, are induced by the external vibrations, which require the external electrical power suppliers such as batteries. However, in severe environments, the general power supply is usually not available, and batteries are with the limited lifetimes, which induce difficulties in replacement and environmental concerns. To solve the power issue of the sensing system, researchers have been dedicated to integrating the energy harvester into the vibration sensing system, where the sensing is directly powered by the ambient environmental energies, including but not limited to solar,\textsuperscript{17,18} vibration,\textsuperscript{19–22} temperature gradient energies,\textsuperscript{23} etc. One of these energy-scavenging techniques, triboelectric nanogenerator (TENG), was regarded as a promising technology to achieve the fully-self-powered systems toward the Internet of Things.\textsuperscript{24–28} The operation mechanism of TENGs is the coupling effect of the triboelectrification and electrostatic induction, featuring high output voltages.\textsuperscript{29–31} Besides, TENGs are not only energy harvesters, but also active sensors, revealing the environmental mechanical signal through the variation of electrical outputs.\textsuperscript{32,47–50} Over the past a few years, TENGs have been successfully employed to monitor the mechanical motions in an active way including accelerations, vibrations, displacements and rotations, etc.\textsuperscript{33–36} Owing to its high voltage output, TENG-based sensors perform high signal-to-noise ratios (SNRs). However, because of the ultralow current of the TENG, the signal preamplification is necessary for the signal processing and transmission, consuming additional energy which is much higher than the energy saved for sensing. Furthermore, it should be noticed that the transferred charge from the TENG to external circuit is extremely trivial (i.e., less than 30 nC for vibrations\textsuperscript{34}), and thus, the sensing performance is easily affected by the EMI such as lightning strikes.\textsuperscript{37–41}

Fiber-optic sensors, by contrast, provide an alternative solution to illustrate the vibration profile through the variation of the light signal such as intensity, interference or polarization without suffering from the EMI issues.\textsuperscript{42–44} However, the faithful transfer of the mechanical signal to the sensor is still a challenging issue. Besides, the fabrication of the sensing components (i.e., Bragg grating) are usually with extremely high cost, and the precisely polarized lighting source is usually required, hindering the wide applications. For the majority of currently available electrical or optical vibration sensors operated at outdoor environments, the operation of the laser relies on the power supplied by batteries or other energy storage devices, leading to the limited lifespan, difficulties in maintenance/replacement, and potential environmental issues.

In this work, a fully self-powered, signal-amplification-free, and EMI-free structural vibration sensing approach was developed by integrating a spring oscillator based TENG, a polymer network liquid crystal (PNLC) and an optical fiber, employing the environmental sunlight as the information carrier. As driven by the external vibration, the tribo-charged PNLC switched its optical behavior between transparent and hazy states alternatively, resulting in the intensity variation of incident light into the fiber without influences of EMI. The sensing system is fully self-powered and very cost-effective with the unpolarized sunlight as the lighting source. The vibration displacement monitoring was performed to validate the sensing effectiveness of the developed paradigm.

