Fiber Optic Sensor based on Long Period Fiber Grating to Monitor Cryogenic Temperatures

José Monteiro, Raquel Martins, Paulo Caldas and Gaspar Rego

***Abstract*—This work presents a fiber optic sensor to monitoring cryogenic temperatures. As a sensing element it was used a Long Period Fiber Grating (LPFG) inscribed in the SMF-28 fiber, using the electric-arc technique. The bendbright fiber, from Draka, was used to allow for small curvature radius and therefore requiring access to only one end of the fiber. The sensor was tested in the range between -200 °C and 25 °C. This test was performed with liquid nitrogen in a chamber with two thermocouples to determine the exact temperature in the area of the Long Period Fiber Grating. Two experiments were conducted. In the first experiment the sensor was submerged in liquid Nitrogen and then was drawn, such that the LPFG zone was in contact with the liquid nitrogen. In the second experiment the sensor was submerged again in nitrogen liquid, but the LPFG zone was not in contact with the liquid nitrogen.**

The results demonstrate that it is possible to monitor cryogenic temperatures with arc-induced Long Period Fiber Grating with the advantage of having access to only one end of the fiber.

***Index Terms*—Optical Fiber Sensors, Cryogenic temperatures.**

I. Introduction

Optical fiber grating sensors at low temperatures offers several advantages over conventional ones. Namely, their immunity to electromagnetic interference, low size and low thermal conductivity, and the possibility to multiplexing several gratings in the same fiber are very important properties at cryogenic temperatures and associated vacuum systems [1].

Fiber gratings consist of periodic perturbations in the properties of the optical fiber, generally of the core's refractive index, and fall in two general classifications, based upon the period of the grating: fiber Bragg gratings (FBGs) and long period fiber gratings (LPFGs).

Fiber Bragg gratings (FBGs) have a sub-micron period and act to couple light from the forward-propagating mode of the optical fiber to a backward, counter-propagating mode. This coupling occurs at a specific wavelength, which depends on the period of the FBG and other parameters like temperature and strain. FBGs can be used as band rejection filters and optical sensors of several parameters [2].

An LPFG is a periodic structure, with period typically in the range 100 µm to 1mm, inscribed in a fibre, which couples light between the core mode and co-propagating cladding modes at specific resonance wavelengths.

The transmission spectrum of the fiber contains a series of attenuation bands centered at these discrete resonance wavelengths, each attenuation band corresponding to the coupling to a different cladding mode. The grating behaves as a selective filter, where the resonance wavelengths depend on the period of the wavelength 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 [2], [3].

Fiber Bragg gratings can also be used as temperature sensors, but they are limited by expensive demodulation schemes and separating their sensitivity of both strain and temperature requires multiple co-located gratings, adding to system costs [4].

Besides, FBGs have shown previously to be largely temperature insensitive below -173.15 °C [5], [6], the response of FBGs to temperature is non linear in the region from room temperatures to cryogenic temperatures [6], [7] and also have problems of discontinuity in this region.

The sensitivity of FBGs to temperature is an order of magnitude smaller than the sensitivity of LPFGs (30-100 pm/°C for the LPFGs and 13 pm/°C for FBGs) [2], unless some techniques are used to enhance FBGs sensitivity, like embedding or bonding them to substrates, or applying a load [6].

In this work, we study the temperature influence on an LPFG, inscribed in a monomode fiber, SMF-28, fabricated by the electric arc technique, and we are particularly concerned at cryogenic temperatures.

II. Theory

For an LPFG, with period Λ, the wavelength $\lambda^{(m)}$ at which the mode coupling occurs is given by:

$$\lambda^{(m)} = \left(n_{eff} - n_{Cl,m}\right)\Lambda, \qquad (1)$$

where n_{eff} and $n_{Cl,m}$ are the effective indices of the core mode and the LP_{0m} cladding mode, respectively. For a given fiber, the grating period determines the cladding modes to which light can be coupled [4].

The sensitivity of an LPFG to temperature can be examined

José Monteiro, Raquel Martins, P. Caldas and Gaspar Rego are with INESC Porto, Rua do Campo Alegre 687, 4169-007 Porto, Portugal and Escola Superior de Tecnologia e Gestão de Viana do Castelo, Av. do Atlântico, Apartado 574, 4900-348 Viana do Castelo, Portugal

by expanding equation (1) to yield:

$$\frac{d\lambda}{dT} = \frac{d\lambda}{d(\delta n_{eff})}\left(\frac{dn_{eff}}{dT} - \frac{dn_{Cl}}{dT}\right) + \Lambda \frac{d\lambda}{d\Lambda}\frac{1}{L}\frac{dL}{dT} \qquad (2)$$

In this equation λ represents the central wavelength of the attenuation band, T is the temperature, $\delta n_{\mathrm{eff}} = (n_{\mathrm{eff}}-n_{\mathrm{Cl}})$, L is the length of the LPFG and the remaining symbols are the same of equation (1).

