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A nanogenerator as a self-powered sensor for measuring the vibration spectrum of a drum membrane

Aifang Yu[1], Yong Zhao[1], Peng Jiang[1] and Zhong Lin Wang[2,3]

[1] National Center for Nanoscience and Technology, No 11 Beiyitiao, Zhongguancun, Beijing 100190, People's Republic of China
[2] School of Materials Science and Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA
[3] Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, Beijing, People's Republic of China

E-mail: zhong.wang@mse.gatech.edu

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Abstract
A nanogenerator (NG) is a device that converts vibration energy into electricity. Here, a flexible, small size and lightweight NG is successfully demonstrated as an active sensor for detecting the vibration spectrum of a drum membrane without the use of an external power source. The output current/voltage signal of the NG is a direct measure of the strain of the local vibrating drum membrane that contains rich informational content, such as, notably, the vibration frequency, vibration speed and vibration amplitude. In comparison to the laser vibrometer, which is excessively complex and expensive, this kind of small and low cost sensor based on an NG is also capable of detecting the local vibration frequency of a drum membrane accurately. A spatial arrangement of the NGs on the membrane can provide position-dependent vibration information on the surface. The measured frequency spectrum can be understood on the basis of the theoretically calculated vibration modes. This work expands the application of NGs and reveals the potential for developing sound wave detection, environmental/infrastructure monitoring and many more applications.

(Some figures may appear in colour only in the online journal)

1. Introduction

Detection of the vibration frequency is an important sensor technology for structural health monitoring, damage detection, security guaranteeing, prediction of natural disasters and more [1–3]. Different application fields have different demands for these sensors. For example, in smart/intelligent material systems and structures, the sensors should be small size, flexible and lightweight in order to be compatible with the systems [4–6]. For unreachable and access-denied extreme environments, the sensors should be self-powered and self-sensing [2, 7, 8]. Most conventional sensors used for the above fields are excessively complex, expensive and incompatible with the systems. So new kinds of sensors are needed to meet these demands [9, 10].

Nanogenerators (NG) based on piezoelectric nanowires (NWs) have been developed as a key technology for converting ambient mechanical energy into electricity. In the last few years, innovative research based ZnO NWs have successfully converted external mechanical energy, biomechanical energy, thermal energy and magnetic energy into electricity [11–14]. Self-powered nanosystems powered by NGs, such as ultraviolet (UV) sensors, wireless data transmission systems and Hg^{2+} ion sensors, have been built [15–17]. The work mainly focused on the ability of the NG to convert ambient energy to electrical energy for powering other devices. If the source for generating the strain has fixed frequency, the frequency will be reflected in the electrical signals. So, the NG can be used as a vibration frequency sensor, as demonstrated previously [18]. Moreover,

