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Wearable polyurethane optical fiber based sensor for breathing monitoring

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Abstract: We experimentally demonstrate a wearable breathing monitoring sensor based on a polyurethane (PU) optical fiber. The mechanical flexibility of the PU fiber allows for the simple measurement of inhalation and exhalation motions through optical transmission variations of the fiber induced by bending and stretching.

OCIS codes: (060.2280) Fiber design and fabrication; (060.2300) Fiber measurements; (280.4788) Optical sensing and sensors.

1. Introduction

Over the last three decades, optical fiber sensors (OFS) have benefited from significant development leading to experimental measurements and monitoring of a wide range of physical parameters such as temperature [1], mechanical strain [2] or pressure [3]. This is because OFS offer meaningful advantages compared to their electrical or mechanical counterparts, including compactness, lightweight, large bandwidth and the ability to operate in a wide range of environments [4]. These properties also make these devices highly suitable for biomedical applications [5, 6].

To date, glass and plastic (i.e. PMMA) remain the most widely used materials for the fabrication of these fibers. However, their relatively high Young's modulus, typically larger than 1 GPa, limits their potential for measuring small forces. On the other hand, a lower Young's modulus material allows for a greater response to external perturbations and several flexible waveguides have been demonstrated for implementation in robotics [7, 8], wearable and human friendly sensors [9, 10]. For such applications, an OFS device requires to be highly stretchable and compressible. We recently reported on the fabrication and characterization of a hollow core PU optical fiber [11]. The remarkable properties of PU material allowed for high levels of elongation and large deformation that led to significant transmission losses [12]. Thus, the detection of pressure variation or deformation was possible through a simple optical intensity measurement.

In this work, we report the fabrication of a wearable sensor for breathing monitoring using a PU fiber. We take advantage of the high mechanical flexibility of the PU fiber to measure the expansion and relaxation of the chest induced by breathing through simple optical intensity measurements. We tested the stability of our device during walking and running and we show that the mechanical response of the polymer fiber allows our device to detect breathing amplitude and frequency, as well as the additional vibrations arising from running. Our results show the great potential of this polymer material for the design of simple wearable fiber based sensing applications.

2. Sensor fabrication

First, we fabricated the PU optical fiber using a standard drawing technique [13]. The preform polymer capillary is stretched down to 1.5 mm diameter in the fiber draw tower. The drawn polymer waveguide has an outer diameter of 1.5 mm and hollow core diameter of 1 mm. This simple design offers two significant advantages; (i) the hollow core allows for light guiding while avoiding the high material loss of PU and (ii) no complex anti-resonant design is required [14].

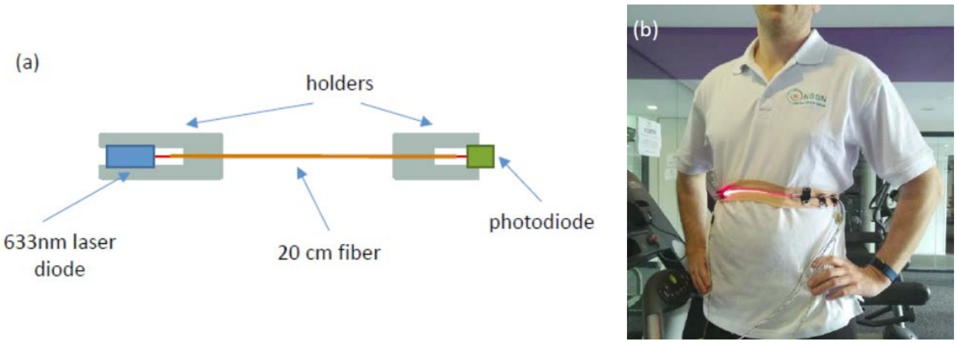

Figure 1. (a) Schematic of the PU fiber based sensor. (b) Picture of the sensor set around the subject's diaphragm.

A schematic of the sensor is shown in Fig. 1(a). The light emitted by a 633 nm continuous wave laser diode is coupled into 20 cm of PU fiber and the optical intensity at the output of the flexible waveguide is measured using a semiconductor photodiode. The laser source, polymer fiber and photodetector are positioned then fixed on two aluminum holders using commercial cyanoacrylate based glue. The overall transmission loss when the fiber is straight, not stretched and uncompressed is around 17 dB, including the fiber loss and coupling. Finally, we fix this optical setup on a regular elastic bandage. This allows for the wearing of the sensor on different parts of the body. An example of the complete sensor worn around the torso at diaphragm level is shown in Fig. 1(b).

