Hydrostatic pressure sensing with surface-core fibers

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ABSTRACT

In this paper, we report the employment of surface-core fibers for hydrostatic pressure sensing. To our knowledge, this is the first demonstration of the use of these fibers for the referenced purpose. Theoretical simulations of the fiber structure were performed in order to estimate fiber phase and group birefringence values and its pressure sensitivity coefficient. In order to test fiber performance when acting as a pressure sensor, the same was placed in an polarimetric setup and its spectral response was measured. A sensitivity of 4.8 nm/MPa was achieved, showing good resemblance to the expected sensitivity value (4.6 nm/MPa).

Keywords: pressure sensor, surface-core fiber, birefringence

1. INTRODUCTION

The development of pressure sensors based on optical fibers is very important due to the numerous advantages provided by this sort of setups. Among them, one can identify their intrinsic electromagnetic immunity, robustness, tunable sensitivity and dynamic range and the possibility of being set in a compact size. Optical fiber pressure sensors are, thus, very useful for acting in harsh environments such as underwater petroleum exploration sites.[1]

Specially designed birefringent optical fibers, such as the photonic crystal ones, are often used for this purpose[1, 2, 3, 4]. Usually, they are set in polarimetric configurations which allow the orthogonal modes that travel along them to interfere. The spectral response of these configurations is characterized by the existence of interferometric fringes whose spectral position shifts according to the pressure conditions to which the fiber is subjected (as a manifestation of the photo-elastic effect). To characterize the relation between this wavelength shift and the applied pressure, one defines a sensitivity coefficient C_S, as expressed in Eq. 1.[3]

$$\frac{\Delta\lambda}{\Delta P} \equiv C_S \approx \frac{\lambda}{G}\frac{\partial B}{\partial P} \tag{1}$$

In Eq. 1, $\Delta\lambda$ is the spectral wavelength shift of an interferometric fringe caused by the application of an external hydrostatic pressure variation ΔP. Besides, λ is the central wavelength of the considered fringe. G and $\partial B/\partial P$ are respectively the fiber group modal birefringence and the phase birefringence derivative with respect to pressure.

In this paper, we report, to our knowledge, the first demonstration of a hydrostatic pressure sensor based on a surface-core optical fiber[5]. The main advantage of using surface-core optical fibers instead of employing photonic crystal fibers in pressure sensing measurements is the ease of fabrication. Preparation of photonic crystal fibers can be very demanding and time consuming. The fabrication method of surface-core fibers is, in turn, very simple since it is based on the merging of a germanium doped silica rod to a silica tube followed by a standard fiber drawing process[5]. The off-center core, on the other hand, can not be trivially spliced to standard single mode fibers – an issue to be addressed in future if all-fiber setups are desired.

In the next sections, the performance of the proposed sensor is analyzed. To do this, a theoretical study of fiber characteristics is firstly provided and then compared to the experimentally measured data.

2. STUDY OF FIBER PRESSURE SENSITIVITY

In order to study the surface-core fiber pressure sensitivity, whose measure is given by the C_S coefficient (Eq. 1), one needs to obtain information about fiber phase and group birefringence. To attain this goal, one proceeded with the performance of numerical simulations by using a commercial finite element-based software. Figure 1a presents the simulated idealized fiber structure. The core region (darker area) was assumed to have an elliptically symmetric graded

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refractive index profile. Pure and doped silica optical and mechanical properties were simulated using a model developed in Cerqueira S. Jr. *et. al.*[6]

Simulation results provided us with the effective refractive index of the fundamental core modes in the orthogonal polarization states – one emphasize that although the fiber supports a few high order modes in the visible wavelength range, our analysis was centered to the fundamental core mode. The knowledge of the orthogonal modes effective refractive index allowed obtaining Figure 1b plot, which exposes the fiber phase birefringence dependency on wavelength. Here, it is seen that the fiber phase birefringence has the order of 10^{-4}.

The observed phase birefringence behavior versus wavelength is found to be linear. Thus, it is possible to estimate the phase birefringence derivative with respect to the wavelength, $\partial B/\partial \lambda$, as the angular coefficient of a line fitted to the simulated points. This derivative is then calculated to be 7.5 x 10^{-8} nm^{-1}. Furthermore, the fiber group birefringence, G, which is given by $G = B - \lambda\, \partial B/\partial \lambda$, could be obtained as 1.43 x 10^{-4} in the studied wavelength range showed in Figure 1b.

In order to account for C_S, it is also necessary to study the birefringence dependence on pressure variations. Thereby, one performed simulations of the fiber effective refractive indexes for different pressurization conditions (at 815 nm wavelength). Results are presented in Figure 1c where it is seen an increase in fiber phase birefringence as the pressure applied on the fiber is incremented. It happens due to the fact that the fiber core structure is asymmetrically exposed to the external environment (one of its axis suffers direct influence of the applied pressure and the other axis is partially shielded by the fiber structure). Thus, the modes on orthogonal polarizations that travel along the fiber core experiences different effective refractive index changes if the pressurization conditions are varied. For low pressures range, up to 10 MPa, one obtains 8.0 x 10^{-7} MPa^{-1} for the birefringence derivative with respect to pressure $\partial B/\partial P$. For higher pressures range, from 10 MPa to 25 MPa, we calculated 3.1 x 10^{-6} MPa^{-1} for $\partial B/\partial P$.

