CHARACTERIZATION OF LONG PERIOD GRATINGS MANUFACTURED WITH FIBER OPTIC FUSION SPLICER FOR SENSOR DEVELOPMENT

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***Abstract*— A Long Period Grating (LPG) is a structure inscribed in an optical fiber that is of great interest in the field of communications and sensors. At Centro de Investigaciones Ópticas (CIOp), an LPG manufacturing process was implemented. It is based on use of electric arcs produced with an optical fiber splicer to generate a series of physical disturbances that modify optical fiber behavior as a light transmission guide. Since transmission response of LPG is sensitive to fiber environment conditions, it can be used to detect changes in certain physical and chemical parameters. In particular, it enables the implementation of optical sensors sensitive to temperature, surrounding medium refractive index and axial deformation. Characterization of locally generated LPGs is essential for future design of sensors applicable in many engineering areas. In this article, typical LPG sensitivities to the three mentioned parameters are reported.**

***Keywords*— Optical sensing, optical fiber, long period gratings, tapered fiber.**

I. INTRODUCTION

For many years the use of different sensing schemes based on optical fibers has attracted the attention of numerous research groups. Mentioned schemes has shown an important evolution allowing access to alternative measurement mechanisms applicable in different areas of knowledge and industry (Krohn *et al*., 2014; Lou *et al*., 2014). This is due to a series of advantages such as small weight and size, possibility of remote sensing, immunity to electromagnetic interference, ability to operate in corrosive or hazardous environments, and the chance of embedding them in different materials without altering its properties. In this context, the generation of new sensor devices that allow different physical and chemical parameters assessment is a fundamental objective tending to achieve laboratory instrumentation transferable to industrial applications. Recently, manufacture of LPGs in standard single-mode optical fibers has been carried out at CIOp, by means of electric arc induction generated with a fiber optic splicer. It consisted of the implementation and optimization of a LPGs manufacturing process that, although it was based on the aforementioned technique, had to be compatible with the infrastructure and instruments available at our lab. This implied the adequacy of some practical procedure aspects according to the existing technical benefits and restrictions. As a result, a reliable, controlled and repetitive LPG manufacturing process was obtained, which allowed adjusting their optical behavior to respond to pre-established characteristics at design time and according to application requirements (Alustiza *et al*., 2019). Taking into account that device design must be carried out in close connection with the metrological application to be addressed, it is necessary to have a complete characterization of its optical behavior under different stimuli.

In this article we expose different tests performed on locally manufactured LPGs in order to characterize their spectral response to the variation of those physical quantities to which they are sensitive. These LPGs will then be applied in the implementation of sensors that allow the evaluation of different parameters related to the durability of concrete used in civil constructions and the monitoring of structural health.

II. THEORETICAL DISCUSSION

An LPG is a structure inscribed in an optical fiber which consists of a periodic modification of the effective refractive index of its core, and in some cases of the fiber cladding too (Martinez-Rios *et al.*, 2012), that extends longitudinally certain distance called *grating length*. This index modulation causes that part of the optical energy associated with the core propagating mode couples to cladding, generating a series of light modes that co-propagate through it if appropriate conditions are verified. The optical propagation path associated with cladding modes has a very high attenuation, so they fade after a short distance. This causes that transmission spectrum of an LPG presents a series of attenuation bands (DIPs) centered on specific wavelengths that identify modes coupled to the cladding. Mentioned wavelengths verify the so-called "phase-matching condition" given by Eq. 1 (Kashyap, 2010)

$$\lambda_m = \left(n_{eff}^{co} - n_{eff}^{cl,m}\right)\Lambda, \qquad (1)$$

where λ_m is the resonance wavelength of the coupling corresponding to the m-th cladding mode, n_{eff}^{co} and $n_{eff}^{cl,m}$ are the effective refractive indices of the core and of the m-th cladding-mode respectively, and Λ is the refractive index modulation period. Figure 1 shows how coupling of light from core to cladding occurs when passing through an LPG.

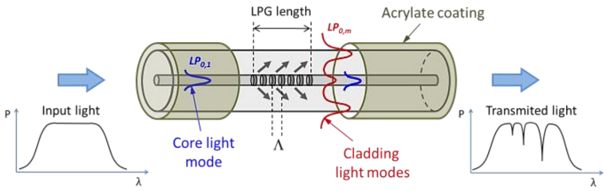

Figure 1. Light coupling from fiber core to cladding when passing through an LPG.

