2017 3rd International Conference on Electrical Information and Communication Technology (EICT), 7-9 December 2017, Khulna, Bangladesh

Measurement of weak low frequency pressure signal using stretchable polyurethane fiber sensor for application in wearables

Md Rejvi Kaysir[1,2,*], Alessio Stefani[1,3], Richard Lwin[1], and Simon Fleming[1,**]
[1]Institute of Photonics and Optical Science (IPOS), School of Physics, The University of Sydney, NSW 2006, Australia
[2]Department of EEE, Khulna University of Engineering and Technology, Khulna 9203, Bangladesh
[3]DTU Fotonik, Department of Photonics Engineering, Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark
*rejvi@eee.kuet.ac.bd, **simon.fleming@sydney.edu.au

Abstract— **The practical realization of low Young's modulus Polyurethane (PU) based optical fibers offers new possibilities for sensing on bodies due to its bio-compatibility and high material sensitivity. Here, we experimentally demonstrate a PU fiber pressure sensor using the simplest possible structure (i.e. a capillary) to measure a weak low frequency signal comparable to respiration/heart rate. We characterized the fiber and measured the sensitivity of a PU capillary using a speaker connected to a function generator. The frequency of the modulated signal was recovered using Fourier Transform (FT). This bodes well for applying more sophisticated structures to wearable devices.**

Keywords—Polyurethane, fiber optic sensors, fiber drawing and fabrication, stretchable waveguide, biomedical signal.

I. INTRODUCTION

The detection/measurement of low frequency signals (such as vibration) is important in many applications, such as aerospace, automotive, architectural, security, and biomedical [1-4]. Measurement of pressure in the environment often involves low frequency signals. There exist different sensors, which convert pressure induced mechanical deformation into an electrical signal, based on their principle of operation such as piezoresistive or piezoelectrical, inductive or capacitive, thermo-electrical or acoustic [5]. These principles have many technological limitations including electromagnetic interference, higher temperature deformation, harsh chemicals or explosion sensitivity that restrict their complete utilization in sensing pressure in various environments.

Optical fiber sensors (OFSs) are an existing technology that overcomes most of those constraints and often also offers better long-term reliability. This technology is also particularly attractive for application in wearable, implantable, and human-friendly devices as it allows both sensing and signal transmission. There are three technologies which are commercially available for pressure measurement with fiber optics sensors: intensity based, fiber Bragg grating and Fabry-Perot [5,6], where the latter two use complicated light detection systems. All these currently used commercial OFS technologies for measuring pressure rely on optical fibers made of high (e.g. >1 GPa) Young's modulus (YM) materials (e.g. glass or PMMA), and their intrinsic sensitivity (which comes from these materials) to the external pressure is very low. Thus, high YM materials limit the maximum response of the overall pressure sensing system and the intrinsic sensitivity could effectively be increased by using low YM materials with good optical properties. Such low YM materials can also be used in stretchable human friendly environments where the fiber can be integrated into the fabrics of garments, which can permit bending and twisting with the human body. One such material is polyurethane which has YM as low as 10 MPa and can be elongated to 600% [7].

Recently, we demonstrated pressure sensing using hollow core PU fiber (outer and inner diameters of ~2100 μm and ~400 μm, respectively) for the application of detecting human movement, such as bed-ridden patients [8]. A comparatively rigid structure with a jacket of the PU material was chosen for this application. We are now interested in monitoring respiration/heart rate signal, which is generally required for either medical diagnosis or daily health monitoring. To demonstrate the suitability of the PU fiber as a sensor for monitoring respiration/heart rate, we used a simple laboratory set-up comprising a speaker connected to a function generator to introduce very low pressure on the fiber surface as a proof of the principle. This problem has been already investigated with the use of optical fiber sensors of high YM materials, but mostly using glass fibers and fiber Bragg gratings [9,10]. Both the material used and the costly detection method make impractical utilizing this technology as a wearable device.

In this work, we demonstrate the detection of a low frequency (e.g. 1 Hz) pressure signal, generated from a speaker connected to a function generator, using a simple PU capillary. The capillary fiber was used here due to its simple structure and ease of characterization (i.e. making a relationship between the transmission loss and the deformation of the fiber caused by applied force). A capillary optical fiber consists of low index air core surrounded by a high index dielectric cladding (PU material in this case), where the light is guided in the air hole by grazing incidence reflection of the waves between the air and dielectric medium. As the loss of this capillary fiber originates from individual reflections, the waveguide needs to be straight to minimize loss. The biggest problem of having capillary guidance is that the loss will

978-1-5386-2307-7/17/$31.00 ©2017 IEEE

increase abruptly with small microbending or gradual bending caused by any external factors/noise. The fiber was kept straight in the laboratory setup to minimize any additional losses during the measurement.