3. Results

First, we test the sensor by adjusting it around the stomach of a male subject and we measured the photodiode signal over 80 s using an oscilloscope while the subject stands still. We specifically chose this position to take advantage of the wide amplitude motion of the thoracic diaphragm; however, similar results were obtained when the sensor was positioned around the chest. The result of this measurement is shown in Fig. 2. Between 0 and 64 s, we observe a periodic modulation of the output signal at a frequency around 0.14 Hz corresponding to the breathing of the subject. Concretely, when air is inhaled the lungs and diaphragm expand, inducing stretching and bending of the fiber which increases the overall transmission loss. Then, when the subject exhales, the volume of the chest decreases and the PU fiber comes back to its original shape. At t = 64 s, after exhaling the subject held his breath until the end of the measurement. As expected, the output signal remains constant and no deep modulation is observed.

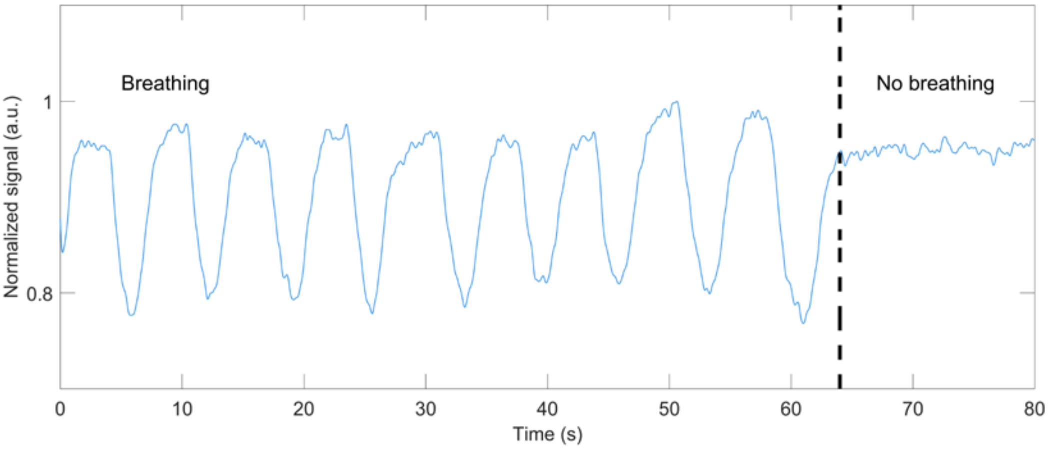

Figure 2. Normalized sensor output signal variations arising from breathing over 80 seconds. The vertical dashed line at t =64s indicates when the subject started to hold his breath.

Next, we assess the stability of our sensor to external perturbations by performing a set of measurements while the subject was moving on a treadmill. We recorded the sensor output signal over 35 s for three different speeds. The results for these measurements are plotted in Fig. 3. For walking speed (i.e. 2 km/h) we observe a modulated output signal at a frequency of 0.2 Hz, as seen in Fig. 3(a), similar to the previous test. Then we increased the treadmill speed to 7 km/h (Fig. 3(b)). While the recorded signal amplitude still displays a low frequency modulation induced by the subject’s breathing, we also observe a higher frequency modulation of the signal. Similar features are seen on the recorded output signal for a treadmill speed of 11 km/h in Fig. 3(c). Analysis of the Fourier spectrum of the signal shown in Fig. 3(b) provides further insight. As seen in Fig. 4(a), the signal displays a low frequency component at 0.27 Hz, corresponding to the response of the PU fiber to the breathing motion, together with several higher frequency peaks around 2.4, 4.8 and 7.2 Hz. These additional spectral components arise from the vibration induced by the running. A 0.8 m stride at 7 km/hr corresponds to a step rate of 2.43 s^{-1}. Thus the first of these peaks is the fundamental frequency of the running pace, and the latter are the second and third harmonics of a non-sinusoidal signal. This indicates that the PU fiber response also allows for the recording of extra parameters. In the present case, amplitude and frequency of the running pace could also be extracted, using the same device. By simply filtering out the high frequency components we can recover the original breathing pattern as seen in Fig. 4(b). As expected, we observe that the breathing frequency increases with the running speed. We measure a breathing frequency of 0.2, 0.26 and 0.32 Hz for 2, 7 and 11 km/h speed, respectively.