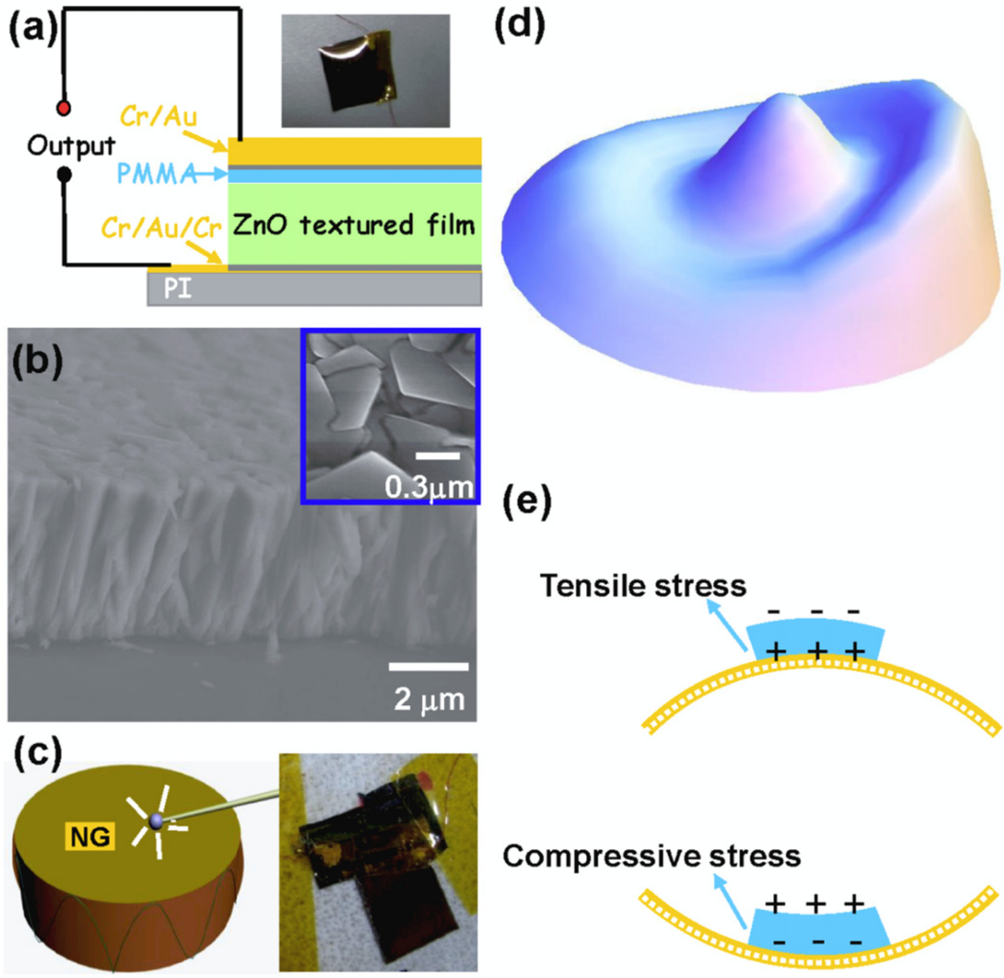

Figure 1. (a) The process of fabrication of an NG—the upper part is a photo of the finished NG. (b) A cross section SEM image of the as-grown textured ZnO film. (c) The schematic setup for measuring the vibration frequency of a drum and optical images of an NG attached to the surface of a drum. (d) The simulated vibration of a drum membrane from a sum of nine modes with $m = 0, 1, 2$, and $n = 1, 2, 3$ at $t = 0.2$ s. (e) The working mechanism of the NG attached to a drum membrane.

it is a self-powered and active vibration sensor that may offer some advantage in comparison to the current technology. The objective of this research is to demonstrate the application of NGs for detecting the vibration status of a drum membrane. A detailed comparison will be presented to illustrate the quantitative information that can be provided by an NG based vibration sensor on a surface.

2. Experimental details

The mechanism of an NG relies on the piezoelectric potential generated inside NWs under the driving of mechanical straining. The piezopotential drives electrons flowing between the two electrodes at the two ends of the NWs in response to the dynamic straining, so the output current/voltage is a direct measure of the vibration characteristics. Figure 1(a) depicts the structure of an NG. It includes a flexible PI substrate (about 60 μm in thickness), bottom electrode, seed layer, ZnO textured film, thin PMMA insulation layer (about 2 μm in thickness) and top electrode. Firstly, a Cr/Au layer serving as the bottom electrode of the NG was deposited on one of the surfaces of the PI substrate. The ZnO NW textured film was then grown by a wet chemical method at 75 °C for 12 h. The nutrient solution that we used in the chemical growth process of the ZnO densely packed NW textured films was 100 mM of Zn $(NO_3)_2 \cdot 6H_2O$ and 10 mM hexamethylenetetramine (HMTA). Before growing NWs, a 5 nm thick Cr adhesion layer and then a 50 nm thick ZnO seed layer were first deposited by sputtering on the Cr/Au layer. A 2 μm thick poly(methyl methacrylate) (PMMA, MicroChem 950k A11) layer was spin coated and subsequently a Cr/Au layer serving as the top electrode of the NG was deposited. The mass of the NG is very low (only 0.04 g) and its size is much smaller than that of the drum membrane. It has been verified that its mass does not affect the vibration frequency of the detected object [18]. The cross section view of the ZnO textured film is shown in figure 1(b); it is composed of compacted ZnO NWs. These ZnO NWs were grown vertically from the substrate that is covered by a layer of ZnO seeds. When the NG is used as a sensor, it can be attached to the surface of a vibrating object, and then its corresponding output electrical signal responds to the change in strain (straining rate and magnitude). The output