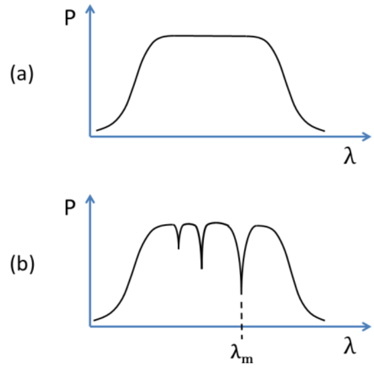

Figure 2. Light signal spectrum: (a) optical power at the input and (b) at the output of an LPG.

Sections of different coloration in core denote the existence of an LPG and the arrows in its surroundings shows that light radiation is coupled from core to cladding. In the case of arc-induced LPGs, the modulation effect of the refractive index is manifested both in the core and in the fiber cladding region, therefore dark gray regions in the core shown in Fig. 1 also extend to the cladding (Mendes do Rego, 2006). In this technique, index modulation is achieved by periodic fiber tapering, which extends along a certain length. The fiber optic segment in which narrowing exists is called "mark" in the context of this article. A mark is essentially a fiber structure known as μ-taper (Lou *et al.*, 2014). A sequence of marks uniformly distributed in axial direction of the fiber defines a longitudinal modulation of the refractive indices of both, core and cladding. Figure 1 shows that radial distribution of energy of core propagation mode ($LP_{0,1}$) weakens after passing through the LPG. Generated cladding modes are denoted as $LP_{0,m}$ being the subscript m associated to the order of the represented mode. Figure 2 (b) shows a typical spectrum of light radiation at the output of an LPG when it is illuminated by a broadband light source (Fig. 2 (a)).

In the transmission spectrum different attenuation bands can be observed, particularly the one centered at λ_m corresponding to the m-th cladding mode. Peak depth observed in the attenuation band can be calculated by Eq. 2 that can be derived from analyzing coupling between light modes.

$$T_m = 1 - \sin^2(k_m L), \tag{2}$$

where T_m is the transmittance of the LPG for m-th cladding propagation mode, k_m is the coupling coefficient for such propagation mode and L is the grating length. In this case, k_m considers the total effect of the light coupling from the core to the cladding produced by all inscribed marks along the length L.

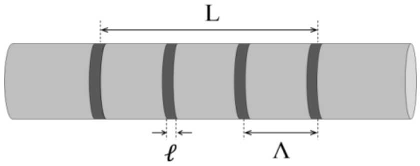

Figure 3. Geometric description of an LPG.

A. LPG characteristics

An LPG is defined according to:

- Physical configuration characteristics: those that describe its physical appearance relating to geometrical parameters.
- Optical behavior characteristics: those that describe its optical response to the pass of a given light radiation through it.

From the point of view of its physical configuration, the fundamental characteristics are:

- Grating length (L): distance between the midpoint of the first mark and the midpoint of the last mark.
- Grating period (Λ): distance between the midpoints of two consecutive marks.
- Mark length (ℓ): length of a mark measured in the fiber axial direction.
- Mark transition profile: (only when the mark consists of µ-taper type structure) it is defined as the way in which fiber diameter axially changes from the original value to that corresponding to the neck of the µ-taper.
- Number of marks (N): total number of marks that conforms the whole LPG.

Variable grating period and apodized shape mark pattern are not covered in this article.

Figure 3 shows a section of a 4-mark LPG indicating the parameters that describe the grating, but without considering the profile of the µ-tapers that make up those marks.

Optical behavior is characterized by:

- Spectral location of the attenuation DIP corresponding to the m-th cladding propagation mode (λ_m): wavelength of the m-th mode that propagates through the cladding. Normally expressed in nm.
- Depth of the attenuation DIP corresponding to the m-th cladding propagation mode (P_m): it is the difference between level of maximum transmitted optical power and the deepest point of the attenuation DIP corresponding to the m-th mode that propagates in the cladding. Normally expressed in dB.
- Bandwidth of the attenuation band of the m-th cladding propagation mode (w_m): wavelength difference between two points of the attenuation DIP in which the optical power is half the maximum value, assuming that the shape of such DIP is Gaussian (FWHM, Full Width at Half Maximum). Normally expressed in nm.

