Temperature and Strain Characterization of Bragg Gratings Impressed with Femtosecond Laser Radiation in Suspended-Silica-Core Fibers

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ABSTRACT

Fiber Bragg Gratings (FBG) are widely used in various fields, including optical fiber sensors. In this work, the temperature and strain response of C-band FBG in pure silica four-leaf clover shaped suspended-core fibers was analyzed. These FBGs were fabricated by femtosecond laser exposure, which enabled the refractive index modulation of the pure-silica-core of the fibers. We compared the Bragg wavelength variation with strain and temperature for two different suspended-core fibers (256b2 and 256b5). The 256b2 fiber has a core diameter of 4,9 μm and a hollow hole inside the core with 1,4 μm; the 256b5 fiber has a solid silica core with a 7,2 μm diameter. For strain and temperature characterization, the sensing head was attached to a translation stage with a resolution of 1 μm and was placed in a tubular oven, which permits a temperature reading to be set with an error smaller than 0,1 ºC. Both have shown the same sensitivity to strain (1,2 pm/με) but different sensitivity to temperature variation (8,4 pm/ºC and 10 pm/ºC respectively). The relative difference between the thermal coefficients of the two selected Bragg signatures is 16%. The results obtained indicate that these gratings can be used in optical fiber sensing, for example in the context of the important problem of simultaneous strain and temperature measurement.

Keywords: Fiber Bragg gratings, optical fiber, two-beam interferometry, femtosecond laser writing, temperature and strain sensor

1. INTRODUCTION

The silica suspended-core fiber is a micro-structured fiber consisting of a silica core surrounded by a hollow cladding, where the core is suspended through 3 or 4 silica bridges (Figure 1).

The silica suspended core fiber has been used for gas sensing through evanescent field interaction (Webb *et al.* [1],Afshar *et al.* [2]). Based on the same optical phenomenon, refractometric applications have also been considered, as is illustrated in a recent work by Huy *et al.* [3] where a fiber Bragg grating photowritten in a suspended germanium doped silica core was used to measure the refractive index of liquids. Fiber Bragg grating fabrication had already been demonstrated with germanium doped fibers. It has been also demonstrated that refraction index modulation is possible in fused silica glass with femtosecond laser pulses (Bellouard *et al.* [4]).

In this work, the sensing properties of suspended-core fibers using photoimprinted fiber Bragg gratings into is further explored. FBGs in suspended-core fibers for refractive index measurement have been recently reported[3]. The suspended-core was doped with germanium, and problems related with the fast desorption rate of the hydrogen photosensitizing of the fiber core were reported (after 15 min outside the hydrogen chamber, it was no longer possible to write the FBGs). It was reported that for a Bragg wavelength reading accuracy of 1 pm, the refractive index measurement resolution was $\approx 3\times10^{-5}$ for liquids with refractive index at around 1,33 inside the holes.

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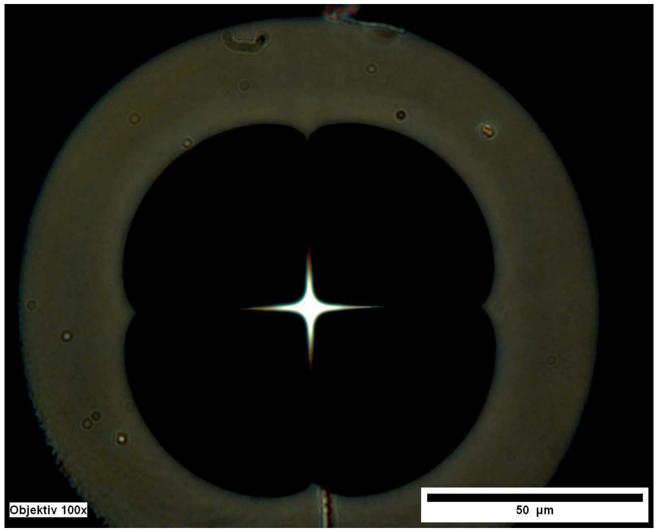


Fig. 1. Suspended core fiber cross section

Using a femtosecond laser to write FBGs avoids the requirement of a germanium doped suspended core and its associated problems. In a second phase, the sensing properties of these devices is studied, considering different interrogation techniques and addressing the measurement of refractive index, pressure, strain and temperature. The target fibers used in the experiments are pure silica steering wheel fibers from the Institute of Photonic Technology. For standard inscription technologies one has to cork the endfaces of the fibers. Presumably the sealed endfaces will prevent reliable Bragg grating measurements during inscription due to coupling losses. Consequently the application of the conventional standard inscription technology to suspended-core fibers is supposed to involve large technological problems. One promising solution of this problem is the fiber Bragg grating inscription with two-beam interferometry inscription with a DUV-femtosecond laser source.

