Reflection-Based Phase-Shifted Long-Period Fiber Grating for Cryogenic Temperature Measurements

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ABSTRACT

In this work, we propose a compact sensor head to perform cryogenic temperature measurements based on a long-period fiber grating. The presented configuration enables the sensor to be interrogated in reflection since a phase-shifted is produced by Fresnel reflection on the end-face of the fiber, cleaved at a quarter-period separation distance from the end of the grating.

Keywords: Long-period fiber grating, optical fiber sensor, cryogenic temperatures.

1. INTRODUCTION

Systems operating at cryogenic temperatures are becoming increasingly important in the energy sector, transportation, and medicine technology. For instance, cryogenic fuels such as liquid hydrogen, oxygen and liquefied natural gas are often considered as major energy alternatives to fossil fuels. To ensure the safe storage, transfer and dispensing of liquefied fuels, highly sensitive and reliable sensor networks are required to provide continuous monitoring of multiple parameters at multiple locations for on-demand, real-time fuel management in cryogenic environments. On the other hand, materials applied in cryogenic systems change their properties and often become very brittle [1, 2]. Therefore, monitoring the systems structural integrity and temperature are essential tasks. Moreover, there are applications where sensors immune to electromagnetic interference, being dielectric and low size are required as in the case of the ITER Project [3].

Optical fiber sensors and, namely, those based on fiber Bragg gratings (FBG), due to their intrinsic properties, have already proved their excellence in structural health monitoring at room temperatures [4]. FBGs have a sub-micron period and act to couple light from the fundamental forward-propagating mode of the optical fiber to a backward, counter-propagating mode. This coupling occurs at a specific wavelength that satisfies the Bragg resonance condition and depends on the grating period and other parameters like temperature and strain. However, as far as temperature measurements are concerned FBGs are essentially insensitive below 100 K. Therefore, several techniques have been applied in order to enhance their thermal sensitivity, such as, by deposition of metal or sol-gel coatings on the fiber cladding or by embedding or bonding them to substrates with very different thermal expansion coefficients [5, 2]. When compared to conventional FBGs, the fabrication of the modified ones is time consuming and the temperature sensitivity improvement is limited.

A long-period fiber grating (LPFG) is a periodic structure, with periods typically in the range of 100 μm to 1mm, inscribed in a fiber, which couples light between the core mode and co-propagating cladding modes at specific resonance wavelengths. The grating transmission spectrum contains a series of attenuation bands centered at these discrete resonance wavelengths, each attenuation band corresponding to coupling of a different cladding mode. The grating behaves as a selective filter, where the resonance wavelengths depend on the period of the LPFG and also on physical parameters, such as temperature, strain, external refractive index and bending radius. LPFGs can, therefore, be used as sensors of these parameters. The thermal behavior of LPFGs from room temperature up to 1200 ºC is well documented and it is known that their temperature sensitivity is an order of magnitude higher than for FBGs [6, 7]. On the other hand, results on the thermal behavior of LPFGs at cryogenic temperatures are scarce, despite the very promising results obtained in 2003 by S. W. James *et al.* [8]. In their work, a LPFG inscribed in a B/Ge co-doped fiber was able to discriminate temperature differences down to 20 K and presented a temperature sensitivity of the order of 200 pm/K for temperatures above 77 K. These results are better than the ones obtained by FBGs even for modified FBGs (coated or embedded/bonded in structures). One

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possible explanation for this minute interest on LPFGs-based cryogenic temperature sensors is related to interrogation issues since these gratings work in transmission and, therefore, require access to both ends of the fiber which may be a drawback for some applications. In 2011 [9], we mitigate this problem by proposing a sensor that comprised a LPFG inscribed in the SMF28 fiber spliced to a short piece of Bendbright fiber, from Draka, that allowed small curvature radius. This way, we have implemented a sensor to monitor cryogenic temperatures by inserting the fiber containing the grating in a glass tube with an internal diameter of 4 mm. The temperature sensitivity obtained for temperatures above 77 K was similar to the values obtained at room temperature, i.e., ~60 pm/K.

Recently, J. Huang *et al.* [10] proposed the fabrication of a phase-shifted LPFG by deposition of a silver-mirror at the end-face of the fiber at a distance of the grating-end corresponding to a quarter of the period. This configuration enabled the LPFG to work in reflection.

In this work, we have implemented a compact sensor head based on a phase-shifted LPFG arc-induced in a standard fiber. The thermal behavior of this sensor, working in reflection, was investigated from 77 K up to room temperature and results show that its temperature sensitivity is higher than the ones obtained for FBGs, even for those especially prepared to have improved sensitivity.