From the obtained values for group birefringence and for the derivative of the phase birefringence with respect to pressure, it is possible to calculate an expected value for C_S around the wavelength of 815 nm for low pressures values: 4.6 nm/MPa. In the subsequent sections an experimental measure for C_S will be presented for comparison to the expected one.

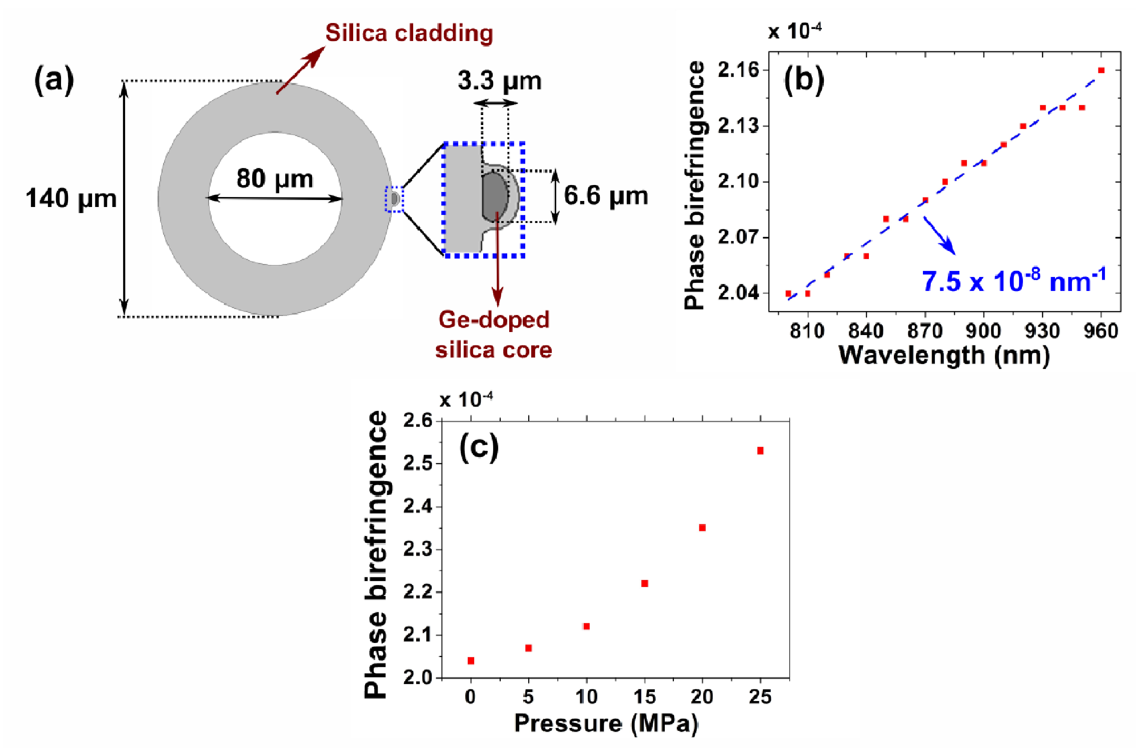

Figure 1. (a) Fiber structure used in simulations with doped core region in dark grey with dimensions 3.3 µm x 6.6 µm. (b) Numerical phase birefringence versus wavelength plot. (c) Numerical phase birefringence versus applied pressure plot.

3. PRESSURE VARIATIONS MONITORING

For performing hydrostatic pressure variations probing measurements, an experimental setup as depicted in Figure 2a was used. Broadband light from a supercontinuum (SC) is used as the light source and an optical spectrum analyzer (OSA) is employed as the detection system. The surface-core fiber is placed in a pressure chamber connected to a pressure pump so it can be subjected to different pressure conditions. Two polarizers (P_1 and P_2) are also used in the experimental configuration: the first one provides the excitation of modes on the two orthogonal polarizations and the second one allows these modes to interfere.

Surface-core fibers tested herein were fabricated at UNICAMP and the details can be found elsehere[5]. Figure 2b shows the cross section of the referenced fiber and Figure 2c presents a zoom of the core area. Brighter regions in Figure 2b and c identifies the fiber core.