2 | RESULTS AND DISCUSSIONS

The left side of Figure 1A illustrates a bridge which installs the developed self-powered sunlight-based vibration sensing system, with the schematic diagram illustrated in inset. The whole sensing system consists of three components: a freestanding sliding TENG (FS-TENG) to harvest the vibration energy, a polymer network liquid crystal (PNLC), and an optical fiber. The slider of the FS-TENG is driven by a spring oscillator. The fabrication process of the TENG is introduced in the Method section. For the stator of the TENG, two identical 8 cm by 9 cm copper tapes were attached onto the inner wall of the 3D-printed stator, serving as the electrodes. A 50 μm thick nylon film was placed above the electrodes serving as the positive triboelectric material. The slider was made by aluminum attached with fluorinated ethylene propylene (FEP) with the dimension of 5.9 cm by 5.9 cm by 2.9 cm and weight of 250.37 g. The stator and slider were connected by a sliding rail and a linear bearing, to ensure free moving of the sliding part with the minimal friction. The slider was supported by a spring surrounding the sliding rail. Attributed to the equilibrium between the gravity of the slider and the elastic force induced by the spring, the slider was naturally located in the middle of electrodes. When the developed TENG was driven by the external vibration, the slider swept back and forth on the stator with the assistance of the spring. The sliding between the nylon and the FEP resulted in the triboelectrification, where the nylon gained the positive charges and the FEP gained the negative charges, which induces electric field by the electrostatic induction to drive electron flows in the external circuit. For the developed TENG part, the electrical degradation is within 1% after 20,000 cycles. And after that, the sensing system is still workable after recalibration.
The TENG was electrically connected to the PNLC for the tribocharging. The fabrication process of the PNLC is described in the Method section and illustrated in Supporting information Figure S1. The right side of Figure 1A illustrates the explosive view of the as-fabricated PNLC, which changes from vertical to random alignments upon tribocharging. Unlike traditional crystal, liquid crystals are soft matter which means they can facilely respond to external stimuli such as electrical, thermal, or even light stimuli. Due to birefringence nature given by LC structure, a rod-like molecule, LC can present different refractive index distribution geometries under external fields. Electrically, the LC has the capacitive characteristics, which is very suitable to be driven by the TENGs. As shown in Figure 1A, the PNLC is composed of two glasses precoated with indium tin oxide (ITO) electrodes, and LC layer which involves cross-linked LC polymers and encapsulated nematic LCs. LC polymer plays an essential role for achieving excellent optical switching. On one hand, when the electrical field is applied, the LC polymer as a network keeps the original orientation, while only the fluid-like LC molecules can respond and orient to be different orientations. Such the different orientations between LC polymer network and LC molecules cause discrepancy on the refractive index distribution and lead to light scattering. On the other hand, the LC polymer is also used in the alignment layer by mixing the LC polymer with the alignment material. In this way, the LC polymer on the alignment surface can greatly
enhance the formation of polymer network. Such the network with increased density, thus, can greatly promote the chance of light diffraction/scattering. Since the LC polymer on the surface is templated by the alignment material and aligned vertically as well, the transparent state can be guaranteed before electrical field loading. When the PNLC was charged by the TENG, the rotation of the nematic LCs driven by the electric field results in the multiple scattering effect owing to the refractive index contrast between the randomized nematic LCs and the fixed LC polymer. Thanks to the dense web of the LC polymer and the alignment layer with the microdomains, the ultrahigh haziness of the PNLC can be achieved upon loading with the ultralow charge density, which can be driven by the TENG. To further minimize the required charge for the PNLC actuation and improve the sensitivity, the ITO electrodes of the PNLC were patterned with the miniaturized active areas of 2 by 2 mm. For the developed PNLC part, the optical switching performance will not be affected within 70,000 cycles. Therefore, the conservatively estimated lifetime of the self-powered sensor should be at least 70,000 cycles. The developed PNLC was set at the top of the stator to collect the incident light from the sunlight or lamps. One end of an optical fiber was placed beneath the active layer of the PNLC to collect optical signals. The other end of the optical fiber was mechanically connected to a spectrophotometer for the in-situ optical intensity detection. The optical fiber employed in this work is a multimode fiber, with the small inner diameter of 400 µm to effectively detect the signal.

Figure 1B illustrates the optical variation of the PNLC in one electric cycle of the TENG driven by the external vibration. When the slider is located in the middle of electrodes as indicated in stages 1 and 3 in Figure 1B and the PNLC is not charged, the PNLC is transparent and the spectrophotometer detects the high-intensity light through the fiber. In contrast, as shown in stages 2 and 4 in Figure 1B, when the slider is located sideward, the PNLC is tribocharged, leading to the haziness of the PNLC. As a result, the detected light intensity is low. The vibration with higher amplitude corresponds to the higher voltage drop loaded on the PNLC, and as the result, the detected light intensity is lower. Since the haziness switching of the PNLC is independent of the direction of its current and voltage drop, the optical oscillation frequency is twice of the electrical frequency of the TENG, as illustrated in Figure 1B.