2. EXPERIMENTAL RESULTS

The reflection-based phase-shifted LPFGs were fabricated in-house using the electric-arc technique [7]. First, several gratings with resonances in the third telecommunication window were fabricated with different attenuation. Afterwards the fibers were cleaved near the grating and placed inside a capillary to control the polishing process. From a series of experiments we concluded that an attenuation of ~7dB leads to a better spectrum which is in accordance to [11]. Therefore, we have chosen a LPFG inscribed in the SMF28 fiber with a grating period of 395 μm in order to produce a resonance wavelength at approximately 1527 nm , corresponding to the LP_{16} cladding mode, with -7 dB of attenuation (figure 1) corresponding to 60 electric discharges. For each set, the fiber was then cleaved near the LPFG and polished while monitoring the reflection spectrum. The end-face was polished until two resonant dips appeared and had almost equal attenuation strength (figure 2).

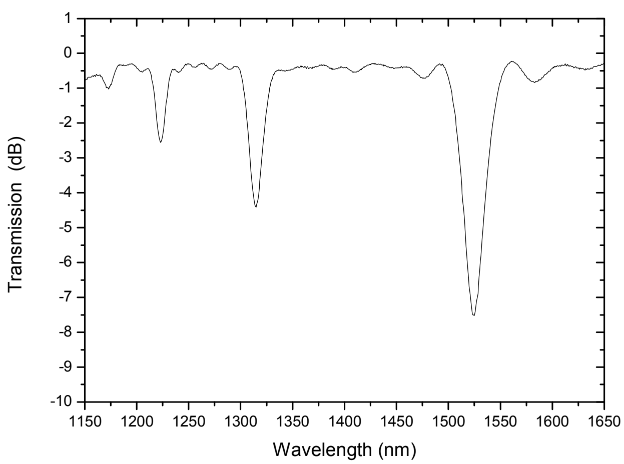

Figure 1. LPFG transmission spectrum.

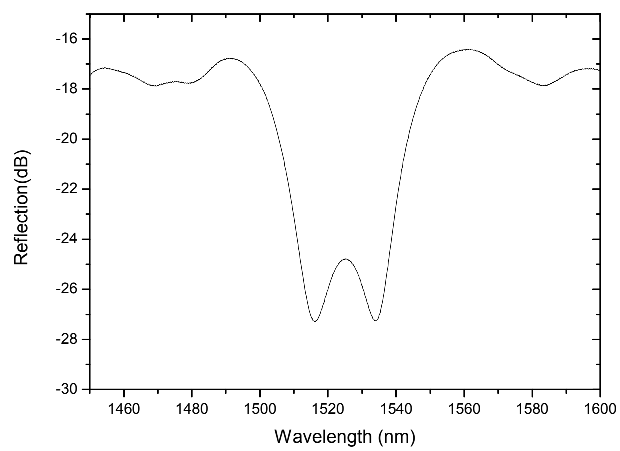

Figure 2. Reflection spectrum of the phase-shifted LPFG.

The objective of this work was to explore the reflection-based phase-shifted long-period fiber grating to monitoring cryogenic temperatures. The experimental set-up represented in figure 3 was used to perform this study.

A Broadband light source (BLS 1550A), centered at 1550 nm, was used to illuminate the reflection-based phase-shifted LPFGs and their spectra were monitored with an optical spectrum analyzer (OSA: Ando AQ6330). A circulator was used to make the connection between the Broadband source, the phase-shifted LPFGs and the OSA. The phase-shifted LPFGs and a FBG were inserted in a tube, sealed at both ends to prevent contact of the fibers with nitrogen. The protected fibers and a temperature probe PT100 (Fluke 5608) were inserted inside the holes of a copper block which was placed in a glass cuvette thermally isolated with Rockwool and Styrofoam. The FBG was used to compare the thermal behavior in the same conditions and its wavelength shift was monitored and recorded using a FS2200 Industrial Braggmeter Octo Channel 1S/s. The temperature was controlled with a Fluke 1502A Thermometer Readout and recorded with the same software.

