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Low-cost and High-Resolution Pressure Sensors Using Highly Stretchable Polymer Optical Fibers

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***Abstract*—This letter reports on the development of a low-cost intensity variation-based pressure sensor using polymer optical fibers (POFs) with high flexibility fabricated through the light polymerization spinning process. The fibers were characterized by tensile tests that indicate a Young's modulus of 18.11 MPa. The pressure response of the proposed system shows a sensitivity five times higher when compared with systems employing commercial POFs. Furthermore, results also show low hysteresis (3.5%) and resolution potentially higher than the systems with spectral based sensors.**

***Index Terms*—Fiber technology, Polymers, Sensors.**

1. Introduction

For sensing applications, polymers are employed in a multitude of devices, which include physical and chemical sensors [1]. In these applications, different approaches are used, including thermosensitive, piezoelectric effects, ionic associations, swelling effects, photoluminescence and conductive polymers [1].

Concurrently, there is a widespread in optical fiber sensors (OFS) technology due to advantages such as multiplexing capabilities, compactness and electromagnetic immunity [2]. In addition, since there is no electrical signals in the sensing head, OFS provide an intrinsically safe solution for underwater, intrusive and harsh environments applications [3]. Besides the commonly used silica optical fibers, the advances in polymer processing enable the development of transparent polymers for optical fibers, which have many sensing applications due to its higher flexibility in fabrication, fracture toughness, lower Young's modulus and higher strain limits [2]. Despite the lower stiffness of polymer optical fibers (POFs), mechanical sensing applications that require high resolutions still rely on sensors with modifications on the fiber structure such as fiber Bragg gratings (FBGs) or interferometers [3,4]. These sensors need specialized equipment for their fabrication and optical spectrum analyzers for the signal acquisition, which increase the associate cost of these technologies. Although intensity variation-based sensors have a relative cost compatible (and in some applications lower) than the ones of electronic sensors, such as capacitive or resistive, the commercially available POFs cannot reach the demands of high sensitivity, repeatability and resolution of some pressure sensing applications.

This letter presents the development, characterization and application of an intensity variation-based sensor for pressure assessment with low cost and high resolution. The POF is fabricated using the light polarization spinning (LPS), which presents high flexibility and customization, leading to POF with remarkably low Young's modulus as depicted in [5]. Then, a pressure sensor is developed using polymer diaphragms.

2. Material Description and Experimental Setup

For the POF fabrication, there is the combination of monomers and additives, instead of the commonly used polymer preforms. In this process, the liquid mixture of polymers comprising of Bisphenol-A acrylate passes through a spinneret, obtaining the fiber shape and are polymerized using a UV lamp, which occurs at two steps. After the first UV curing step, the polymer is stretched until the desired diameter for the POF is obtained. Then, the second UV curing stage occurs [5]. The process resulted in highly stretchable optical fibers, which can reach strain limits as high as 800% and the highest reported sensitivities for FBG sensors [5]. Moreover, this fiber has a numerical aperture of 0.47, refractive index of 1.54 for the core and 1 mm diameter with optical losses of 4.2 dB/m at 650 nm.

Material characterizations were performed prior to the pressure sensor application. The mechanical characterization was performed by means of tensile tests in different POF samples. In addition, the coefficient of thermal expansion (CTE) was measured by evaluating the linear displacement as a function of the temperature on the fiber subjected to a constant stress. In this analysis, a CTE of 1.8×10^{-5} K^{-1} was obtained, which is lower than the one of PMMA (7.3×10^{-5} K^{-1}).

For the pressure sensing using the proposed LPS-POF, the fiber is positioned in-between nitrile rubber diaphragms with 0.8 mm thickness with retainer rings to create the sensing cavity. A light source at 650 nm and a photodetector are used for the light transmission and acquisition, respectively. The sensor is characterized by applying forces ranging from 1 N to 4 N in the sensor with 30 mm diameter through calibrated weights (with 25 mm diameter) positioned on the top of the diaphragm, resulting in an applied pressure of 1.4 kPa to

4.6 kPa. Figure 1 presents the fiber fabrication process and the experimental setup for the sensor characterization.

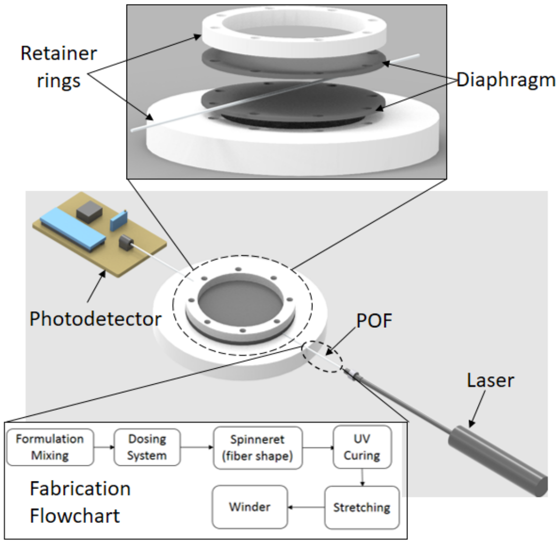


Figure 1. Experimental setup, sensor assembly and POF fabrication flowchart.