The first term after the equal sign in equation (2) is the material contribution and is related to the change in the differential refractive index of the core and cladding due to the thermo-optic effect. This contribution is dependent upon the composition of the fiber and is strongly dependent upon the order of the cladding mode.

The second term is the waveguide contribution as it results from changes in the LPFG period. The magnitude and sign of the term depend upon the order of the cladding mode.

Thus, by an appropriate choice of LPFG period is possible to balance the contributions of the temperature sensitivity to produce a temperature-independent contribution band and also to produce attenuation bands with temperature sensitivities (positive or negative) appropriate to specific applications. Altering the fiber composition, such that the thermo-optic coefficient of the core is either larger or smaller than that of the cladding, can also be used to obtain the desired temperature sensitivity [2].

The sensitivity of an LPFG to various measurands is dependent on the composition of the fiber, the period of the LPFG and the order of the cladding mode to which coupling occurs. It's possible to construct an LPFG sensor to several measurands, by the choice of the grating period and fiber composition to obtain attenuation bands insensitive to a particular measurand. Alternatively, the differential shifts in two or more resonant bands of a single LPFG may be used to measure simultaneously and independently several parameters, if we consider the difference in their sensitivities to the measurands [2].

We can mention several studies related to the influence of temperature on long period gratings, like for instance [5], where a B-Ge co-doped fiber was subjected to a change of temperature, from near -196.15 °C to 6.85 °C, being observed that the response is approximately linear from -196.15 °C to 6.85 °C, and below this temperature its sensitivity decreases, being no linear.

The non-linearity in the wavelength shift for the long-period grating bands can be attributed primarily to the temperature dependence of the thermo-optic coefficients of the core and the cladding [4]. But, still, LPFGs show a larger sensitivity to cryogenic temperatures, when compared to FBGs, due to the dependence of the coupling wavelengths upon the difference between the index of refraction of the core and the cladding [5].

Other works show us that the temperature sensitivity of LPFGs increases with their period [8] and the strength of the grating (transmission at the resonant wavelength) increases with temperature [9]. A study [10] compared the use of different types of fibers inscribed with LPFGs, having concluded that the sensitivity at low temperatures is greater with photosensitive fibers.

The wavelength shift due to temperature can also be enhanced by using appropriate coating around the grating [4].

The recoating of the fiber can be used to achieve a lower sensitivity to temperature in LPFGs, depending on the refractive index of the outer cladding [11].

The temperature insensitivity can be obtained by other processes, like doping the core region of the fiber [12].

III. Experimental setup

The experimental set-up is presented in Fig. 1.

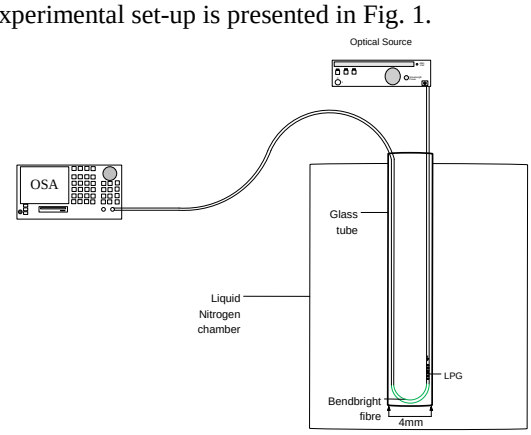

Fig. 1 – Diagram of the setup.

A broadband source centered at 1550 nm and bandwidth of approximately 80 nm, and an optical spectrum analyzer (OSA) were used to monitor the evolution of the spectrum with changes in temperature, with a resolution of 0.05 nm. The fiber with the LPFG was placed inside a glass tube with 4 mm internal diameter and 6 mm external diameter, using a special fiber, a *Bendbright* fiber from Draka, to enable the bending inside the tube. This way one needs access to only a single end of the fiber. The LPFG was fabricated with the electric arc technique in a standard SMF-28 fiber. It was used a Dewar Vase with liquid nitrogen, for testing the sensor. Inside the glass tube it was put two thermocouples for temperature control. In the first experiment we submerged the sensor in liquid nitrogen, such that the LPFG was in contact with the liquid, and then the sensor was drawn.

In the second experiment the sensor was submerged again in liquid nitrogen, but the tube was sealed, avoiding contact of the LPFG with the liquid nitrogen. Then, the liquid nitrogen was gradually heated.