The flexibility of PU allows high levels of deformation of the air core of the capillary fiber that directly induce transmission losses. The response of the PU fiber can be related to the applied force and the sensitivity is much higher than that of the same fiber made of a higher YM material (e.g. PMMA). The frequency of the speaker head was recovered by using the FT signal. This analysis provides a pathway for characterizing more sophisticated PU fiber structures, which is a potential candidate for wearable devices.

II. SENSOR FABRICATION AND CHARACTERIZATION METHOD

A. *Fiber fabrication*

We used a simple PU capillary for the experiments. The final capillary was realized by standard fiber drawing and the final dimension determined by the ratio between feeding and drawing. The simple structure helps to elucidate the loss mechanism and determine the relationship between the transmission loss and corresponding deformation of the fiber. The fabricated capillary was 30 cm long having inner and outer diameters 613 µm and 892 µm, respectively.

B. *Experimental setup for dynamic response measurement*

The fiber was characterized in terms of sensitivity (S) that is defined as a change in transmission loss (in dB) of the fiber per unit change in the force (in N) applied on the fiber. As a PU capillary is used here, the light guides in the air core of the capillary. In the experimental setup, the fiber was kept straight by fixing at the input and output terminals and the force was applied on a small area of the fiber. Thus, the variable loss mainly originates from the deformation of the core by the applied force. To minimize the effect of other static losses in the system including launching, scattering and coupling to the detector, we kept the setup fixed throughout the measurement. Thus, the dominant loss in the system is the deformation of the core which modulates the transmission loss. To measure the low frequency signal, we investigated the dynamic response of the fiber, described in the following section.

Light from an inexpensive (~$1/unit) 655-nm laser diode was launched into the fiber through a 4X lens. This laser was driven by a laboratory power supply, however a 3V battery could be used as a power source for intended wearable devices. The output of the fiber was coupled to a Si-photodetector (THORLABS-SV2) that is connected to an oscilloscope. The dynamic force implementation was achieved using a speaker connected to a function generator. The head of the speaker (1 cm diameter) was in contact with the fiber surface, whereby modulations of the speaker head caused deformation on the air core fiber, thus causing loss.

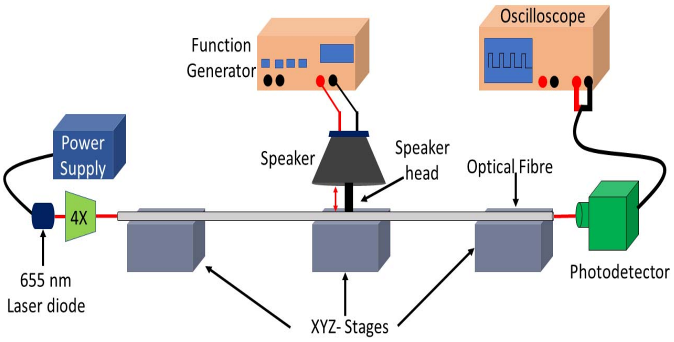

Figure 1. Schematic diagram of the experimental setup for the dynamic response measurement of the PU capillary.

The fiber was located on three XYZ stages of which two stages were fixed for launching to the input of the fiber and coupling to the detector. The middle stage was used to apply dynamic force from the speaker head. The fiber was secured using adhesive tape on the middle stage. This also ensured that the deformation of the air core does not create propagating waves along the fiber resulting in transients, spurious responses and other losses.

III. EXPERIMENTAL RESULTS

A. *Fiber characterization*

We characterized the fiber in terms of sensitivity using the setup shown in Fig. 1. The change in the output power from the fiber with the applied force by the speaker head was measured by using both the Si-Photodetector (SV-2) connected to an oscilloscope and a THORLABS (PM100D) power meter (not shown in Fig. 1). Direct power measurements by the power meter would assist in determining the right detector for any specific applications.