It has been shown that the two-beam inscription technology of fiber Bragg gratings is compatible with DUV-femtosecond laser sources [5] and can be applied to pure silica microstructured fibers [6].

Also, the temperature sensitivity of the pure silica fiber is small when compared to that of the germanium doped one. Therefore, this characteristic can be used to obtain a sensor which is substantially insensitive to temperature, while it is expected to have a substantial sensitivity to pressure. Optimization issues can be considered to obtain a versatile sensing head for temperature independent pressure measurement.

2. EXPERIMENTAL SETUP

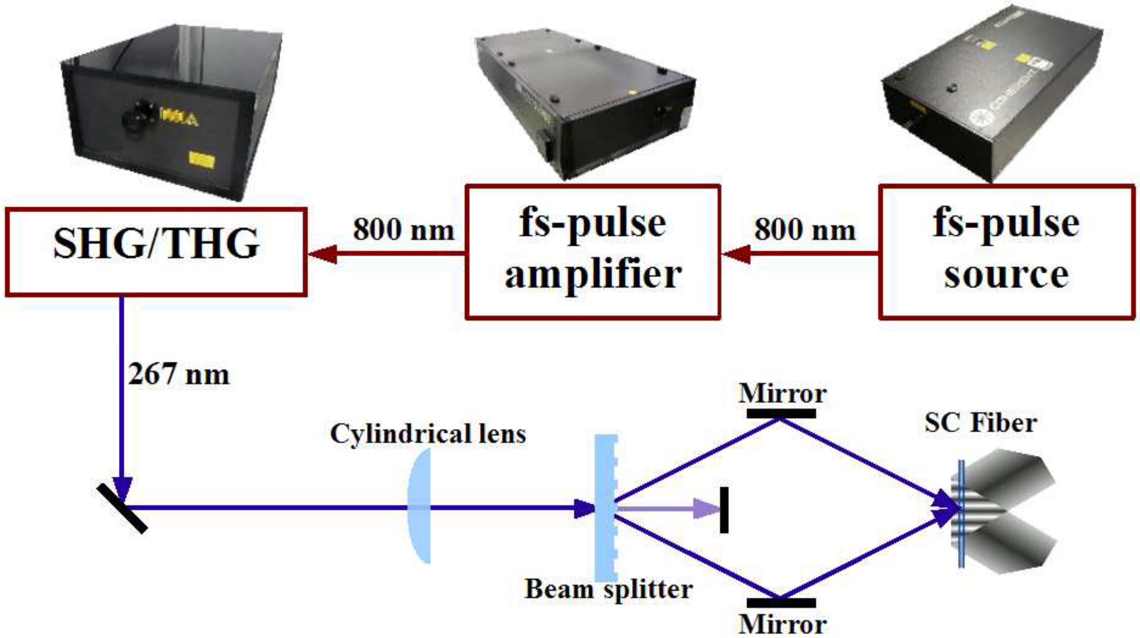


Fig. 2. DUV femtosecond laser inscription setup situated at the IPHT-Jena for non-photosensitive fibers

2.1 Femtosecond FBG inscription system

The fabrication setup represented in Figure 2 is composed of an infrared oscillator femtosecond pulse source (Coherent Mantis) and regenerative Ti:Sapphire amplifier with integrated pump laser (Coherent Legend Elite) generating 130 fs pulses at 800 nm with 3,6 W at 1 kHz pulse repetition rate. The pulses are passed through a third harmonic generation unit (Coherent) which produces ≈ 350 fs pulses with 650 mW at a wavelength of 267 nm. The pulses are then used in a Talbot interferometer, meaning they are focused through a 335 mm focal length cylindrical lens, split with a phase mask, optimized for 267,2 nm wavelength, with a grating period of 1065,3 nm. The direct transmitted light is absorbed by a stop plate and the two first diffraction orders are reflected by two computer controlled rotation mirrors and interfered in the focal plane of the cylindrical lens were the fiber is positioned producing a power density of ≈ 47 GW/cm^2.