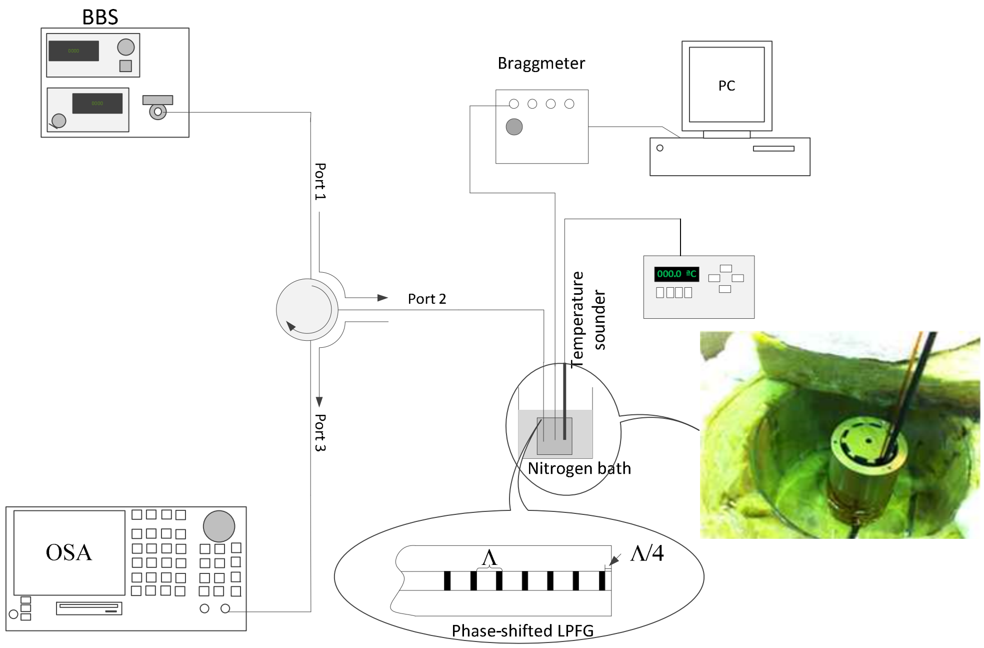

Figure 3. Scheme of the experimental setup.

Liquid nitrogen was poured into the glass cuvette surrounding the copper block and we wait until the whole system reached thermal equilibrium at the temperature of 77 K. Afterwards, the copper block was removed from the bath, and left at room temperature to heat-up. The spectra of the reflection-based phase-shifted LPFG and FBG were recorded between 77 K and 286 K, in steps of 5 K at the beginning, and then in steps of 10 K. Figure 4 shows the spectra of the phase-shifted LPFG for several temperatures. As can be seen the spectra move towards longer wavelengths with the temperature increase.

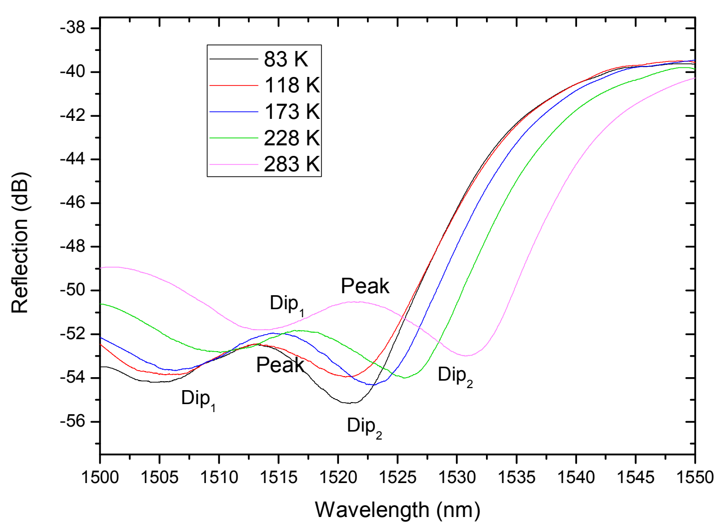

Figure 4. Reflection spectra of the phase-shifted LPFG at several temperatures.

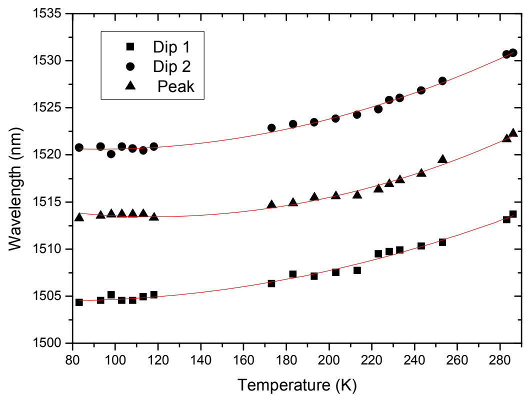

Figure 5. Wavelength of the two Dips and the Peak of the reflection-based phase-shifted LPFG as a function of temperature.