IV. Results and Discussion

In the first experiment we inserted the sensor in liquid nitrogen and the LPFG was in contact with the liquid. Fig. 2 shows the evolution of the resonance peak with temperature variation

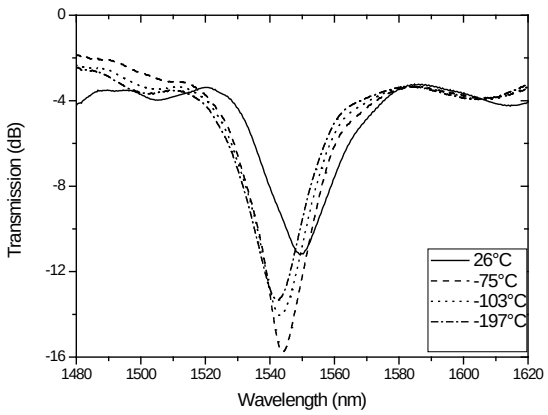

Fig. 2 - Evolution of the resonance peak with temperature increase.

from -197 °C, when it was fully inserted in liquid nitrogen, to 26 °C. To reach room temperature the sensor was removed slowly from liquid nitrogen.

By examination of Fig. 3 it is verified that in this range of temperatures the behavior of the sensor is non-linear. However, it is possible to distinguish two distinct zones: a linear region between -75 °C and 26 °C and other non-linear between -200 °C and -75 °C.

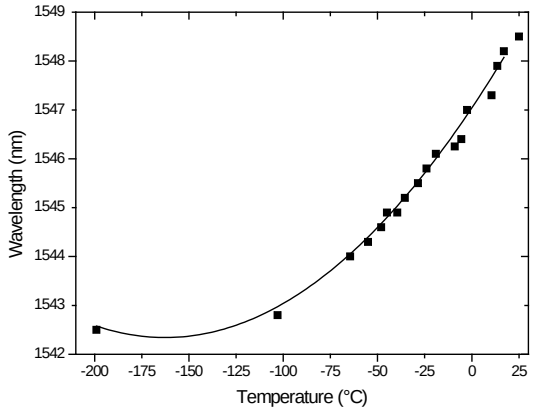

Fig. 3 - Behavior of the peaks with temperature increase.

In Fig. 4 we can see the response of the sensor. In this second experiment the sensor was in liquid nitrogen, but there was no contact with the LPFG. The liquid nitrogen was heated slowly. By comparing Fig. 3 and Fig. 4 it is observed that the resonance wavelength is lower for the former case, that is, with contact with the liquid nitrogen. This is a consequence of the effect of the refractive index of the liquid nitrogen, that also depends on temperature, on the effective index of the cladding modes, affecting the resonance wavelength according to equation (1). The sensitivity reported for these four points is 60 pm/°C, which is very close to the sensitivity obtained at room temperature and 4 times greater than the values obtained using FBGs.

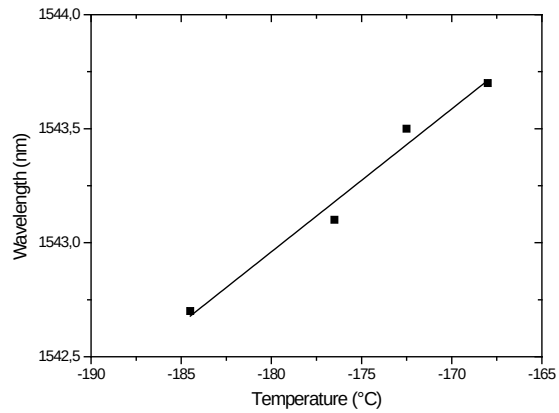

Fig. 4 - Behavior of the peaks with temperature increase.

V. Conclusions

This experiment proves that it is possible to use LPFGs to monitor at cryogenic temperatures. The response to temperatures around the ambient temperature is linear. In the first experiment we put the sensor in liquid nitrogen, and then we removed it. When the sensor was in liquid nitrogen, it was contact with the LPFG.

In the second experiment we isolate de LPFG zone from the liquid nitrogen. The sensor was in liquid nitrogen, but there was no direct contact with the liquid, therefore, there was no effect on the effective refractive index of the cladding modes, like in the first experiment. Therefore, care should be taken to avoid direct contact between the LPFG and the fluid. We reported a linear response of the sensor at those temperatures.

Finally, it should be emphasized the benefit of using the bendbright fiber which can be very useful in situations where only access to one end of the fiber is available.

A set of experiments to characterize LPFGs inscribed in different fibers at cryogenic temperatures, as low as 4 K, are ongoing and results will be published elsewhere.

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