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All-fiber vibration sensor based on nano-wire grid polarizer

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Abstract. We propose a novel all-fiber vibration sensor without any bulk optical element by employing an in-line nano-wire grid (NWG) fiber polarizer. The NWG is directly fabricated on tip of a single mode fiber (SMF) by focused ion beam technology. According to effective medium theory, the sub-wavelength NWG has strong polarization properties. In our experiment, the reflection contrast between transverse electric and transverse magnetic modes reaches 14 dB, which is sensitive enough to monitor polarization change induced by photoelastic effect. We apply a sinusoidal vibration signal generated by a piezoelectric transducer onto the fiber. The output light signal from the SMF coincides well with the vibration source. The frequency response of the sensor is measured from 20 Hz to 4 kHz showing great consistency. [DOI: 10.1117/1.OE.51.5.050504]

Subject terms: optical fiber sensors; grating in fibers; nanotechnology; vibration measurement.

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1 Introduction

Optical fiber sensors are extensively studied and utilized in the industry for various applications,[1,2] for they have a number of inherent advantages over conventional sensing techniques, such as lightweight, high sensitivity, large bandwidth, immunity to electromagnetic interference, and so on. Among them, optical fiber vibration sensors are widely used in damage monitoring of industry construction, which overcome the problem of electrical isolation induced by conventional piezoelectric vibration sensors.[3] The most common optical fiber vibration sensors are based on intensity-based measurement or Fiber Bragg grating.[4] However, the sensing frequency bandwidth is usually limited. Other optical fiber vibration sensors include fiber Fabry-Perot systems[5] or polarization optical time domain reflectometers,[6] but they are either with bulk light element or relatively expensive.

In this letter, we propose an optical fiber vibration sensor based on polarimetric measurement and it is a compact all-fiber system without any bulk optical element. The response frequencies from 20 Hz to 4 kHz are demonstrated, which satisfies the most damage monitoring applications.

2 Theory and Experiments

Our all-fiber vibration sensor is based on photoelastic effect of optical fiber. Dynamic pressure applied on fiber can change the polarization state of the light in the fiber. So it is basically a polarimetric sensing system. However, to read the photoelastic polarization change, an in-line sub-wavelength nano-wire grid (NWG) fiber polarizer on tip of an optical fiber is employed. The transverse electric (TE) wave with electric field parallel to the wires will generate the movement of electrons so the NWG behaves in a similar manner to a reflective metal film. The transverse magnetic (TM) wave with electric field perpendicular to the wires still may pass through the grid due to the separation between adjacent wires. The sub-wavelength NWG thus can be treated as a transflective polarizer according to effective medium theory.[7] In addition, the transmission and reflection signals can be monitored simultaneously for heterodyne analysis $(I_{trans} - I_{ref})/(I_{trans} + I_{ref})$,[8] which is insensitive to the light source power variation. Here I_{trans} and I_{ref} correspond to the light transmittance and reflectance, respectively. The system stability thus is greatly improved, which is another advantage, as discussed in detail in our previous work.[8]

The sub-wavelength NWG polarizer is fabricated by focused ion beam (FIB) technology right on tip of a single mode fiber (SMF). A 3 cm-section SMF (from Yangtze corp.) is employed. First, we deposit a 100-nm-thick layer of Au film on one tip of the fiber by magnetron sputtering

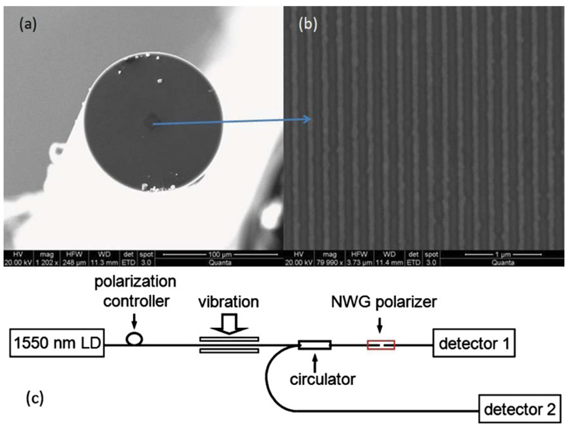

Fig. 1 (a), (b) The scanning electron photomicrographs of the NWG polarizer on tip of a SMF; (c) Experimental setup of the vibrate sensor.