As indicated in Figure 2, the open-circuit (OC) voltage and the charge transfer under the short-circuit (SC) condition of the TENG driven by the external vibration were measured by the electrometer Keithley 6514. Since the vibration frequency of most bridges ranges from 1–4 Hz, in

**Figure 2** Electrical characterization results of the TENG and the TENG powered PNLC. For (A), (B), and (D), the electrical characterization was performed at the 1.5 Hz, 40 mm displacement vibration condition. (A) The measured OC voltage of the TENG. (B) The measured transferred charge of the TENG under the SC condition. (C) The measured relationship between the SC transferred charge and the displacement at the 1.5 Hz vibration. (D) The measured charge transfer on the PNLC. (E) The measured relationship between the transferred charge and voltage drop on the PNLC when the vibration displacement is 40 mm. (F) The measured relationship between the PNLC voltage drop and the displacement at the 1.5 Hz vibration.
this work, the frequency of external vibration was set to be 1.5 Hz, as simulated by a linear motor. As indicated in Table S1 in the supporting information, varied motion parameters were set to achieve the various vibration amplitudes at a given frequency of 1.5 Hz. The displacement ranges from 40 to 110 mm. The characterized OC voltage and the SC charge transfer of the TENG under the vibration displacement of 40 mm are illustrated in Figure 2A and B. It can be identified that the oscillation frequency of the slider during the triboelectrification process is 1.5 Hz, identical to that of the external vibration. In a half-electric cycle, there are two adjacent extreme points owing to the spring-assisted oscillation. The mechanical behavior of the slider under the 1.5 Hz external vibration is illustrated in Video S1 in the supporting information. As shown in Figure 2B, the maximal SC charge transfer is as low as around 10 nC. As shown in Figure 2A, the peak OC voltage is around 20 V. Considering the inner capacitance of 300 pF in the electrometer functioning as the voltmeter, the peak inner capacitance of the TENG is estimated to be around 50 pF, which is low enough to generate relative high voltage. At the given external vibration frequency of 1.5 Hz, the SC charge transfer was characterized under the different displacements ranging from 40 mm to 110 mm. It can be identified that with the increase of the displacement, the SC charge transfer increases with the increase of the triboelectrification area. As shown in Figure 2C, the SC charge transfer presents a linear relationship with the displacement, demonstrating the excellent sensing capability of the developed TENG. When the vibration TENG is electrically connected to the developed PNLC, the voltage drop of the PNLC is characterized using the same setup, as shown in Figure 2D. The PNLC voltage drop peaks at 12 V, which is lower than the OC voltage of the TENG. To investigate the equivalent circuit model of the developed PNLC, a two-channel synchronous electrical characterization was constructed to measure the voltage drop $V$ on the PNLC and the charge transfer $Q$, as shown in Figure S2 in the supporting information. Two Keithley 6514 electrometers were employed, functioning as the coulomb meter and the voltmeter, respectively. The $V$-$Q$ relationship under the mechanical stimuli of 1.5 Hz in frequency and 40 mm in displacement is illustrated in Figure 2E. It can be observed that the charging and discharging profiles of the PNLC powered by the TENG are two nearly-overlapped straight lines. This indicates that the developed PNLC can be electrically regarded as a capacitor. The capacitance of the PNLC is estimated to be around 116 pF, which is small enough to allow relative high voltage drop. It can be also identified that the capacitance of the PNLC is not affected by the rotation of the nematic LC upon the charging. The relationship between the voltage drop of the PNLC and the vibration displacement was also investigated, as illustrated in Figure 2F. Similar to the measured SC charge transfer under different displacements as shown in Figure 2C, an excellent linear relationship was observed between the PNLC voltage drop and the displacement as indicated in Figure 2F.

To evaluate the sensing performance, an optoelectrical synchronous measurement setup was constructed, as shown in Figure 3A. A laser, the fabricated PNLC, a photodetector (PD) and the linear motor were mechanically fixed on an optical platform. The developed TENG was triggered by the linear motor. The emission spectrum of the laser peaks at 650 nm. The beam diameter emitted by the laser is around 3 mm. The laser, the PNLC, and the PD were well aligned to guarantee that the beam emitted from the laser passed through the active area of PNLC, and eventually collected by the PD, with the effective size of 2 by 2 mm. The output voltage of the PD has the linear relationship with the radiant power of the collected light, revealing the incident light intensity. A Keithley 6514 electrometer was used to characterize the voltage drop of the PNLC while charged by the TENG. To achieve the optoelectrical synchronous characterization, both the electrometer and the PD output terminals were connected with the NI-DAQ synchronous data acquisition system. As discussed above, when the PNLC was charged, a great number of incident photons were multiply scattered, attenuating the incident light intensity measured by the PD. As shown in Figure 3B, the lowest output voltages of the PD were sampled when the PNLC was powered by the TENG with different displacements. It can be identified that when the vibration displacement increases, the PD output voltage linearly decreased with the increased PNLC voltage drop.