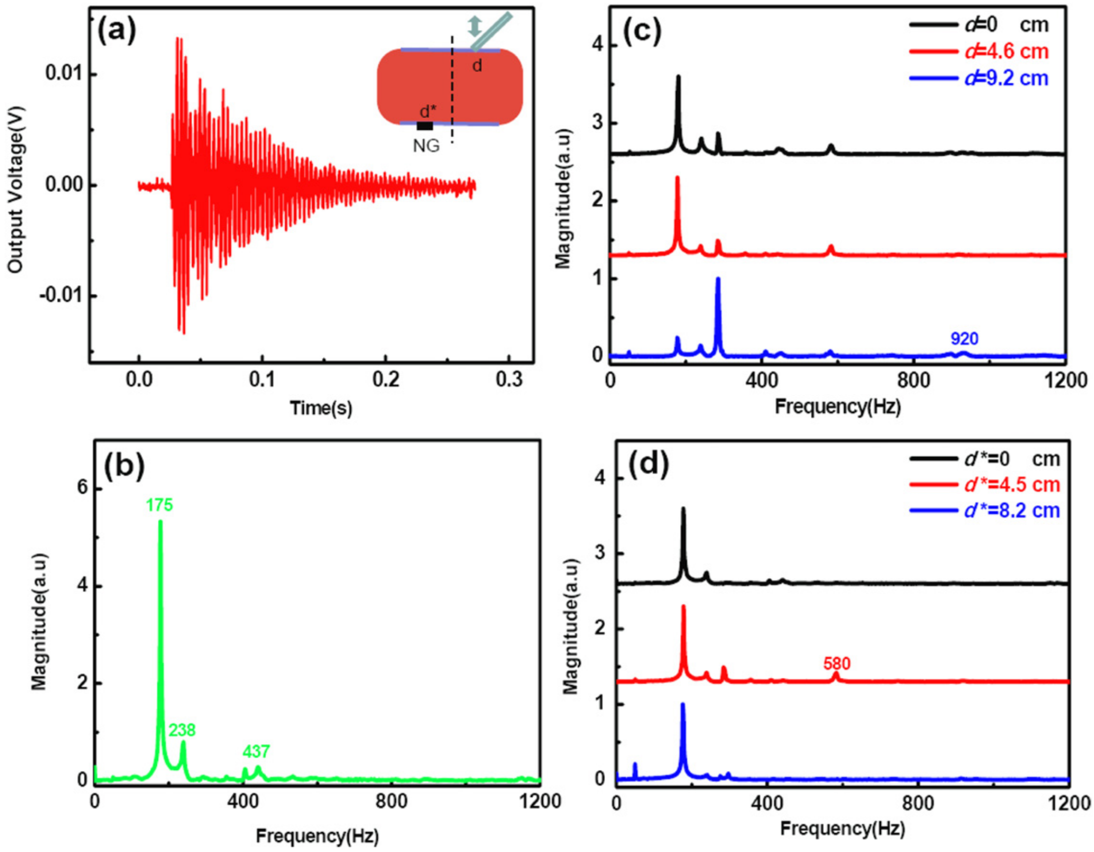

Figure 2. (a) The output voltage of an NG fixed at the center of a drum ($d^* = 0$) in response to a strike at $d = 4.6$ cm on the membrane at the opposite side (the inset shows the schematic diagram of the drum). (b) The vibration spectrum of the membrane detected by taking a Fourier transform of the data presented in (a). (c) The vibration spectra acquired by placing an NG at $d^* = 4.5$ cm on one membrane while striking at different positions on the other membrane: $d = 0$, 4.6 and 9.2 cm. (d) The vibration spectra acquired by placing an NG on one membrane at $d^* = 0$, 4.5 and 8.2 cm, while striking at $d = 4.6$ cm on the other membrane. An offset is introduced in the plots in (c) and (d) for comparison purposes.

current/voltage signal of the NG can be used to derive the vibration amplitude, vibration speed, frequency and position. Our experiment setup is shown schematically in figure 1(c). The NG was attached to the membrane surface of a drum that is made of a cylindrical wood frame with a diameter of 23 cm and height of 17 cm, which is covered by buffalo leather at the two ends. When the drum is struck at an arbitrary position with a drumstick, the drum membrane will vibrate and produce sound. Consequently, the vibration of the drum membrane will be detected by an NG. The output signal of the NG was amplified by using a low-noise voltage preamplifier (Stanford Research System Model SR560). The laser vibrometer is a single-point vibrometer (Polytec), which includes an OFV-534 Compact Sensor Head and OFV-5000 Modular Vibrometer Controller.