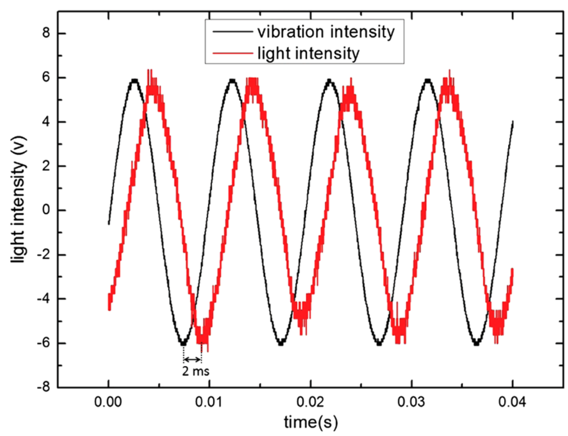

Fig. 2 A comparison between the response of transmission light and the applied vibration signal.

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technology. After that, a FIB (Strata FIB 201) is used to make the grid structure on the Au coating. The grating area is $10 \times 10\ \mu m^2$ around the core area of the fiber tip to make sure the grid covering most of the light field of the fiber. The period and duty cycle of the wire grid are set at 200 nm and 0.5. The milling time is carefully controlled to ensure that the etched groove depth is just equal to the thickness of the Au coating. Figure 1(a) and 1(b) shows the scanning electron photomicrographs of the NWG on tip of an SMF we fabricated.

Figure 1(c) depicts the schematic diagram of our experimental setup to characterize the NWG polarizer and demonstrate the vibration sensing. The fiber with the NWG polarizer is connected directly to another fiber inside a 127 μm glass-tube. Some epoxy could be further applied on the two ends of the glass tube to fix and package this tiny in-line fiber polarizer. As shown in Fig. 1(c), light from the 1550 nm source (Santec TSL-210) may experience a photo-elastic polarization change then monitored by the NWG polarizer and detectors. Although the semiconductor laser normally has a polarized light output, a polarization controller is still employed to tune the initial light polarization freely before the light enters the sensing section. To measure the transmitted and reflected light simultaneously, a circulator