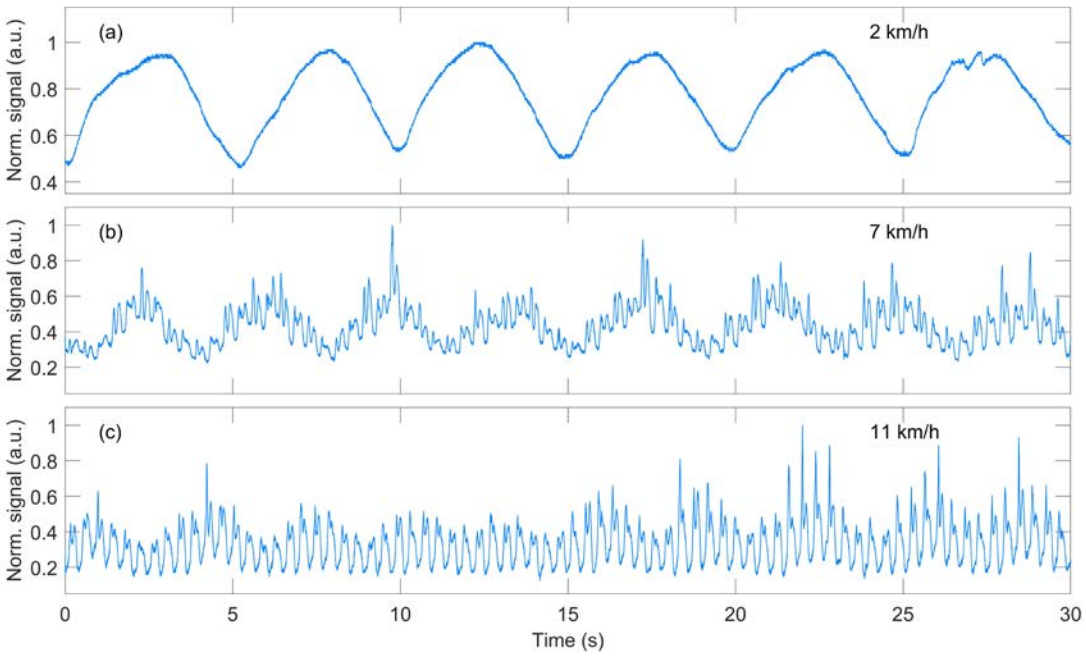

Figure 3. Normalized sensor output signal recorded over 30s for a treadmill speed of (a) 2, (b) 7 and (c) 11 km/h.

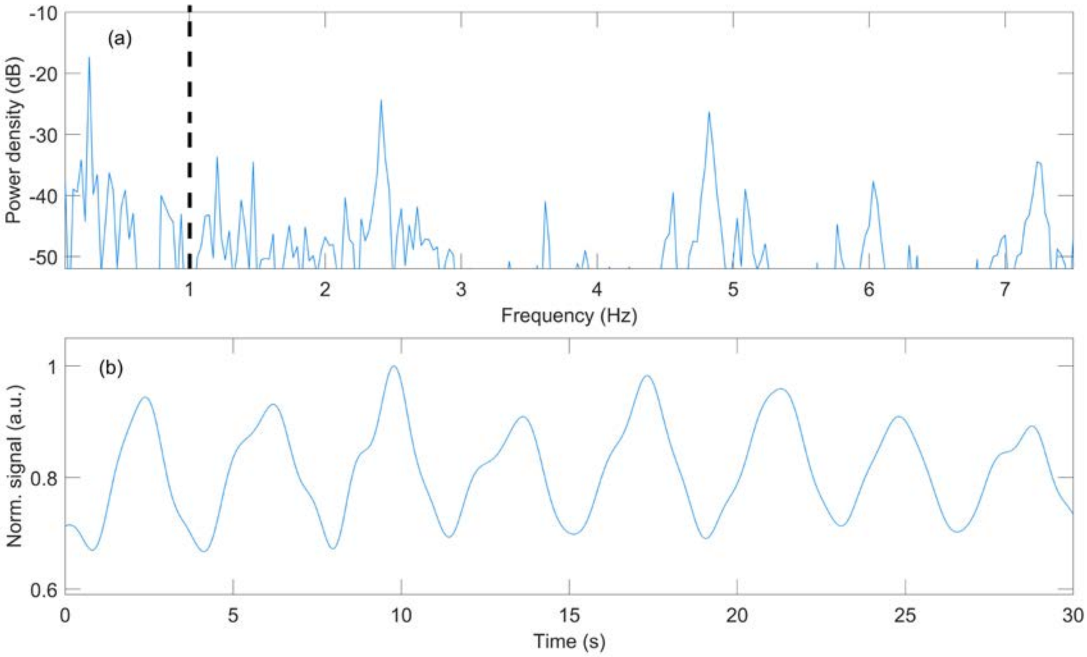

Figure 4. (a) Fourier spectrum of the signal recorded for a treadmill speed of 7 km/h. The vertical dashed line indicates the cut-off frequency of the filter used to recover the breathing pattern. (b) Filtered signal.

4. Conclusion

We fabricated and characterized an optical fiber breathing sensor taking advantages of the high flexibility of PU material. Our sensor allows for the detection of the breathing motion by using a simple optical power measurement scheme. When the upper body volume increases due to inhalation, the fiber is stretched, leading to higher transmission loss. After exhalation, the polymer waveguide returns to its original shape. The device stability was tested for walking / running at different speeds and we showed that the breathing pattern can be easily extracted using straightforward Fourier analysis. Moreover, the mechanical response of the PU fiber allows for the detection of several parameters using a single device. This device demonstrates the potential of PU material for the fabrication flexible optical waveguides with low Young's modulus using conventional fiber drawing technique. Our results open the way for the development of optical sensors fully integrated into clothes.

5. Acknowledgment and funding information

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