3. Theoretical simulation

In order to present a theoretical model for the proposed mechanism for the NG used as a self-powered sensor for measuring the vibration spectrum of drum membranes and calculating the vibration modes of a drum, the drum is ideally simplified down to a circular membrane under uniform tension and fixed at its rim. The NG is assumed as a massless and sizeless point located at a distance d^* from the center of the membrane. For general excitation, the actual vibration of a membrane must be expressed as a sum of its normal modes rather than a single, pure normal mode motion. For the initial conditions at $t = 0$,

$$Z(r,\phi,t)|_{t=0} = 0,\qquad \left.\frac{\mathrm{d}Z(r,\phi,t)}{\mathrm{d}t}\right|_{t=0} \propto \frac{1}{r}\delta(r-d)\delta(\phi-\phi_0) \tag{1}$$

where d is the distance of the striking point from the center, φ is the polar angle in polar coordinates, ϕ_0 is the polar angle of the striking point and the δs are the Dirac δ-functions. So, a mathematical expression for the general transverse motion of a circular membrane, fixed at its rim, may be written in cylindrical coordinates as a sum of its normal modes [19]:

$$Z(r,\phi,t) = \sum_{m,n} \frac{DJ_m(\eta_{mn}\frac{d}{a})}{\eta_{mn}\left[J_{m+1}(\eta_{mn})\right]^2} J_m\left(\eta_{mn}\frac{r}{a}\right) \cos m\phi \sin\left(\eta_{mn}\frac{c}{a}t\right) \tag{2}$$

where Z is the displacement of the membrane from its equilibrium position, D is an arbitrary constant that sets the overall amplitude, J_m is the mth integer order Bessel function, c is the speed of a transverse wave in the membrane, a is the