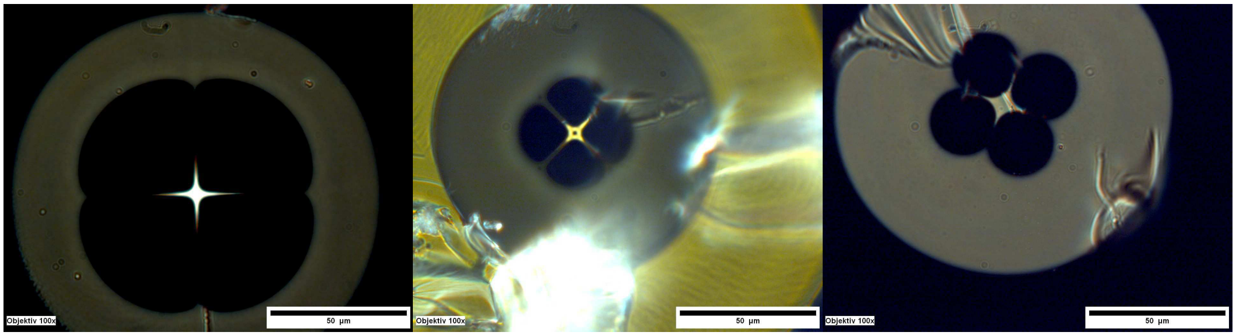
2.2 Suspended core fibers

The fibers shown on Figure 3 were manufactured at the Institute of Photonic Technology (IPHT).

The fiber IPHT-256b1, Figure 3a, has a core diameter of 5,0 µm, hollow holes surrounding the core with a diameter of 92 µm, 135 µm cladding diameter and 1,5 µm bridge width.

The fiber IPHT-256b2, Figure 3b, has a core diameter of 4,9 µm with a small hollow hole inside the core with 1,4 µm diameter, hollow holes surrounding the core with a diameter of 41 µm, 106 µm cladding diameter and 1,0 µm bridge width.

The fiber IPHT-256b5, Figure 3c, has a core diameter of 7,2 µm, hollow holes surrounding the core with a diameter of 57 µm, 123 µm cladding diameter and 0,9 µm bridge width.



(a) IPHT-256b1 SC Fiber; (b) IPHT-256b2 SC Fiber; (c) IPHT-256b5 SC Fiber

Fig. 3. Suspender core fibers (Scale: 50 μm)

The fibers in Figure 3 are exposed to the femtosecond DUV radiation for approximately 30 min. The growth of the Bragg grating resonance is observed in real time and the experiments end when further exposure does not produce an increase in the reflection spectrum.

The fiber Bragg gratings produced are then characterized in terms of temperature and strain. For the strain characterization, the fiber is carefully attached to a translation stage with 1 μm resolution. The staged is moved to pull the fiber and apply tension to the grating region. For the temperature characterization, the fiber is placed in a tubular oven, which permits a temperature reading to be set with an error smaller than 0,1 ºC.

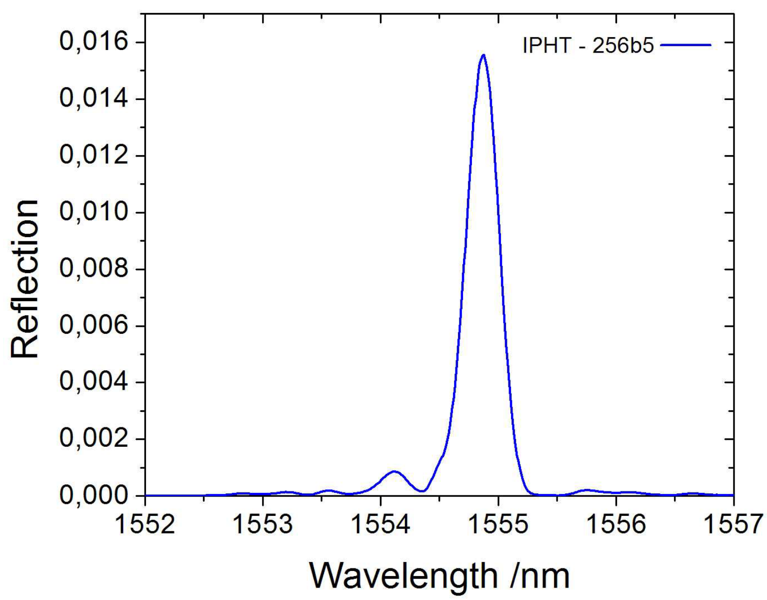


Fig. 4. FBG in suspended core fiber 256b5 written with 1 kHz laser pulse repetition rate

3. RESULTS

3.1 Fiber Bragg Gratings Fabrication

In order to measure the grating growth in real time it is necessary to obtain a good splice between the suspended core fiber and a normal telecommunications fiber. It is then possible to lunch light from a broadband source connected through the telecommunication fiber and observed in reflection on an Optical Spectrum Analyzer (OSA) the grating being formed when the suspended core fiber is exposed to the femtosecond laser pulses. Supposed the splice is optimized for low coupling losses and parasitic back reflection, because many of the gratings produced were very weak and the noise introduced by that reflection would make them impossible to be observed in the OSA.