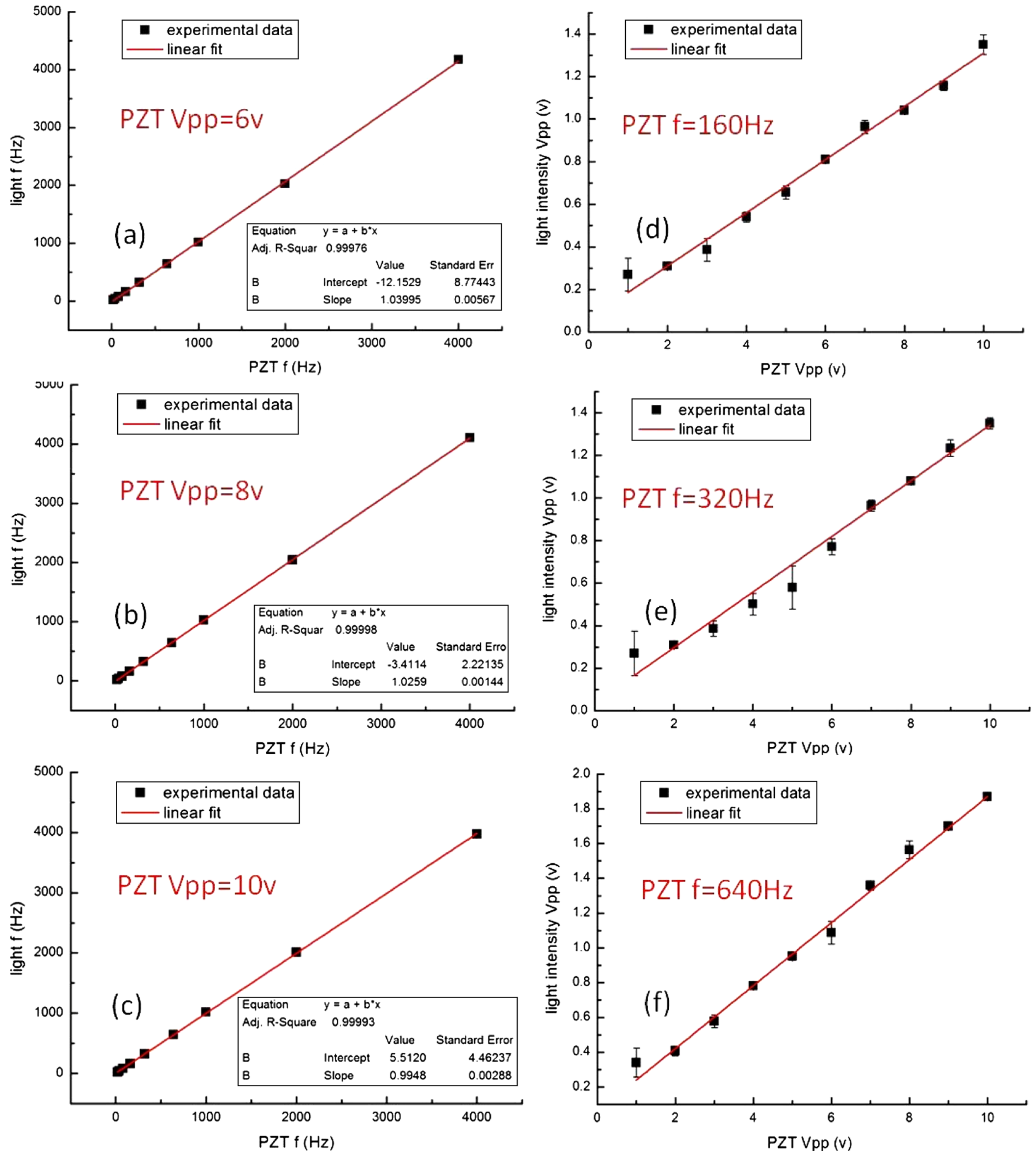

Fig. 3 (a), (b), (c) The measured signal frequency as a function of the applied vibration frequency; (d), (e), (f) The measured signal intensity as a function of the applied intensity.

is also used. As a result, we can detect the vibration by either the transmission signal, or the reflection signal, or even both of them,[8] which provides more flexibility in applications. Before our sensing experiments, the polarization performance of the NWG polarizer is characterized. The polarization extinction ratio of reflection signal and transmission signal are measured of 14 and 5 dB, respectively. The large extinction ratio difference is due to the unwanted leakage of the TE light that greatly deteriorates the corresponding extinction ratio. To improve it, the Au-film with higher quality should be used. However, although the NWG's current performance may be not as good as conventional bulk optical polarizer, it is already adequate for measuring polarization change excited by photoelastic effect.

As the polarization state of input light can be modulated free by the polarization controller, the whole setup is just equivalent to a typical polarization interferometer. Any phase-retardation induced in the fiber between the fiber polarization controller and the NWG polarizer can be detected from the transmission or reflection light intensity variation. In our experiment, a 368-cm-long fiber between the polarization controller and the circulator is wound to form a coil and placed between two 15×15 cm^2 flat glass plates on an optical table. This coil has direct contact with the top and bottom glass plates. Then a PZT piezoelectric transducer, which we use to generate vibration, is tightly attached to the glass plate, so the vibration can be well transferred to the fiber.

3 Results and Discussion

A sinusoidal wave electric signal is applied to the PZT to generate vibration signal with similar wave curve and same frequency onto the fiber coil. An oscilloscope is connected to the light power detector to record the corresponding intensity variation of the transmission light. As shown in Fig. 2, the frequency of the electric signal is 100 Hz. The red bold curve shows the response light signal after being magnified 600 times in the oscilloscope. The corresponding experimental light signal coincides well with the applied vibration signal except for a $\sim$2 ms time delay. We think it is due to the separation between the transducer, the glass plates and the fiber during the operation. As a result, when the radio frequency (RF) driving signal to the PZT is applied, the fiber cannot feel the periodic pressure change instantly. A time delay thus may come out.

To characterize the dynamic response of the sensor, we measure the signal response to vibration with different frequencies and intensities, respectively. First, we fix the intensity of the PZT's driving signal and then change the frequency from 20 Hz to 4 kHz (limited by the work performance of the PZT transducer we used). Figure 3(a)–3(c) shows the results of this frequency response experiment as vibration intensity set at 6, 8, and 10 V, respectively. The slope of the linear fitting curves of the experiment dots are measured of 1.0399, 1.0259, and 0.9948, which means the responsive frequency of the output light is just equal to the frequency of the vibration applied on the fiber. Second, we fix the frequency of the vibration at 160, 320, and 640 Hz, and change the vibration intensity from 1 to 10 V. Figure 3(d)–3(f) shows the responsive intensity of the transmission light as a function of the intensity of the electric signal, which is proportional to the intensity of the vibration. The best fitting curve still shows nice linearity which means our sensor has linear response over a wide intensity range. So in short, within the work frequency and intensity range of the PZT transducer, the all-fiber vibration sensor works effectively with negligible frequency distortion and nonlinearity. In addition, with the help of a high frequency vibration source, perhaps we may demonstrate such an all-fiber sensor with a wider response range in future work.

4 Conclusion

We demonstrated and fabricated an all-fiber vibration sensor based on a novel NWG polarizer. The sensor is based on an all-fiber configuration without any bulk element in the system, which may greatly reduce the sensor's size and improves its stability. Frequency response from 20 Hz up to 4 kHz is characterized showing nice linearity. We wish the novel feature and performance could give rise to future applications in plant damage monitoring systems.

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