B. Use of LPG as sensors

Equation 1 exhibits λ_m dependence with grating period and with the difference between the effective refractive

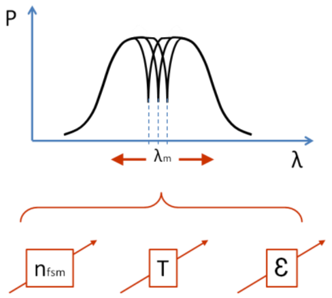

Figure 4. Effects of n_{fsm}, T and ε variations on attenuation DIP position.

indices of core and cladding. Grating period can be modified if the fiber is subjected to physical processes that deform it by contracting or expanding longitudinally. This occurs if there is an applied axial tensile or compressive stress, or a temperature change in the grating environment. Also, the cladding effective refractive index is a function of the refractive index of the medium surrounding the fiber. Thus, a change in the wavelength of the attenuation DIP is induced if any of the following magnitudes change: refractive index of the medium surrounding the fiber, temperature or longitudinal deformation (James and Tatam, 2003). Assuming that there is no correlation between mentioned quantities, Eq. 3 shows this dependence in mathematical terms:

$$\Delta\lambda_m = f(\Delta n_{fsm}, \Delta T, \Delta\varepsilon), \tag{3}$$

where $\Delta\lambda_m$ is the induced change in the attenuation DIP position, Δn_{fsm} is the variation of the refractive index of the medium surrounding the fiber, ΔT is the temperature variation, $\Delta\varepsilon$ is the longitudinal deformation variation per unit length (*strain*) and f is the mathematical function that relates such changes. Assuming that only one of the independent variables in Eq. 3 changes, keeping remaining ones constant, following expressions can be established:

$$\Delta\lambda_m = f_{\Delta n}(\Delta n_{fsm}), \tag{4}$$

$$\Delta\lambda_m = f_{\Delta T}(\Delta \mathrm{T}), \tag{5}$$

$$\Delta\lambda_m = f_{\Delta\varepsilon}(\Delta\varepsilon). \tag{6}$$

The mathematical function $f_{\Delta n}$ from Eq. 4 suggests that a change detected in λ_m would allow to calculate the change in n_{fsm} that induced it (if there are no thermal or deformation variations). The same applies to functions of Eq. 5 and 6. This fact justifies the use of LPGs as transduction elements for detection of changes in temperature, surrounding medium refractive index, and axial strain. A given state of the LPG (determined by n_{fsm}, T and ε) can be considered as a reference point for the determination of $\Delta\lambda_m$ when any of the three magnitudes to which the LPG is sensitive changes. Figure 4 schematizes the influence of n_{fsm}, T and ε variations on the value of λ_m, showing the shift of the attenuation DIP in the transmission spectrum.

C. Analysis of sensitivities

Sensitivities of λ_m to those magnitudes mentioned in the previous section can be determined by:

$$S_{n_{fsm}} = \frac{d\lambda_m}{dn_{fsm}}, \tag{7}$$

$$S_T = \frac{d\lambda_m}{dT}, \tag{8}$$

$$S_\varepsilon = \frac{d\lambda_m}{d\varepsilon}, \tag{9}$$

where $S_{n_{fsm}}$, S_T and S_ε are sensitivities to the change in surrounding medium refractive index, temperature and strain to which LPG is subjected. Expressions reached after performing calculations are the following:

$$S_{n_{fsm}} = \frac{d\lambda_m}{d\Delta n_m}\frac{dn_{eff}^{cl,m}}{dn_{fsm}}, \tag{10}$$

$$S_T = \frac{d\lambda_m}{d\Delta n_m}\left[\frac{dn_{eff}^{co}}{dT} - \frac{dn_{eff}^{cl,m}}{dT}\right] + \frac{d\lambda_m}{d\Lambda}\frac{\Lambda}{L}\frac{dL}{dT}, \tag{11}$$

$$S_\varepsilon = \frac{d\lambda_m}{d\Delta n_m}\left[\frac{dn_{eff}^{co}}{d\varepsilon} - \frac{dn_{eff}^{cl,m}}{d\varepsilon}\right] + \frac{d\lambda_m}{d\Lambda}\Lambda, \tag{12}$$

where,

$$\Delta n_m = \left(n_{eff}^{co} - n_{eff}^{cl,m}\right), \tag{13}$$

Equation 10 relates surrounding medium refractive index with position of attenuation DIP corresponding with the m-th cladding mode, defining the corresponding sensitivity. Equation 11 shows an equivalent dependence on temperature. Left term of the sum exposes a dependency with temperature due to thermo-optical effects (both n_{eff}^{co} and $n_{eff}^{cl,m}$ change with T). Right term of the sum shows a dependency with the grating length (L) due to thermal expansion or contraction of the optical fiber. Finally, first term on the right side of Eq. 12 shows the contribution to the sensitivity of elasto-optical effects induced by axial stress that leads to a longitudinal deformation. Second term on the right side exhibits the contribution of the change in the grating period due to the deformation produced by axial stress. This deformation responds to a contraction or elongation depending on whether the mechanical stress is compression or traction.