Different laser pulse repetition rates were used from 333 Hz to 1 kHz, and it was observed that the lower the repetition rate, the slower the growth of the grating and the lower the maximum achievable reflection. The angle on the controlled rotation mirrors was also changed to obtain different Bragg resonance wavelengths. The following graphics use the reflection produced by the telecom fiber at the fiber to air interface as a reference to normalize the reflection. The losses introduced by the splice between the fibers are not taken into account in the results. Those losses are approximately -3 dB.

Figure 4 shows the spectrum of one of the first FBG obtained in this project. A laser repetition rate of 1 kHz was used with a IPHT - 256b5 suspended core fiber. From the fibers tested this one has the largest core diameter which made the splice coupling with normal telecom fibers easier and thus this was the first fiber to be tested.

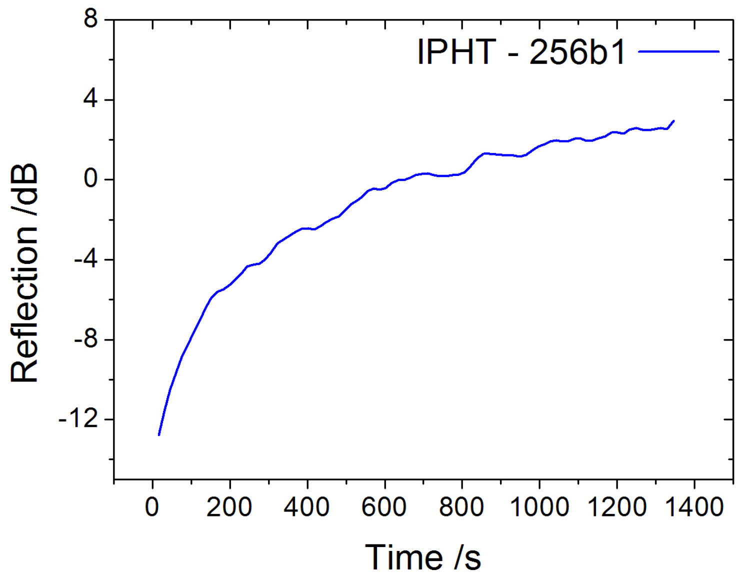


Fig. 5. FBG reflection as a function of the exposure time for the 256b1 fiber

Figure 5 shows the Bragg grating reflection increasing with exposure time. After approximately 25 min no further increase in the grating reflection was observed.

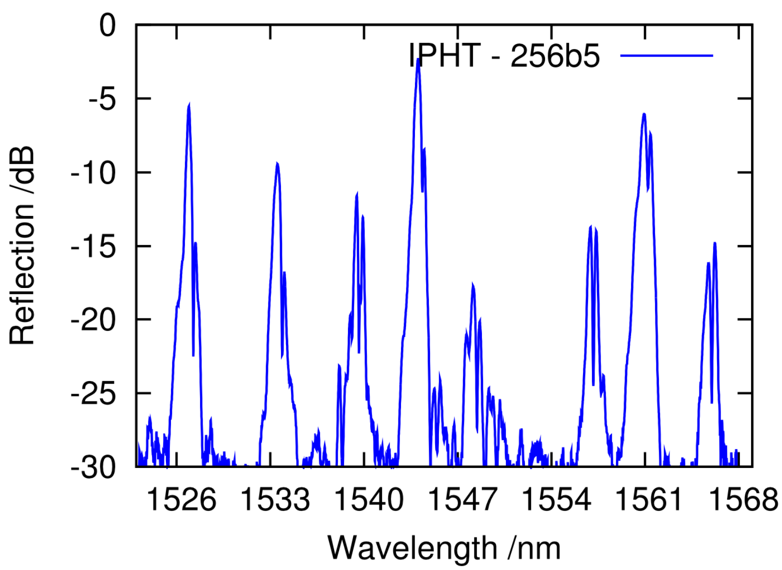


Fig. 6. FBG Array in suspended core fiber 256b5 written with 333 kHz laser pulse repetition rate

An array of fiber Bragg gratings with different wavelengths written in different positions along the suspended core fiber is shown in Figure 6.