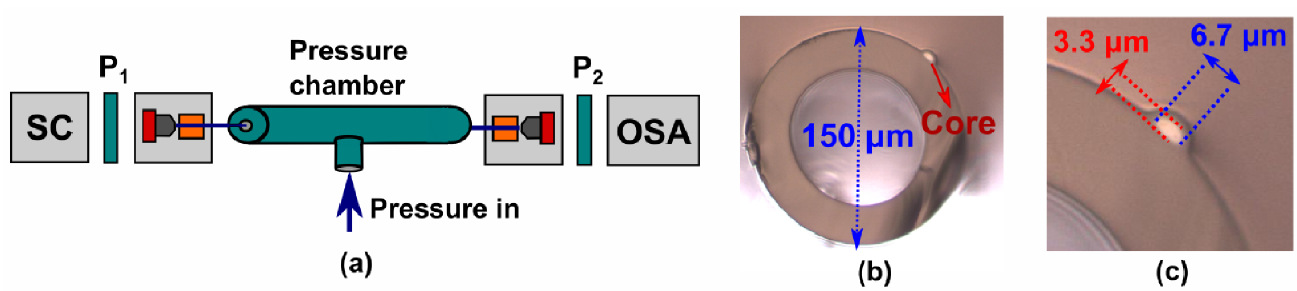

Figure 2. (a) Experimental setup. SC: supercontinuum; P_1 and P_2: polarizers; OSA: optical spectrum analyzer. (b) Surface-core fiber cross section. (c) Core region zoom.

As the orthogonal modes that travel along the fiber are associated to different effective refractive indexes, the transmission spectrum measured in the experimental setup of Figure 2a is characterized by the existence of interferometric fringes. The spectral position of the interferometric fringes is dependent on the pressure conditions to which the fiber is subjected. Therefore, when one alters the applied pressure value on the fiber, the fringes are expected to experience a spectral shift.

Figure 3a shows the transmission spectra measured in Figure 2a setup for different pressurization conditions from 0 to 0.4 MPa. One can observe that as the pressure applied on the fiber is increased, the interferometric fringes blueshift. Figure 3b presents the fringes wavelength shift versus applied pressure plot. By fitting this plot data, one can calculate the fiber sensitivity to pressure variations. A sensitivity of 4.8 nm/MPa was found.

The attained pressure sensitivity value is slightly higher than the one found for PM-1550-01 fiber (3.42 nm/MPa, measured around 1550 nm)[2], which is a commercial fiber fabricated by NKT Photonics and usually employed in pressure sensing experiments. The highest pressure sensitivity value remains being, to our knowledge, the one reported by Anuszkienwicz *et. al.* when studying rocking-filters induced on microstructured-fibers (177 nm/MPa)[4].

Figure 3a data also allows obtaining an experimental measure for fiber group birefringence. For calculating it, one uses $G \approx \lambda^2/(S \, . \, L)$, where λ is a central wavelength between two consecutives maxima (or minima) in the transmission spectrum, S is the spectral distance between the considered maxima (or minima) and L is the fiber length. At 815 nm, one obtained 2.63 x 10^{-4} for group birefringence. The measured value is higher than the one predicted by simulations (1.43 x 10^{-4}). We believe that simulated and measured values are different because the fiber structure used in simulations was idealized.

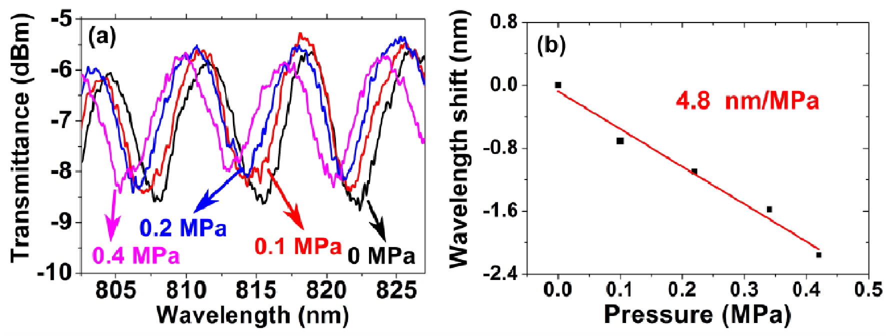

Figure 3. (a) Transmission spectrum measured for different pressurization conditions. (b) Wavelength shift versus applied pressure plot.

CONCLUSIONS

In this paper, a hydrostatic pressure sensor based on surface-core optical fibers was presented. To our knowledge, this is the first time that this kind of fibers is studied under this approach.

Firstly, fiber sensitivity to pressure variations, which is mediated by the photo-elastic effect, was theoretically characterized by simulating the fiber properties using a commercial finite-element-based software. Fiber phase and group birefringence was estimated and then the expected value for sensitivity coefficient C_S was calculated – 4.6 nm/MPa.

A polarimetric setup was employed for testing the surface-core fiber sensitivity to pressure variations. The spectral response of the setup was analyzed for different pressurization conditions and the spectral shift of the interferometric fringes was accounted. We obtained 4.8 nm/MPa for the surface-core fiber pressure sensitivity. One can observe that a good resemblance between experimental and simulated values was attained.

As future steps in this study, we plan adjusting fiber characteristics in order to optimize its response to pressure variations. Other configurations, as rocking filters induced on the fiber reported herein, are also to be tested.

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