3. Results and Discussions

The stress-strain curve presented in Figure 2 shows a large linear range for the fiber with strain range as high as 17% with high repeatability in 4 tests performed. The Young's modulus was estimated following the ISO 527-1:2012 Standard for tensile properties in polymers, which resulted in a Young's modulus of 18.11 MPa, which is orders of magnitude lower than the one of commercial polymethyl methacrylate (PMMA)-POFs (about 4 GPa).

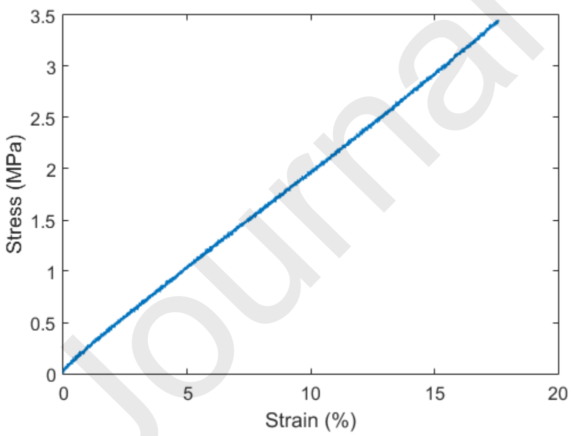


Figure 2. Stress-strain curve of LPS-POF.

Intensity variation sensors are based on two principles: macrobendings in the fiber caused by the transverse force or pressure and the refractive index variation due to the stress-optic effect as modelled in [6]. For both effects, the fiber Young's modulus plays an important role in the sensor responsivity, where a lower Young's modulus leads to a higher sensitivity for the pressure sensor. In order to characterize this influence, pressure tests were performed in the LPS-POF fabricated and a commercially available PMMA-POF with the same diameter (1 mm). The results for 4 pressure application tests are presented in Figure 3, where it was necessary to apply higher pressures in the PMMA-POF sensor in order to obtain a significant optical power variation. Furthermore, Figure 3 inset shows the optical power variation as a function of the time for LPS-POF.

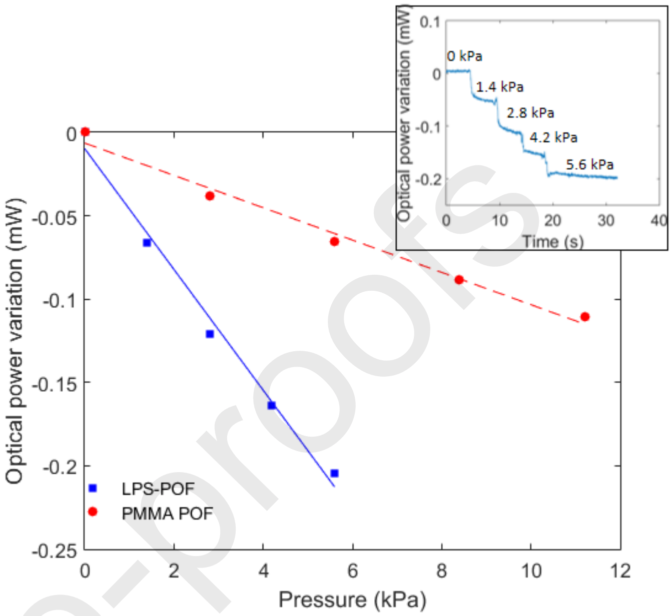
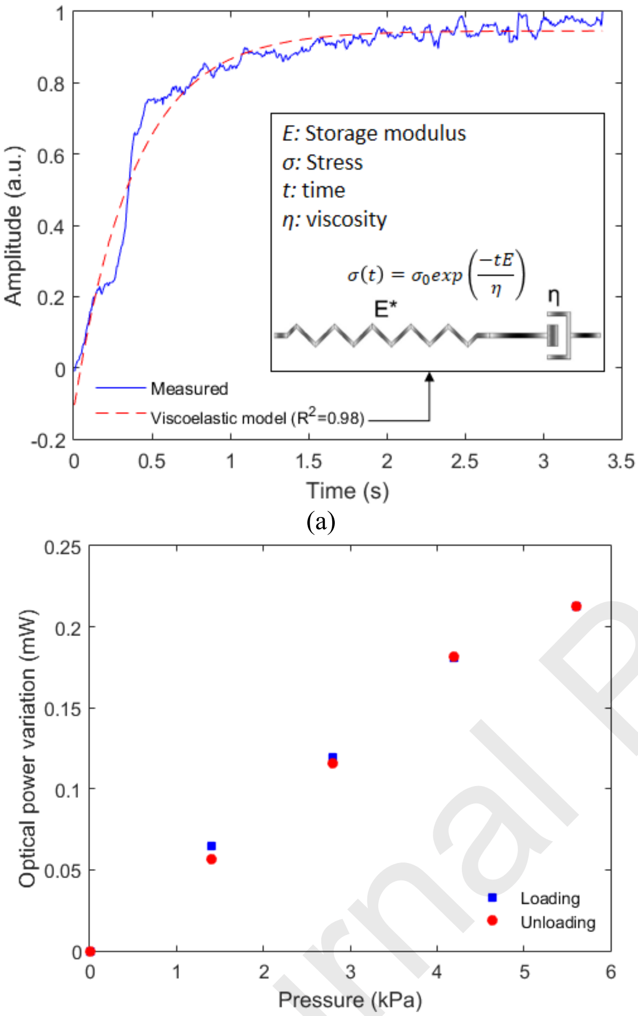