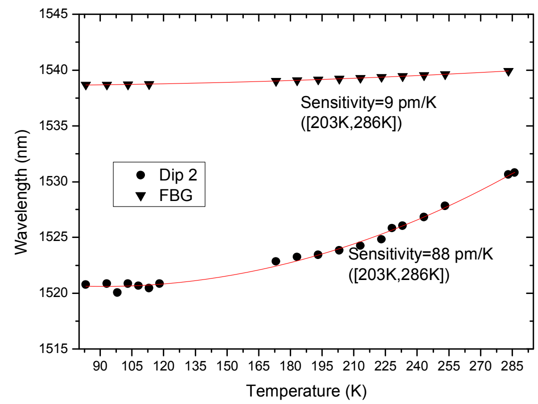

Figure 6. Wavelength of the second Dip of the reflection-based phase-shifted LPFG and of the FBG resonance as a function of temperature.

Figure 5 shows the temperature sensitivity of the phase-shifted LPFG for the two Dips and the Peak. It can be observed that the wavelength displacement is quadratic on temperature. The comparison between the thermal behavior of the second Dip and of the FBG is presented in figure 6. It is clearly shown that the temperature sensitivity is considerably higher for the phase-shifted LPFG reaching a mean value in the range 203-286 K of 88 pm/K (9 pm/K for the FBG grating) that corresponds to an improvement in the sensitivity by a factor of ~10. However, for the lower temperature range further experiments are required in order to confirm the apparent decrease of the temperature sensitivity.

3. CONCLUSIONS

We have studied the thermal behavior of a phase-shifted long period fiber grating, working in reflection, from 77 K up to room temperature. The results show that this configuration can be used to implement a compact cryogenic temperature sensor requiring access only to one end of the fiber, as is the case of FBGs, but exhibiting the higher temperature sensitivities of LPFGs for this temperature range. Several improvements are now being implemented, such as, the use of an optimized LPFG inscribed in a B/Ge co-doped fiber, the deposition of a metal-coated mirror on the fiber end-face, insertion of the fiber into a silica capillary for sensor protection and the extension of the temperature range down to 4 K. Results from these developments will be presented at the conference.

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REFERENCES

[1] Chen, T., Xu, D., Buric, M., Maklad, M., Swinehart P. R. and Chen, K. P., "Self-heated all-fiber sensing system for cryogenic environments," Meas. Sci. Technol. 21(9), 094036 (2010).

[2] Habisreuther, T., Hailemichael, E., Ecke, W., Latka, I., Schröder, K., Chojetzki, C., Schuster, K., Rothhardt, M. and Willsch, R., "ORMOCER coated fiber-optic Bragg grating sensors at cryogenic temperatures," IEEE Sensors J. 12(1), 13-16 (2012).

[3] www.iter.org

[4] López-Higuera, J. M., Cobo, L. R., Incera, A. Q. and Cobo, A., "Fiber Optic Sensors in Structural Health Monitoring," J. Lightwave Technol. 29(4), 587-608 (2011).

[5] Freitas, R. A., "Optical fiber temperature sensors for cryogenic applications," MSc. Thesis, FCUP (2013)

[6] Bathia, V., "Applications of long-period gratings to single and multi-parameter sensing," Opt. Exp. 4(11), 457-466 (1999)

[7] Rego, G. M., "Arc-induced long-period fibre gratings: fabrication and their applications in optical communications and sensing," PhD. Thesis, FEUP (2006).

[8] James, S. W., Tatam, R. P., Twin, A., Bateman R. and Noonan, P., "Cryogenic temperature response of fibre optic long period gratings," Meas. Sci. Technol. 14(8), 1409-1411 (2003).

[9] Monteiro, J., Martins, R., Caldas, P. and Rego, G. "Fiber optic sensor based on long period fiber grating to monitor cryogenic temperatures," Proc. IX SEONS, Post Deadline Paper (2011).

[10] Huang, J., Lan, X., Kaur, A., Wang, H., Yuan, L. and Xiao, H. "Reflection-based phase-shifted long period fiber grating for simultaneous measurement of temperature and refractive index," Opt. Eng. 52(1), 014404 (2013).

[11] Humbert G. and Malki, A., "High performance bandpass filters based on electric arc-induced π-shifted long-period fibre gratings," Electron. Lett. 39(21), 1506-1507 (2003).