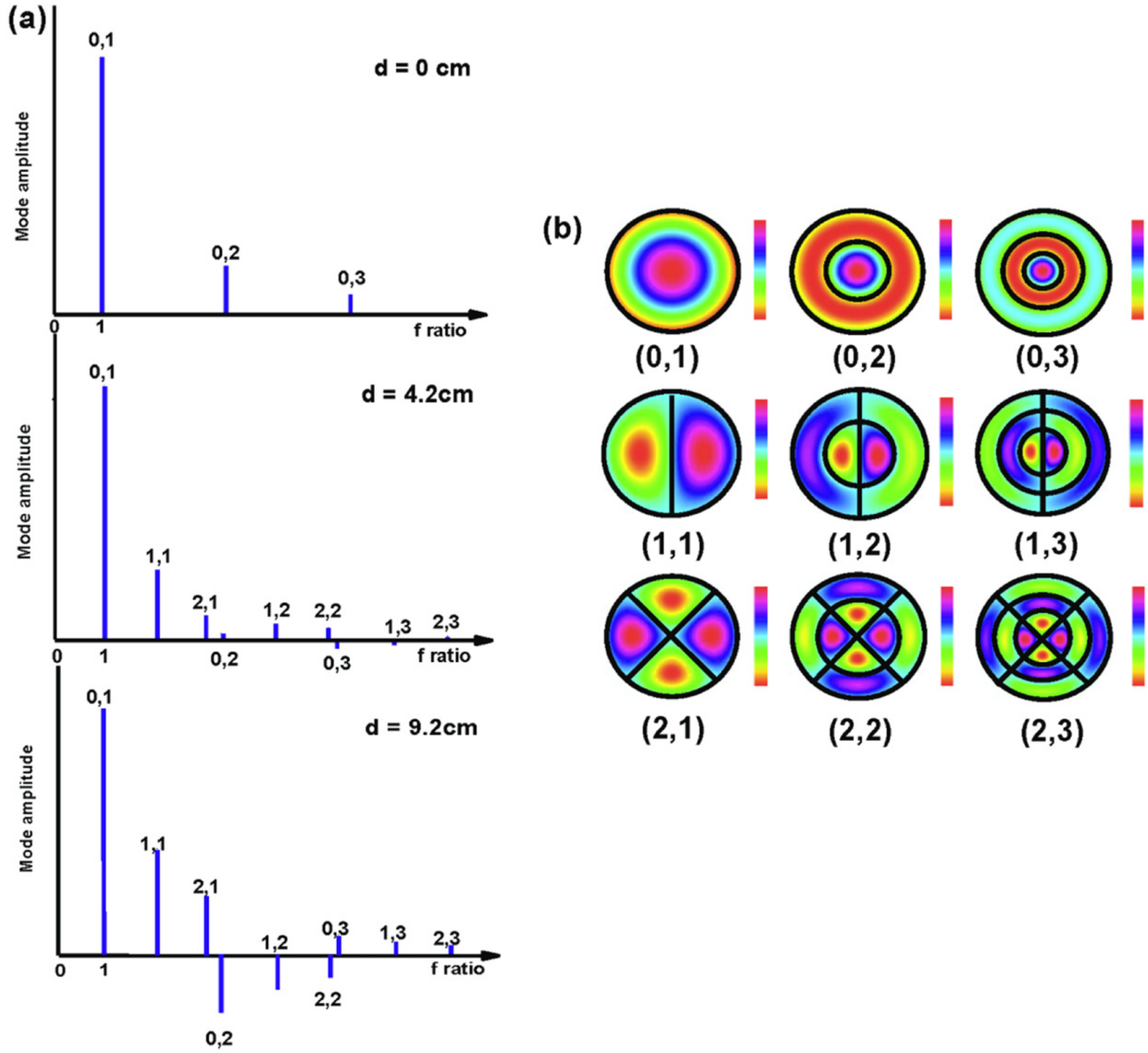

Figure 3. (a) The theoretically calculated relative amplitude of each vibration mode when exciting at different positions of the drum membrane: $d = 0$, 4.6 and 9.2 cm. (b) The vibration shape of the drum membrane at each mode. The dark lines and circles represent nodal lines and nodal circles. The bar represents the relative vibration displacement of the drum membrane.

radius of the membrane, and η_{mn} is the nth root of the equation $J_m(\eta_{mn}) = 0$. A pair of integers (m, n) denotes a mode. The frequency of each mode is expressed as $f_{m,n} = \frac{c}{2\pi a}\eta_{mn}$. According to equation (2), the vibration of the drum can be simulated. Figure 1(d) displays the surface profile of the drum at $t = 0.2$ s after a strike at $d = 4.6$ cm, which provided insight into the displacement of the drum membrane. The shapes are computed from a sum of nine modes with $m = 0$, 1, 2, and $n = 1$, 2, 3. In figure 1(d), one can see that the drum moves up and down under the tension force after excitation. The larger the displacement is, the more strain the drum will suffer. Although the drum membrane is stretched during the vibration process, the direction of displacement may be different for different positions and different times (see figure 3(b)). So the NG attached to the drum membrane may suffer from compressive and tensile stress during one cycle of vibration. When the drum membrane moves upwards, the NG will suffer from tensile stress in parallel to the ZnO thin film. Because the NWs are densely packed and perpendicular to the substrate, tensile stress will result in a compressive strain along the NW direction (e.g., the c-axis direction, normal to the thin film), thus creating a piezopotential drop from the roots of the NWs to their tips, as shown in figure 1(e). By the same token, when the drum membrane moves downwards, compressive stress will result in a tensile strain along the NW direction, and thus the top ends of the NWs have a higher piezopotential than their roots. These piezopotential distributions will generate induced charges in the top and bottom electrodes as a result of electron flow in order to minimize the total energy, consequently generating an output voltage and current in the external load.