III. MATERIALS AND METHODS

Optical fiber used for local manufacture of LPGs is a standard SM fiber (Furukawa), commonly used for communications. Its basic descriptive parameters are:

- Maximum Attenuation (@1550nm): <0.20dB/km
- Cutoff Wavelength: <1260nm
- Mode Field Diameter (@1550nm): (10.5 ± 0.8)µm
- Cladding Diameter: (125 ± 1)µm
- Coating Diameter: (245 ± 5)µm
- Concentricity Cladding/Coating: <12µm
- Temperature Range: -60ºC a +85ºC
- Tensile Stress: 100kpsi.

Other transmission characteristics verify the requirements established in the ITU-T standard G.652.

The geometrical and optical characteristics of the LPGs are:

- Grating Length (L): (17.050 ± 0.001)mm
- Grating period (Λ): (550± 1)µm
- Mark length (ℓ): (120 ± 10)µm
- Number of marks (N): 32
- λ_m: 1555nm
- P_m: greater than 20dB
- w_m: between 20nm and 30nm

In all experiments described below, an SLD (Exalos (EXS210066-01)) was used as light source emitting in the spectral region located in 1450-1650nm range. Light

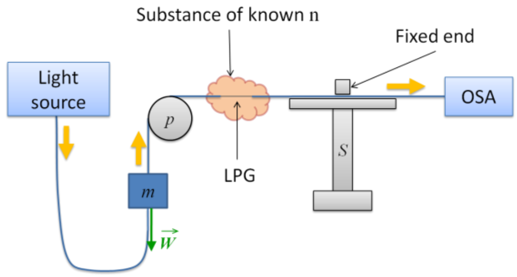

Figure 5. Scheme of the experimental arrangement implemented for the sensitivity test to change of n_{fsm}.

source was chosen in order to reach a significant illumination bandwidth. It allows detecting at least one of the attenuation DIPs of the transmission spectrum, as well as practically any wavelength shift caused by sensed magnitudes variation effect. In order to execute monitoring and data logging related to light signal spectrum evolution, an optical spectrum analyzer (OSA) (Yokogawa AQ6370B) was used.

A. Measurement of $S_{n_{fsm}}$

The experimental arrangement designed for measuring the sensitivity to changes of n_{fsm} is schematized in Fig. 5.

Test consisted in varying the environment refractive index that surrounds the fiber sensitive region, in order to log data measurements associated with the observed changes in the LPG transmission spectrum. For this, the sensitive region was embedded with the following liquid substances, whose refractive indices are known:

- Acetonitrile (ACN or C_2H_3N): n = 1.3460
- Isopropyl alcohol (IPA or C_3H_8O): n = 1.3776
- Ethyl alcohol (EtOH or C_2H_5OH): n = 1.3610
- Heptane (C_7H_{16}): n = 1.3855
- Tetrahydrofuran (THF or C_4H_8O): n = 1.4070
- Methyl Alcohol (MeOH or CH_3OH): n = 1.3292
- Distilled water (H_2O): n = 1.3330
- Diethylamine ($C_4H_{11}N$): n = 1.3864

These values were taken from tables evaluated in line D of sodium (@ 589.3nm). In order to keep fiber optic tension invariant between measurements, a pulley/mass mechanism was implemented (m and p in Fig. 5). The other end of the fiber was fixed to a column type support (S). Therefore, attenuation DIP did not undergo changes in its position due to variations of mechanical strain on the grating. Observations of the optical spectra were made by monitoring possible temperature changes that could alter the LPG response. The logged temperature would be used to correct attenuation DIP position shift due to thermal effect.