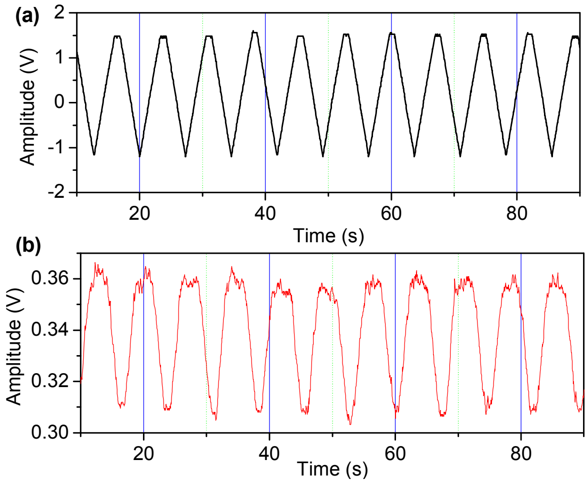

Figure 2. (a) Input signal to the speaker from a function generator for characterizing the PU capillary fiber and (b) the corresponding response of the fiber taken from the oscilloscope. There is a saturation effect shown at the top and bottom of the response signal as the speaker did not have enough strength to apply more force to deform the fiber.

We first used a triangular wave signal from the function generator to modulate the speaker head (i.e. modulate the force on the fiber) to determine the maximum dynamic range of the output signal change due to the applied force. Figure 2 (a) shows the input signal to the speaker in which the positive signal means the speaker head moving downwards, hence compressing the air core of the fiber. On the other hand, the negative signal moves the speaker head upwards and releases the compression on the fiber. Figure 2(b) shows the corresponding response of the fiber with the applied force. When the input signal to the speaker is maximum, the output signal reaches the lowest value, as expected due to increasing transmission loss caused by deforming the air core. Thus, there exists an approximately linear relationship between the force and the corresponding loss of the fiber, for such small deformation regime.

The maximum transmission loss of the fiber was found to be 1.9 dB. We also measured the force of the speaker head using a laboratory scale and determined it to be 0.09 N. Thus, the sensitivity of the fiber can be calculated as 23.3 dB/N. At this stage, we were interested to measure the deformation of the air core of the PU capillary fiber with the applied force. This information helped us to relate the deformation of the core with the applied force, which is described in the following section.

B. Fiber deformation measurement:

The deformation of the PU capillary fiber was measured by using a microscope camera. The change in the diameter of the PU capillary with the applied force is shown in Fig. 3. There is a small change in the diameter up to the force of ~1.5 N, after that the diameter reduces abruptly up to ~4 N. From the slope of the graph, we found the deformation sensitivity to be ~66 µm/N. A PMMA capillary of the same dimensions was also investigated under the same force and no visible change in diameter was observed.

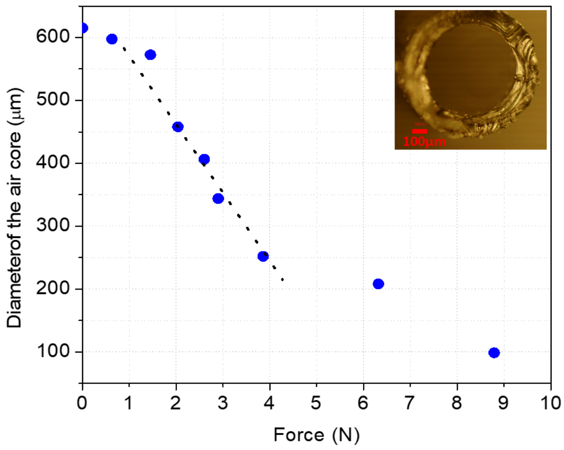

Figure 3. The change in core diameter of the PU capillary fiber with the applied force. A linear fit to the data is also presented here, which shows the mechanical deformation sensitivity of ~ 66 µm/N. Inset: cross section of the PU capillary fiber.