4. Results and discussion

When the output voltage is captured, the vibration frequency will be calculated by taking the Fourier transform of the time-dependent vibration amplitude. Figure 2 gives the results for the NG as a vibration frequency sensor. First, the electrical

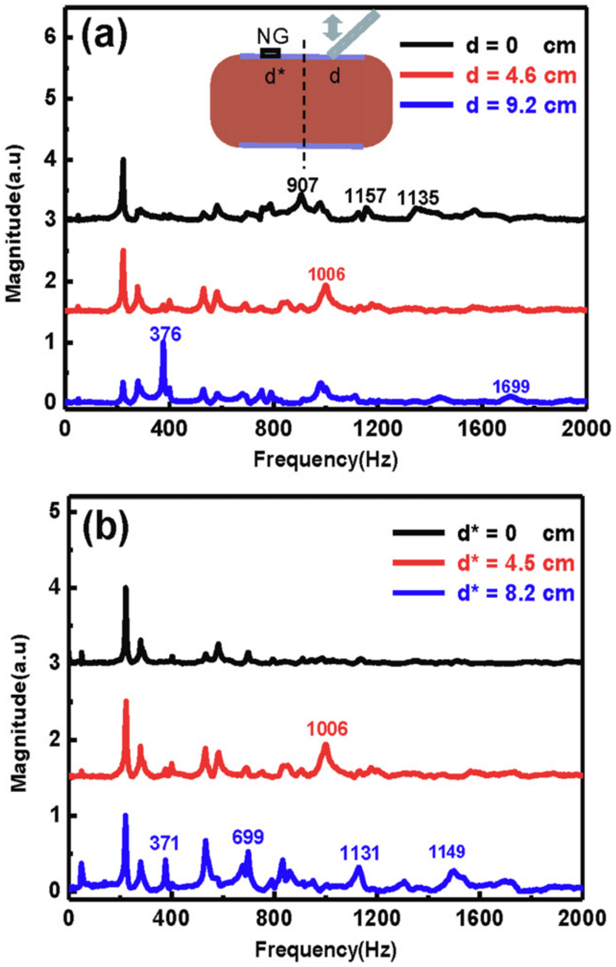

Figure 4. Vibration spectra of the drum membrane when the NG and the striking points are on the same membrane (as shown in the inset) for the following cases: (a) the NG attached at $d^* = 4.5$ cm and the striking positions $d = 0$, 4.6 and 9.2 cm; (b) the NG attached at $d^* = 0$, 4.5 cm and 8.2 cm, and the striking point at $d = 4.6$ cm. An offset is introduced in the plots for comparison purposes.

signal after striking the drum membrane is detected, as shown in figure 2(a). The inset in figure 2(a) shows the schematic geometry, to illustrate the relative positions of the striking point and the NG on the top and bottom membrane surfaces of the drum. For simplicity, the striking position and the location of the NG are aligned radially. The striking position is $d = 4.6$ cm from the center of the drum center. It can be seen that the signal decays quickly (in a fraction of a second) owing to the damping in air. Then, the frequency spectrum of the drum, as shown in figure 2(b), was obtained upon Fourier transforming the data of figure 2(a). In figure 2(b), a fundamental frequency of 175 Hz and two other overtones can be clearly seen. This result indicates that the NG can be used as a sensor responding to the vibration frequency of a drum membrane. In order to further study the NG used as a frequency sensor to detect vibration, the initial striking position d and the location of the NG, d^*, on the drum membrane was changed. The data in figure 2(c) were obtained by fixing the NG at $d^* = 4.5$ cm and striking at $d = 0$, 4.6 cm and 9.2 cm. Note that an excitation at $d = 9.2$ cm stimulates higher frequencies than excitations at the other two positions. The highest frequency detected was 920 Hz. Four frequencies were observed when striking at $d = 4.6$ cm. In figure 2(d), by fixing the striking position ($d = 4.6$ cm) of the drumstick and changing the position of the NG, it was found that the NG located at $d^* = 4.5$ cm detects more and higher frequencies in comparison to those at $d^* = 0$ cm and $d^* = 8.2$ cm. The highest frequency detected is 580 Hz. It is noted that the fundamental frequency was detected in all tests.