B. Measurement of S_T

The experimental arrangement for measuring temperature sensitivity is schematized in Fig. 6. The LPG was subjected to constant strain during the test, using a mechanism similar to that of Fig. 5. Support column thermal expansion was considered negligible over temperature range swept. In addition, optical fiber was placed inside

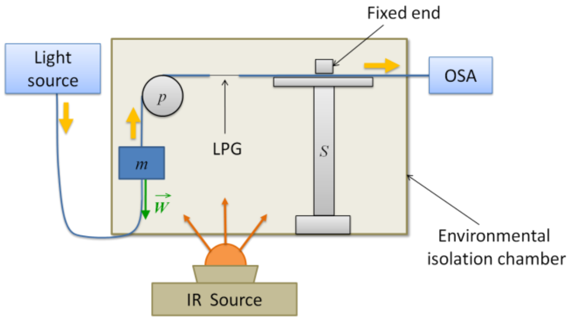

Figure 6. Experimental arrangement for temperature sensitivity measurement.

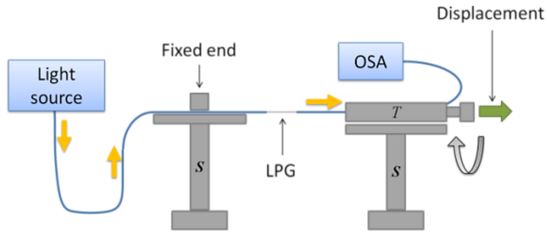

Figure 7. Experimental set up for strain sensitivity measurement.

a glass chamber to isolate it from possible disturbances due to the existence of thermally influencing air currents. Internal chamber environment was isolated causing that fiber surrounding medium remains constant its refractive index.

In order to generate a thermal variation it was used an infrared (IR) radiation source located outside the isolation chamber and at a certain distance from it. By varying such distance and the angle of incidence of the IR emissions with respect to the plane of the chamber wall, different points of thermal stabilization of the LPG were achieved. The spectral response of the LPG was recorded for each thermal stabilization point for subsequent analysis. The LPG temperature measurement was implemented through the use of a K type thermocouple assembly and multimeter Meterman 23XT (Wavetek). Temperature of the LPG was considered similar to that of its surrounding environment, so thermocouple was placed in a region very close to it.

C. Measurement of S_ε

Figure 7 schematizes the experimental arrangement used for strain sensitivity measurement.

It shows the LPG mounted between two attachment points, one which is fixed (left) while the other is mobile (right). The moving point was achieved through the use of a micrometric linear translation stage (T in Fig. 7), whose resolution is 1µm. Strain achieved by stretching the fiber was produced by means of displacing the point attached to the translation stage. Initially, the attachment points were located at a reference distance (before starting the movement sequence) whose value was (227.8 ± 0.1) mm. Each length increment caused by the movement of the mobile clamping point was 10µm. Then, longitudinal strain was calculated by using Eq. 14.

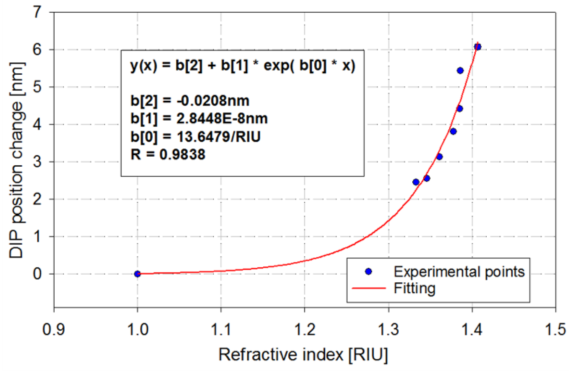

Figure 8. DIP position change vs. n_{fsm}.

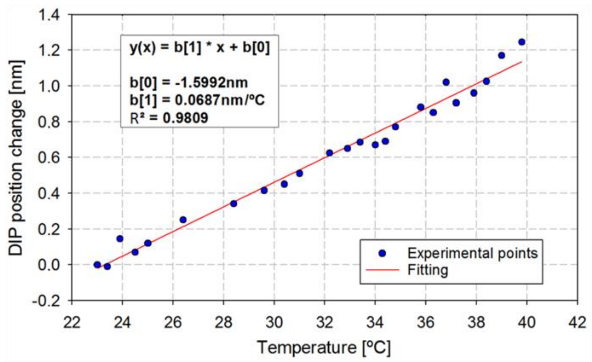

Figure 9. DIP position change vs. temperature.