Also the Bragg grating resonance increased in wavelength along the exposure time, and decreased suddenly right after the termination of the exposure (Figure 7). The wavelength difference suggests a temperature in the exposure regions between 20 ºC and 120 ºC, depending on the repetition rate, the temperature was higher for higher laser pulse repetition rates.

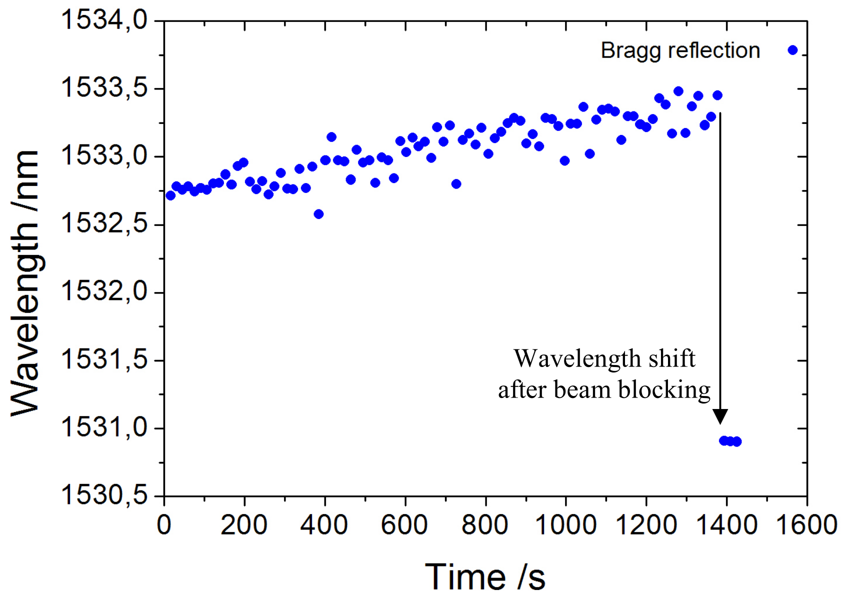


Fig. 7. Bragg reflection wavelength peak variation with the femtosecond exposure time

3.2 Temperature and Strain Characterization

The FBG resonance of the 256b2 and the 256b5 suspended core fibers were measured with temperature and strain variation and the results are shown in Figures 8 and 9.

The strain measurements in Figure 8 show that both fibers have the same sensitivity to strain, 1,2 pm/με, however, the sensitivity to temperature variation, Figure 9, is different for both fibers, 8,4 pm/ºC for the 256b2 fiber and 10 pm/ºC for the 256b5 fiber. The relative difference between the thermal coefficients of the two selected Bragg resonances is 16%. This difference is expected due to the presence of the hollow air hole inside the core of the 256b2 fiber.

Results for these suspended core fibers sensitivity to strain have also been demonstrated with birefringence measurements in a Sagnac interferometer by Frazão *et al.* [7].