The active area of the PNLC as charged by alternating current (AC) output from TENG without the laser illumination is visualized in Video S1 in the supporting information, which alternatively changed its optical appearance between the transparent and hazy states. Figure 3C and D illustrates two snapshots of the discharged and charged PNLC driven by the TENG. As shown in Figure 3C, when no charge was loaded on the PNLC, the PNLC presented an ultrahigh transparent performance, with the active area clearly visualized. When the PNLC was charged by the TENG, in contrast, as shown in Figure 3D, an ultrahigh haziness occurred at the PNLC, which is white in color since the refractive contrast between the nematic LC and the LC polymer over the whole visible light spectrum is very tiny. Besides, it can be found the white haziness is extremely uniform on the PNLC active region, meaning that the incident light was greatly randomized, attributed to the dense web of the LC polymer and the microdomains. To evaluate the light diffusion behavior of the charged PNLC, characterizations of the transmittance and haze ratio were performed. The PNLC was powered by a
commercial voltage source in AC mode with the oscillation frequency of 1 kHz.

The transmittances and haze ratios under various voltage drops of the PNLC were characterized. The transmittance refers to the light intensity ratio between the light after and before passing through the PNLC. The haze ratio is defined as the power ratio between the light without and with passing through the PNLC. As shown in Figure S3 in the supporting information, driven by a commercial voltage source, the relationships between the transmittance of the PNLC and the incident light wavelength at both 0 and 30 V are illustrated. The dependence of the transmittance and haze ratio on the voltage drop of the PNLC is shown in Figure 3E. It can be observed that, the higher voltage results in lower transmittance and higher haze ratio. Figure 3F illustrates the synchronous measured results of the PD output voltage and the voltage drop on the PNLC. The minimal PD output voltage corresponds to the peak voltage drop on the PNLC regardless of the directions of the voltage and current. In contrast, when the voltage drop on the PNLC is 0 V, the PD achieved the highest output voltage corresponding to the normally transparent state. The optical oscillation frequency is twice of the electrical frequency of the TENG, which is consistent with our analysis. These results indicate that the environmental mechanical motion profile can be effective revealed by the optical signal.
As shown in Figure 4A, the PNLC and TENG were integrated with the optical fiber to achieve the in-situ vibration sensing, with the structure introduced above. The PNLC was positioned at the top surface of the developed sensing system, facing the environmental light. Through the optical fiber, the incident sunlight intensity was remotely monitored by a spectrophotometer. The right side of the Figure 4A illustrates the photograph and the spectrum of the lighting source for environmental illumination. This work was undertaken in the lab space, where the ceiling fluorescent lamps functioned as the environmental illumination source, stimulating the sunlight. As shown in the right bottom corner of the Figure 1A, the fluorescent lamp illumination spectrum presents its extreme value at three

**FIGURE 4** Structural illustration and sensing results of the developed full-self-powered, sunlight-modulation-based vibration sensing system. (A) Photographs of the self-powered sensing system, environmental illumination source and its corresponding emission spectrum. (B) The spectral evolvement of the light incident into the fiber in half cycle of the TENG. (C) The measured time-variant light intensity incident to the fiber when the whole system was triggered by the vibration with 1.5 Hz in frequency and 40 mm in displacement. (D) The measured relationship between the measured light intensity and the displacement at 1.5 Hz vibration.
regions, blue, green, and red, attributed to the three corresponding phosphors excited by the discharged ultraviolet (UV) irradiation. Supporting information Video S3 and S4 illustrates the spectrophotometer-characterized spectrum variation without and with the TENG-charging. It is observed that when the TENG was not charging the PNLC, the vibration of the sensing system cannot induce the spectrum variation. By contrast, the detected spectrum varies greatly with the TENG-charging. Figure 4B illustrates the spectrophotometer-sampled spectrum in half cycle of the TENG under vibration with the frequency of 1.5 Hz and displacement of 40 mm, where the set integration time is 7.2 ms. It is observed that during the first 151.2 ms, the detected light intensity keeps decreasing. After that, the light intensity recovers to its highest value at the transparent state of the PNLC. As shown in Figure 4C, the unexpected noise associated with the optical signal may arise from the tiny vibration of the optical fiber. As illustrated in Figure 4C, the intensity variation is defined by the total light intensity contrast between the transparent and hazy states of the PNLC, which reveals the amplitude of the mechanical motions. The relationship between the vibration displacement and the optical intensity variation is illustrated in Figure 4D. It is identified that the intensity variation linearly increases with respect to the displacement, demonstrating the effectiveness of the developed paradigm for the vibration sensing applications.