According to equation (2), the displacement of the drum membrane is a sum of all modes. So, these modes should be reflected in the detected voltage signal and corresponding frequency spectrum. But in figures 2(c) and (d), only seven frequencies were clearly observed. The NG can only detect the modes that have larger amplitudes at the position where the NG is attached. In a case where a mode does not induce strain, or strain does not generate a piezopotential along the NWs, the mode will not be detected. So, we simulated the vibration for modes with $m = 0$, 1, 2 and $n = 1$, 2, 3, and we give a simple qualitative explanation for the results in figure 2. First, the relative amplitude (the $\frac{DJ_m(\eta_{mn}\frac{d}{a})}{\eta_{mn}[J_{m+1}(\eta_{mn})]^2}$ term in equation (2)) induced by the striking position d was calculated; it is shown in figure 3(a). It can be seen from figure 3(a) that the same mode has different amplitudes when striking at different positions. The vibration amplitudes for frequencies with $m \neq 0$ were greatly suppressed when striking at the center and thus will not be detected by the NG. But these modes may be easily detected when striking at $d = 9.2$ cm because their amplitudes are larger than those generated when striking at $d = 0$ and 4.6 cm. Therefore, more frequencies were detected in figure 2(c). Figure 3(b) gives the vibration shape (calculated from the $J_m(\eta_{mn}\frac{r}{a})\cos m\phi$ term in equation (2)) for a drum membrane for each mode. The bar in figure 3(b) represents the relative amplitude of each position $Z(r, \phi)$. For the position location on the dark lines and the circles, the local displacement is almost zero. If the NG was attached to or near these positions, the corresponding vibration modes might not be detected because of small strain. The fundamental frequency can be detected when striking anywhere because of the large amplitude and the nodal circle locating on the rim. In contrast, frequencies with $m \neq 0$ will not be detected when striking at the center regardless of where the NG is attached. Figure 3 gives a good explanation of the results in figure 2. Our study shows that a matrix of NGs has to be introduced on the surface if one is interested in the multiple modes of the vibration.

The drum used in our experiment is a typical Chinese drum, which has two surfaces. During the above experiment, the struck surface and the one on which the frequency is measured are two different surfaces. In the next experiment, the frequencies of the drum were also studied when the striking position d and the location of the NG d^* were all on the same drum membrane. This will present full and detailed information about the vibration of the drum. Figure 4 gives the results. As observed in figure 2, the observed frequencies in figure 4 are also tightly related to the location of the NG and the striking position. In contrast to the results in figure 2, more and higher frequencies were detected in figure 4. The