C. Square wave signal response:

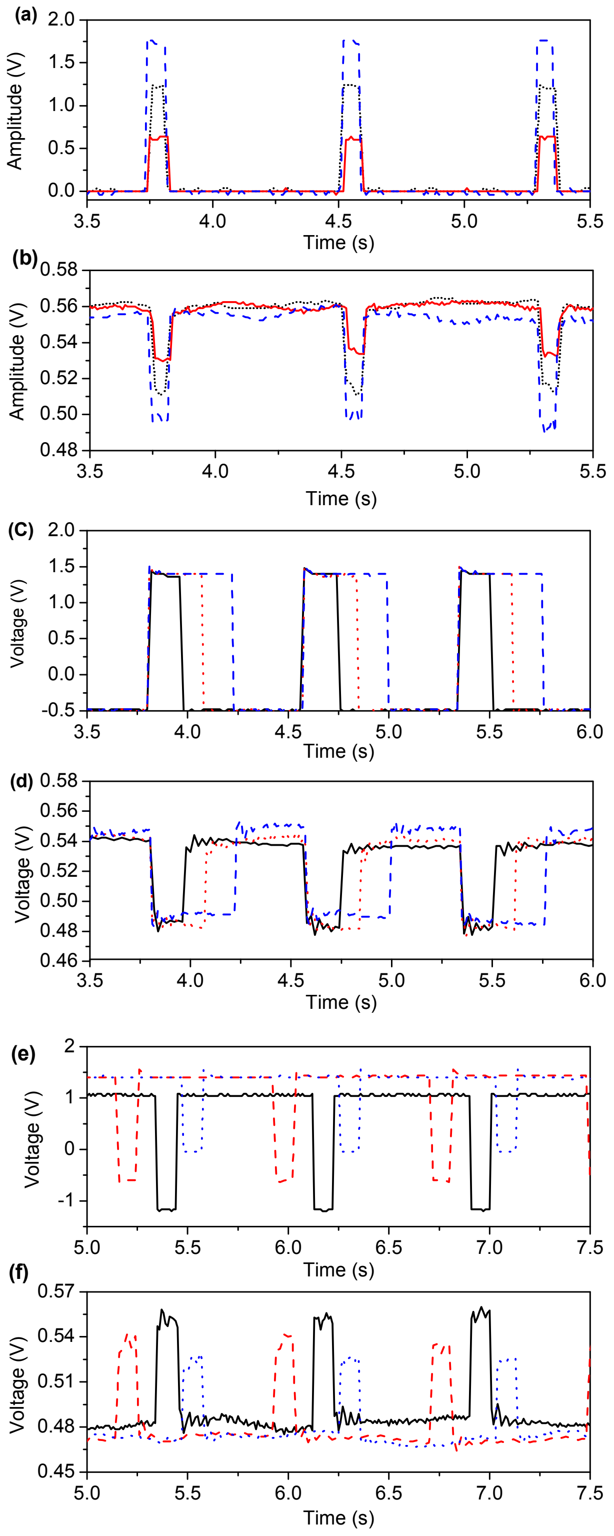

Figure 4. (a) Amplitude, (c) duty cycle and (e) dc offset variation of the input signal to the speaker and corresponding response of the PU fiber: (b), (d) and (f), respectively.

As stated, since we aimed at detecting/measuring a low frequency signal using PU fibers, we first set a low frequency (< 5Hz) input square wave signal from the function generator to modulate the movement of the speaker (i.e. modulate the applied force on the fiber). Then, different parameters (amplitude, duty cycle and dc offset) of the input signal to the speaker were changed. Figure 4 shows the various input signals to the speaker and their corresponding responses from the PU fiber.

Figure 4 (a) and (b) show the variation of the amplitude of different input signals to the speaker and the responses of the PU fiber respectively, where the same color is used to identify the corresponding response of the PU fiber. In general, the higher amplitude of the signal to the speaker means the fiber experiences larger force, which deforms the air core of the fiber further. Thus, the magnitude of the PU response signal depends on the corresponding polarity and magnitude of the input signal to the speaker. However, there are saturation effects at the bottom of the response signal (see Fig. 4(b)) as the speaker did not have enough force to deform the fiber further. This situation was also observed earlier when characterizing fibers with triangular wave signals, which is discussed in section IIIA.

Figure 4(c) and 4(d) show the variation of input signals to the speaker by changing the duty cycle and the response of the PU fiber, respectively. As there is no change in the magnitude and polarity of the input signal, the magnitude of the response signal should not change. Here, we observed the time response of the PU fiber with the same pulse ends at different time, which verifies that there is no delay in the response of PU system within the range of applied force.

Figure 4(e) and 4(f) show the variation of input signals to the speaker by changing dc offset and their response, respectively. As both the magnitude and dc level of the signal change, the response of the PU fiber should follow both magnitude and dc offset. The response graph clearly shows the changes as expected. It is noted that, there is a small change in the background of the PU responses due to variation of input power. However, the fiber clearly showed the distinguishable responses from the background signal due to the extreme sensitivity of the PU fiber.

D. Frequency response using FT:

As the goal of this work is to measure/detect low frequency signal, we used the Fourier transform of the PU response data to identify the input signal frequency to the speaker. We used FFT in the MATLAB environment to get the frequency response data from the time domain signal. Figure 5 shows the response of the PU time domain signal and their corresponding frequency domain signal using FFT. The input frequency of the function generator was set as 1.3 Hz. The clear peak at 1.3 Hz in the FFT demonstrates that the frequency information of the speaker can be effectively recovered by the PU fiber allowing for example to recover the heart rate and determine its variability.