3 | CONCLUSIONS

To sum up, through the combination of a TENG, a PNLC and an optical fiber, a fully self-powered, sunlight modulation-based structural vibration sensing system was successfully developed without the impact of EMI and the demands of signal preamplification. Ubiquitous natural light, rather than the expensive, well polarized, and precisely collimated laser light, was utilized for the lighting source for the optical fiber sensing, serving as the information carrier. The TENG powered PNLC switched its transparency alternatively, resulting in the intensity variation of the incident sunlight into the optical fiber. Thanks to the dense web of the LC polymer and microdomains in the PNLC, ultrahigh transparency variation can be obtained by the ultralow charge loading (i.e., 5 nC). The self-powered displacement sensing under 1.5 Hz vibration was successfully demonstrated, validating the effectiveness of the developed paradigm.

4 | MATERIALS AND METHODS

4.1 | Fabrication of the vibration triggered TENG

First of all, a fixture for holding the spring-oscillator system was 3D-printed. Then, two pieces of copper tapes with the size of 80 by 90 mm were attached to the inner wall of the 3D-printed fixture, serving as the electrodes. The distance between the two electrodes is 10 mm. And a 100 μm thick nylon film was attached on the top of the two electrodes, serving as the positive triboelectric layer. Afterwards, 180 mm long sliding rail was mechanically fixed on the 3D-printed fixture surrounded by two springs with the linear-diameter of 0.6 mm, along which an aluminum-based weight block moves through a linear bearing when driving by the external vibrations. A 29 by 39 mm FEP film was attached on the surface of the block, serving as the negative triboelectric layer.

4.2 | Fabrication of the PNLC

Two 15 by 20 mm glasses were firstly coated with the ITO patterned with the 2 by 2 mm active area and a line-shaped electrical connector. Afterwards, for each ITO-coated glass, the LC monomer doped alignment layer was spin-coated, followed by the 60 s baking at 80°C and the 30 s of cooling with the rate of 1°C/s for the phase separation purpose, achieving the puddle-like morphology. The two spin-coated substrates were precisely aligned to face each other via the silicon dioxide spacers, followed by the encapsulation of the mixture of the nematic LCs and LC monomers. After the UV light irradiation for the cross-linking, the PNLC was successfully fabricated.

ACKNOWLEDGMENTS

This work was funded by HKSAR the Research Grants Council Early Career Scheme (Grant no. 24206919), HKSAR Innovation and Technology Fund (Grant no. ITS/085/18), and Tencent University Relations Programme (contract no. T-576-INV-20200507-01).

AUTHOR CONTRIBUTIONS

J.W., H.M., and Y.Z. conceived the idea, designed the experiment, discussed the results, and prepared the manuscript. J.W., H.M., and S.L. designed, fabricated and characterized the TENG. J.W., P.L., C.M., and H.K. designed, fabricated, and characterized the PNLC based natural-light modulator. J.W. and H.M. constructed the vibration sensing system and analyzed the sensed data.
CONFLICT OF INTEREST
The authors declare no conflict of interest.

ORCID
Yunlong Zi https://orcid.org/0000-0002-5133-4057

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**SUPPORTING INFORMATION**

Additional supporting information may be found in the online version of the article at the publisher’s website.

**How to cite this article:** Wang J, Man H-Y, Meng C, et al. A fully self-powered, natural-light-enabled fiber-optic vibration sensing solution. SusMat. 2021;1:593–602. [https://doi.org/10.1002/sus2.31](https://doi.org/10.1002/sus2.31)