Figure 3. Optical power variation with respect to the pressure applied on the diaphragm for PMMA and LPS-POF. Figure inset shows the time response of the LPS-POF.

The response of the proposed LPS-POF presented higher sensitivity when compared with the commercial PMMA-POF. The sensitivity of the LPS-POF is −143.21 ADC/kPa, which is one order higher than the one of the PMMA-POF (−38.70 ADC/kPa) with a signal-to-noise (SNR) ratio of 40.34 dB for the LPS-POF. Considering an analog-to-digital converter of 16 bits and the measured SNR, the resolution of the LPS-POF for pressure sensing can be as low as 0.13 kPa. Comparing with previous works [5], FBG inscribed in the LPS-POF results in a sensitivity of −2.8 nm/MPa, where this sensitivity leads to a resolution lower than 0.35 kPa, if an optical analyzer with 1 pm accuracy is considered, which is a resolution lower than the one obtained from the proposed system (0.13 kPa). However, it should be mentioned that, in this case, a diaphragm was used as pressure transducer and the sensor response depends on its material and geometrical properties. Nevertheless, a higher resolution was obtained by a system with lower cost when compared with the materials and components needed for the FBG sensor system.

As the proposed sensor is also intended for dynamic applications, the dynamic response of the system is presented in Figure 4(a), where a step pressure input of 1.4 kPa was applied to the fiber. In this case, it is possible to estimate and model the viscoelastic response of the material using differential models, which are obtained from combinations of springs (elastic component of the response) and dashpots (viscous component) [7]. The schematic representation of the springs and dashpots combination that resulted in the best correlation as well as the equation for the material responses are also presented in Figure 4(a). The comparison between the sensor measured response and estimated model is also presented and resulted in a high correlation between the theoretical and experimental approaches with a determination coefficient (R^2) of 0.98 between them.

The sensor hysteresis is estimated from sequential loading and unloading cycles in the sensor, as depicted in Figure 4(b). The results indicated a hysteresis of about 3.5%, which can lead to a maximum error of 0.21 kPa in the pressure estimation.



(a)

(b)

Figure 4. Sensor response (a) step input and (b) loading and unloading cycles.

4. Conclusions

This paper presented the development of a low-cost pressure sensor with high resolution using a POF fabricated from the LPS process. The fiber presented a high linearity on the stress-strain curves with exceptionally low Young's modulus (18.11 MPa). The pressure response of the LPS-POF was compared with the one obtained from commercial PMMA-POFs, where the proposed system showed a fivefold sensitivity increase. The resolution was evaluated with respect to the one achieved with FBGs inscribed in the LPS-POF and, the low-cost system proposed in this work showed a higher resolution. Moreover, the dynamic modeling and hysteresis estimations were performed, which show the possibility of reducing the hysteresis by analyzing the fiber's viscoelastic response. Therefore, the proposed sensor system is reliable, low cost and with high resolution, which can be used for many applications from the oil and gas industry to biomedical applications.

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Declaration of interest

The authors whose names are listed immediately below certify that they have no affiiations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

Conflict of interest statement

This manuscript has not been published and is not under consideration by another journal. We have read and understood your journal's policies, and we believe that neither the manuscript nor the study violates the journal policies. Furthermore, there are no financial (and non-financial) conflicts of interest to declare.

Credit Author Statement

Arnaldo Leal-Junior: Conceptualization; Methodology; Formal analysis; Writing - Original Draft; Writing - Review & Editing; Supervision.
Vinicius Campos: Methodology; Formal analysis; Investigation.
Anselmo Frizera: Writing - Review & Editing; Visualization; Project administration; Funding acquisition.
Carlos Marques: Methodology, Writing - Review & Editing; Visualization; Supervision; Project administration; Funding acquisition

Highlights

- Polymer optical fiber with exceptionally low Young's modulus and high strain limit.
- Thermal and mechanical characterizations for pressure sensors applications.
- Dynamic response and viscoelastic modeling of the fiber in sensors applications.
- Five times higher sensitivity when compared with systems employing commercial fibers.