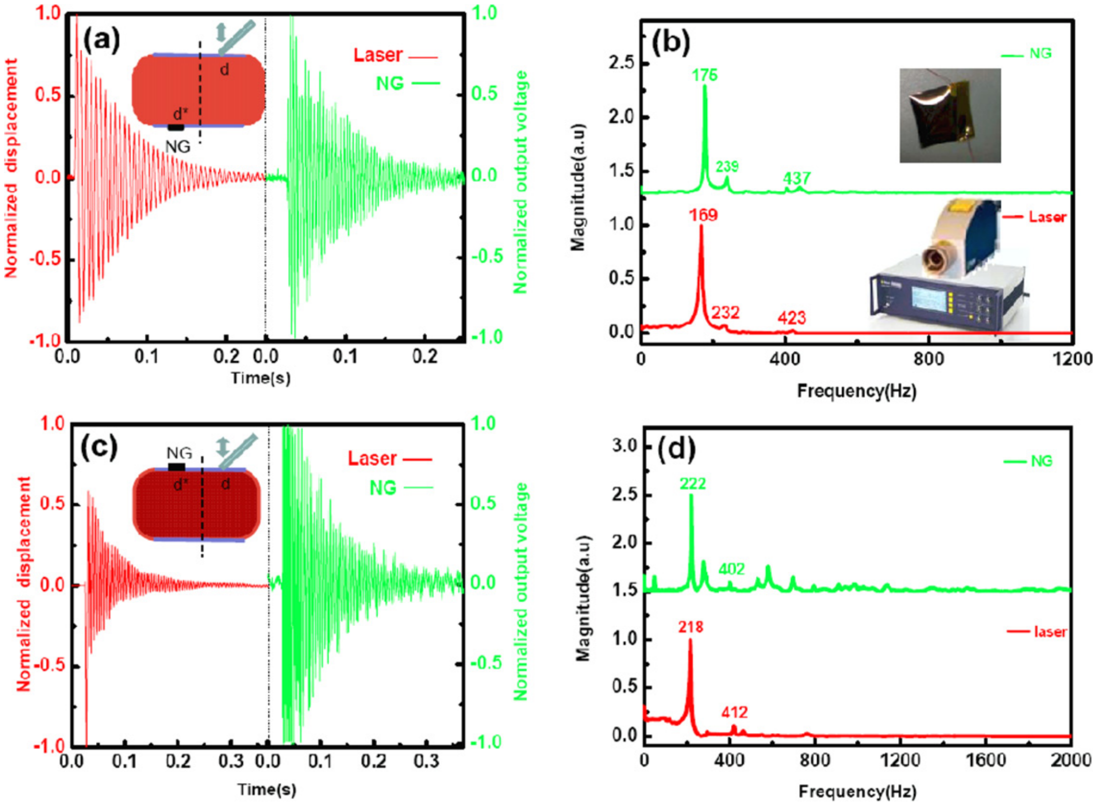

Figure 5. The normalized signal generated by a laser vibrometer and an NG, obtained by detecting the vibration spectrum of the same drum. ((a), (b)) The struck surface and detected surface are on different membranes. ((c), (d)) The struck surface and detected surface are the same membrane. The insets in (b) are a photo of a laser vibrometer and an NG, showing their huge difference in size/volume and weight. An offset is introduced in the plots in (b) and (d) for comparison purposes.

highest frequency detected is 1699 Hz. This may be due to the NG feeling a higher amplitude when the striking position and location of the NG are on the same drum membrane, while the damping of the air in the case of figure 2 may suppress the magnitudes of the these frequencies.

In order to verify these results obtained by using the NG, the vibration of the drum membrane as detected by a laser vibrometer is shown in figure 5. The parameter directly obtained by laser vibrometers is the displacement of the drum membrane. For the laser vibrometer measurement system, a laser beam with a diameter of about 100 μm is focused on a single point on the drum membrane. The striking position d is 4.6 cm from the center of the drum membrane center. The NG and laser points are all located at the center of the drum membrane. It can be seen that the displacement signal and the voltage signal measured by the laser vibrometer and the NG have the same shape after being normalized, in figure 5(a). Taking the Fourier transform of the displacement–time data, the frequency spectrum of the drum vibration was obtained (figure 5(b)). Clearly, the vibration frequencies of the drum measured by these two kinds of methods are consistent, which proves that using an NG as a frequency sensor is precise and feasible. The insets in figure 5(b) give a photo of the laser vibrometer measurement system that typically had a size of ~50 cm and the NG measurement system. The laser vibrometer measurement system includes a sensor head and a large size vibrometer controller, while the NG measurement system only includes a small size and light weight NG. Additionally, because the NG is flexible and small in size, it can be used in any object with any shape.

The data presented in figures 5(a) and (b) were acquired by placing the NG and the striking point on the top and bottom membrane surfaces of the drum, respectively. Considering the damping of the air, the vibration amplitude of the surface with the NG may not be very large, so the linear approximation may be valid. However, on placing the NG and the striking point on the same surface, the large local vibration amplitude can produce a rather large non-linear effect. We measured such a vibration both by using the NG and by using a laser vibrometer, as presented in figures 5(c) and (d). The data clearly present the excitation with high frequencies. The signal provided by the NG is sensitive even to the high frequencies, while the vibrometer is mainly sensitive to the fundamental frequencies, possibly because any directional strain (tensile, twist, shear) on the drum membrane can generate electricity. This study shows the high sensitivity of an NG used for detecting high frequencies and the possibly non-linear effect.

In summary, we have fabricated a light and flexible NG based on ZnO textured film via a wet chemical method and successfully demonstrated that the NG can be used as an active sensor for detecting the vibration spectrum of a drum without the use of an external power source. The output voltage of the NG is a direct measure of the vibration frequency and vibration amplitude of the local vibrating surface, and it is sensitive even to high frequencies, which are great merits in comparison to the large size laser vibrometer used today. A spatial arrangement of the NGs on the surface can provide position-dependent vibration information on the surface. The measured frequency spectrum can be understood on the basis of the theoretically calculated vibration modes. This work expands the application of NGs and should inspire the development of a self-powered vibration sensor for sound wave detection, machine monitoring and many more applications.

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