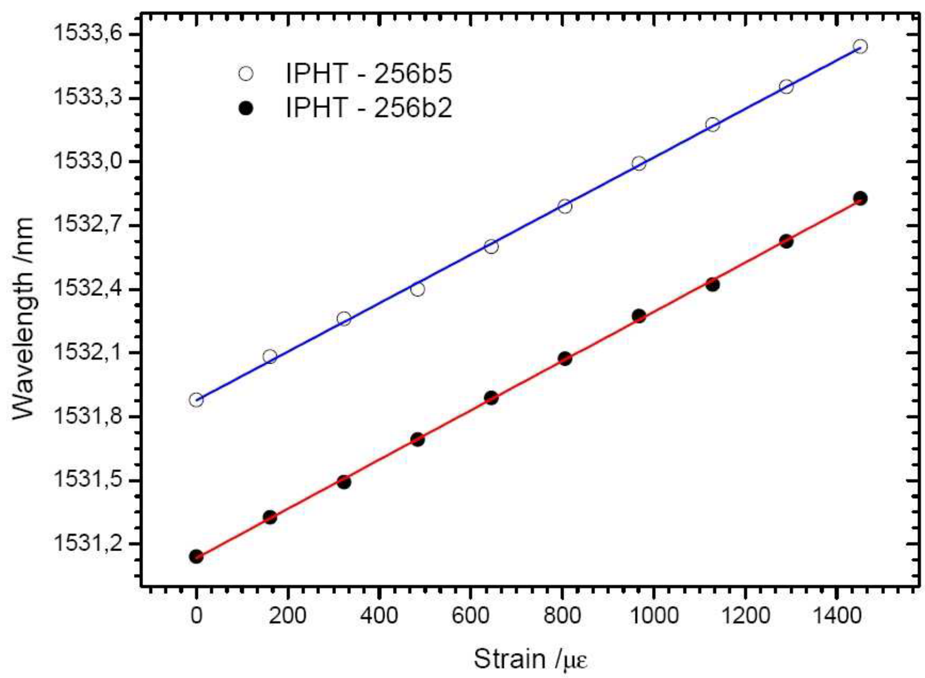


Fig. 8. Comparison between strain responses for FBGs in 256b2 and 256b5 fibers

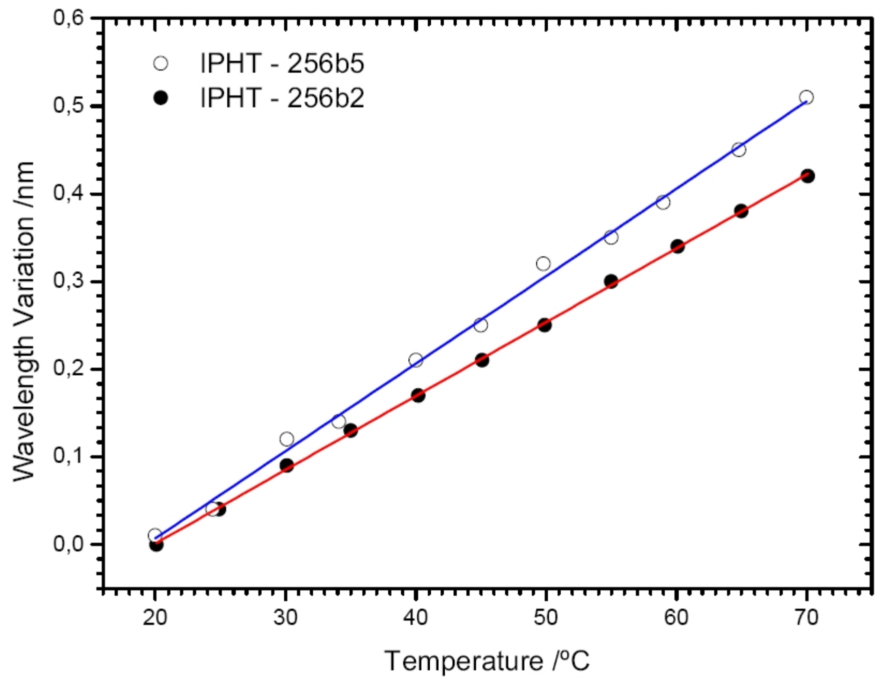


Fig. 9. Comparison between temperature responses for FBGs in 256b2 and 256b5 fibers

4. CONCLUSIONS

The fabrication of fiber Bragg gratings in pure silica suspended-core fibers was successfully demonstrated and it was possible to control the device wavelength in the C-band telecom window.

The FBG final reflection depended strongly on the laser repetition rate; higher repetition rates produced stronger gratings but also produced wider gratings bandwidths. Both fibers showed a strain sensitivity of 1,2 pm/με and temperature sensitivity of 8,4 pm/ºC and 10 pm/ºC for the IPHT-256b2 and IPHT-256b5 SC fibers respectively.

The lower sensitivity of the FBG in the IPHT-256b2 SC fiber to temperature variations is due to the air hole inside the core of the fiber. The thermo-optic effect of air is very different than the thermo-optic effect of pure silica and in fact the index of refraction of silica increases with temperatures while the index of air decreases. The results obtained for the strain and temperature characterization indicate that these gratings can be used in optical fiber sensing, for example in the context of the important problem of simultaneous strain and temperature measurement. Specially with the IPHT-256b2 SC fiber, further reduction of the sensitivity may be achieved, enabling FBG sensors better suited for measurements where temperature variation may be a problem. It also suggests the possibility of using the air hole inside IPHT-256b2 SC fiber for pressure or gas concentration measurements. Microfluidic systems can also be implemented in these fibers taking advantage of the hollow cladding for evanescent wave measurements of the fluids.

5. ACKNOWLEDGMENTS

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