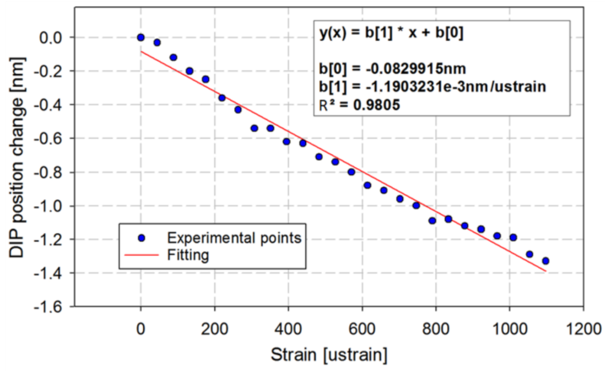

Figure 10. DIP position change vs strain.

$$\varepsilon = \frac{(x - x_{ref})}{x_{ref}}, \quad (14)$$

where ε is the strain, x_{ref} is the reference distance between fixed attachment points being the fiber relaxed, and x correspond to distance value between those points after an axial effort (traction) was applied. Optical fiber that contains the LPG used in this test was subjected to a maximum strain of approximately 1100µƐ in order to do not generate permanent damage or deformation. Temperature measurements were taken in order to correct attenuation DIP position shift due to thermal effects. Again, internal chamber environment was isolated causing that fiber surrounding medium remains constant its refractive index.

IV. EXPERIMENTAL RESULTS

In order to evaluate and judge the goodness of fitting made on the experimental points, all plots presented show the fit against the raw data for visual comparing. In the case of Fig. 8, the experimental points were fitted using an exponential curve and the value of the R parameter indicates that there is a good correlation between the data and the fit curve. In the same way, the values of the R^2 parameter indicated in Figs. 9 and 10 also show a satisfactory measure of the goodness of the linear fits made in each case.

A. Surrounding medium index sensitivity

Figure 8 shows a graph describing the induced change in DIP position ($\Delta\lambda_m$) due to variations in surrounding medium refractive index (n_{fsm}). Vertical axis denotes DIP position change with respect to a reference value that was established in $\lambda_{n,reference} = 1555$nm. This value was established taking into account the following conditions:

- Axial tension: produced by a mass of 14.31g.
- Temperature: corresponding to the environment at test execution time (21°C).
- Fiber optic surrounding medium refractive index: 1.0002926RIU (air).

Mathematical function that describes the vertical axis of graph in Fig. 8 is given by Eq. 15:

$$\Delta\lambda_n = \lambda_{n,measured} - \lambda_{n,reference}, \quad (15)$$

where $\lambda_{n,measured}$ is the attenuation DIP wavelength measured when the substance in contact with LPG was changed. Dot points in graph represent experimental data measurements, while continuous line is the corresponding fitting curve.

Taking into account Eq. 7 and 15, as well as the function that fits experimental data, sensitivity $S_{n_{fsm}}$ is determined by Eq. 16:

$$S_{n_{fsm}} = b_1 b_0 e^{b_0 n_{fsm}}, \quad (16)$$

where b_0 and b_1 result from the fitting process.

B. Temperature change sensitivity

Figure 9 shows the induced change in LPG attenuation DIP position when temperature varies.

Same graph considerations mentioned in the previous section are applied to the vertical axis. Sensitivity S_T remains approximately constant in the swept temperature range, being valued in 68pm/°C. Positive sign of the slope of the fitting line indicates that attenuation DIP position shift is increasing when the LPG temperature increases.

C. Strain change sensitivity

Figure 10 shows the induced attenuation DIP position change when axial strain varies. Same considerations mentioned in previous section are applied to the vertical axis.

Sensitivity S_ε remains approximately constant in the considered deformation range, being -1.190pm/µε (according to the fitting process made on the experimental data). The negative sign of the slope of the adjustment line indicates that the shift of the attenuation DIP position is towards lower wavelengths when the strain applied on the LPG increases.

V. CONCLUSIONS

This work shows a typical LPG manufacturing and characterization performed in our laboratory by means of adapting the electric arc induction technique. These devices will be used in the development of sensors to be applied in different technological fields (civil engineering, bioengineering, etc.). Results obtained reflect that sensing characteristics of locally generated LPGs makes them a competitive alternative to other sensing technologies, also having the advantage of being able to be designed according to the needs of the specific engineering field in which the LPGs will be applied. Currently, sensors based on LPGs are being developed in our lab, whose response has been previously characterized as described in this work. They are intended to carry out studies of concentration of chemical agents within pieces constituted by cement-based materials (cement paste, mortar, and concrete) to investigate the durability of these materials.

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