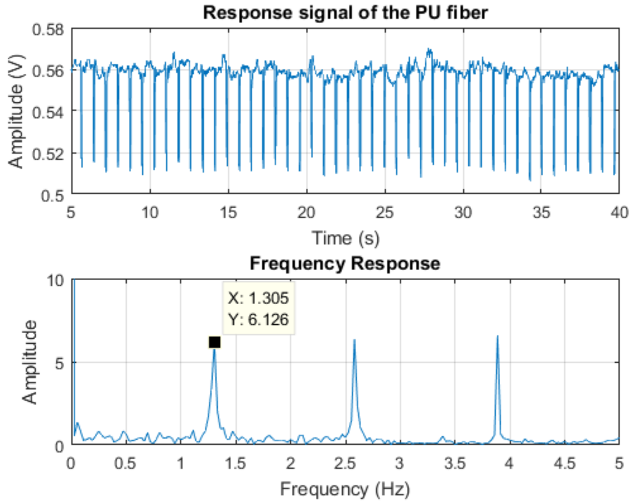

Figure 5. (a) The response of the PU fiber with the applied signal frequency to the function generator at 1.3 Hz. (b) FFT data of the time domain signal.

IV. CONCLUSION

We successfully characterized and demonstrated the frequency response of a PU capillary fiber. The sensitivity of the capillary fiber was found to be 23.3 dB/N, which makes it suitable for detecting a very small force of 0.09 N. We recovered the input frequency of the speaker by applying FFT to the PU fiber response signal. The sensitivity of the PU fiber could be effectively tuned by different useful design. This analysis also gives a pathway to characterize more sophisticated and complex fiber structures. Thus, fiber sensors made of PU (low YM materials) could open up new opportunities for sensors in wearable/ biomedical applications.

ACKNOWLEDGMENT

This work was performed in part at the OptoFab Node of the Australian National Fabrication Facility (ANFF), utilizing Commonwealth and NSW State funding, and was supported by ARC (DP170103537) and NSW Smart Sensors Network (NSSN) funding. This work was supported by the Marie Sklodowska-Curie grant of the European Union's Horizon 2020 research and innovation programme (708860).

REFERENCES

[1] S. Wang, X. Fa, Q. Liu, and Z. He, "Distributed fiber-optic vibration sensing based on phase extraction from time-gated digital OFDR," *Optics Express*, vol. 23, no. 26, pp. 33301-33309, Dec. 2015.

[2] E. Reithmeier, S. Mirzaei, and N. Kasyanenko, "Optical vibration and deviation measurement of rotating machine parts," *Optoelectronics Letters*, vol. 4, no. 1, pp. 45-48, Jan. 2008.

[3] A. Wada, S. Tanaka and N. Takahashi, "Multipoint vibration sensing using fiber Bragg gratings and current-modulated laser diodes," *Journal of Lightwave Technology*, vol. 34, no. 19, pp. 4610-4614, Oct. 2016.

[4] D. Jiang and H. Wei, "Review of applications for fiber Bragg grating sensor," *Journal of Optoelectronics Laser*, vol. 13, no. 4, pp. 420-430, Oct. 2002.

[5] Éric Pinet, "Pressure measurement with fiber-optic sensors: Commercial technologies and applications," *Proc. of 21st Int. Conf. on*

optical fiber sensors (SPIE), May 20011, pp. 775304(1)-775304(4), vol. 7753.

[6] W. J. Bock, M. S. Nawrocka, W. Urbanczyk, J. Rostkowski and T. Martynkien, “Fiber-optic sensor for automotive applications [pressure and temperature measurement],” *Proc. of IEEE Sensors,* 2004, pp. 248-251 vol.1.

[7] S. Fleming, A. Stefani, X. Tang, A. Argyros, D. Kemsley, J. Cordi, and R. Lwin, “Tunable metamaterials fabricated by fiber drawing”, *JOSA B*, vol. 34, no. 7, pp. D81-D85, 2017.

[8] M. R. Kaysir, A. Stefani, R. Lwin, and S. Fleming, “Flexible optical fiber sensor based on polyurethane,” *Proc. of Pacific Rim conference on lasers and electro-optics (CLEO-Pacific Rim)*, 2017.

[9] P. Roriz, O. Frazão, A. B. Lobo-Ribeiro, J. L. Santos, J. A. Simoes, “Review of fiber-optic pressure sensors for biomedical and biomechanical applications,” *J. Biomed. Opt.*, vol.18, no.5, pp. 050903-050918, May 2013.

[10] C. Massaroni, P. Saccomandi, and E. Schena, “Medical smart textiles based on fiber optic technology: an overview,” *J. Funct. Biomater*. vol. 6, no. 2, pp 204-221, Jun 2015.