Non-Linear Behavior of Long Period Grating Thermal Sensitivity in Different Surroundings

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Abstract— We report the thermal sensitivity dependence of long period gratings on the surroundings refractive index, with a noticeable non-linear behavior for surrounding media with refractive indexes above 1.404. For refractive indexes ranging from 1.000 to 1.447, the grating thermal sensitivity changes from 0.040 ± 0.001 nm/ºC to 0.393 ± 0.015 nm/ºC. The higher observed non-linearity occurs when the refractive index *of* the external medium is close to 1.447. For this case, two different average thermal sensitivities are obtained: 0.393 ± 0.014 nm/ºC and 0.213 ± 0.002 nm/ºC. If this non-linear behavior is not properly considered, the error in the measurement of the grating resonance wavelength is 3.16 nm for temperatures about 40 ºC. The presented results indicates that the non-linearity in the thermal sensitivity response is an important behavior that must be considered when a long period grating device is designed to operates as a temperature sensor in the presence of different external media, or as a refractometer working at different temperatures.

***Index Terms* —** Long period grating, optical sensor, non-linear thermal sensitivity.

I. INTRODUCTION

Along the last years, long period gratings (LPGs) have been successfully applied as surrounding refractive index sensors. In fact, the LPG refractometer has been used as chemical concentration sensors [1]-[3] and liquid level sensor [4]. However, because LPGs are also inherently sensitive to temperature, there is a potential cross-sensitivity problem when they are used in such application. Although previous works report the efforts to produce devices with improved refractive index and thermal sensitivities, a little attention has been devoted to the performance of such sensors when they are subject to the simultaneous changes of two or more parameters.

Long period gratings are formed by inducing a periodic refractive-index modulation in the core of an optical fiber. The phase-matching condition causes light from the fundamental guided mode to be coupled to forward propagating cladding modes at distinct wavelengths, given by the following relation [5]:

$$\lambda^m = \left(n_{co} - n_{cl}^m\right)\,\Lambda \tag{1}$$

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where n_{co} and n_{cl}^{m} represent the refractive-indexes of the core guided mode and the m-th LP_{0m} cladding mode, respectively. The n_{co}, n_{cl}^{m} and grating period Λ can be affected due to changes in the external parameters, such as strain, temperature or refractive index. As a result, the coupling wavelength (λ^{m}) experiences a shift that can be used to measure the parameter being changed.

The optical power coupled to the cladding modes is strongly affected by fiber imperfections, micro and macro bending, and by boundary conditions at the cladding-external medium interface. Thus, the light coupled from the core to the cladding modes leaks out the fiber, leaving several dips in the transmission spectrum, each one corresponding to a specific coupling governed by (1). For resonant wavelengths the transmission T through the core is [6]:

$$T = \cos^2\left(DL/2\right) \tag{2}$$

where L is the grating length and D is the coupling coefficient.

In the case of LPG refractive index sensitivity, Chiang *et al* [7] developed an analytical expression to describe the wavelength shift, $\delta\lambda_0$, when the external refractive index changes from n_{ex0} to n_{ex}:

$$\delta\lambda_0 \approx \frac{u_\infty^2\ \lambda_0^3\ \Lambda}{8\,\pi^3\ n_{cl}\ \rho^3}\left[\frac{1}{\left(n_{cl}^2 - n_{ex0}^2\right)^{1/2}} - \frac{1}{\left(n_{cl}^2 - n_{ex}^2\right)^{1/2}}\right] \tag{3}$$

where u_∞ is the m-th root of the Bessel function J_0 [8], λ_0 is the resonant wavelength at n_{ex0}, Λ is the grating pitch, n_{cl} is the cladding fiber refractive index and ρ is the cladding radius.

According to (3) the refractive index sensitivity presents a non-linear behavior that is more pronounced when the external refractive index is close to the cladding refractive index. An expression for LPG sensitivities S to the external media refractive indexes can be obtained by differentiating (3) with respect to n_{ex}:

$$S = \frac{d\lambda}{dn_{ex}} = -\frac{u_\infty^2\ \lambda_0^3\ \Lambda}{8\,\pi^3\ n_{cl}\ \rho^3}\left[\frac{n_{ex}}{\left(n_{cl}^2 - n_{ex}^2\right)^{3/2}}\right] \tag{4}$$

In accordance with Quin *et al* [9] the thermal sensitivity of a LPG is caused by two factors: the thermal expansion effect and the thermo-optic effect. The thermal-expansion coefficient for silica is about 10^{-7} ºC^{-1} [10], while the coupling thermo-optic coefficient (α) is about 10^{-5} ºC^{-1} [9]. Therefore the thermal sensitivity of LPG mainly depends on the coupling thermo-optic coefficient given by [9]:

$$\alpha = \frac{1}{n_{co} - n_{cl}^{m}}\frac{d\left(n_{co} - n_{cl}^{m}\right)}{dT} \tag{5}$$

Temperature sensitivities of LPGs produced in single mode fibers are rather low, reaching only values between 0.04 and 0.1 nm/ºC [11]. Some techniques have been adopted to improve this temperature sensitivity. A significant increase of 3.4 nm/ºC was achieved with a bare LPG inscribed in a commercial Boron/Germanium co-doped fiber operating in the dispersion turning point region [12]. A still higher sensitivity of 19.2 nm/ºC was obtained for a bare LPG immersed in a liquid with a high thermo-optic coefficient (α_s) and refractive index close to that of the fiber cladding [13]. He *at al* [14] measured wavelength shifts of 60 nm and 0.6 nm within the temperature range of 0 ºC to

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100 ºC, using acrylate-based polymer and silicone resin as recoating materials on the LPG, respectively. Recently, Chormát *et al* [15] obtained sensitivities of 0.56 nm/ºC for a bare LPG produced in a graded-index optical fiber and 0.86 nm/ºC when the same grating was recoated with a polymer layer. In these works the change in the temperature sensitivity was obtained by properly doping the fiber core, by altering the fiber structure and geometry, by coating the LPG with a polymer layer or by surrounding it with a temperature-sensitive liquid.

Although several authors report the efforts in achieving devices with optimized thermal sensitivities, a little attention has been devoted to the performance of such sensors when they are supposed to work immersed in media with different refractive indexes. In this work long period gratings are produced by the use of a point-to-point writing method, applying on a bare fiber an electrical discharge from a fusion splicer. The influence on the coupling strength of both the longitudinal tension and number of discharges per point applied in fabrication process are analyzed. We also show a non-linear behavior of the LPG thermal sensitivity, depending on the magnitude of the surroundings refractive index.

II. EXPERIMENTAL SET-UP

A. LPG Fabrication

The experimental set-up employed to produce the long period gratings is similar to that used by Rego *et al* [16]. A bare fiber without its protective coating is placed between the electrodes of a fusion splice machine. To keep the fiber under constant longitudinal tension, a small mass is suspended in one of the fiber extremities, while the other one is attached on a computer controlled translation stage with resolution of 5 μm. An arc discharge with current of 12 mA is then applied during 0.5 seconds. After this, the fiber is moved by the translation stage along a distance equals to the grating period ($\Lambda = 595$ μm) and another arc discharge is applied. After a suitable number of point-to-point discharges, a periodic pattern is engraved in the refractive index profile of the fiber. The gratings spectra are recorded using an optical spectrum analyzer (Anritsu MS9710B, wavelength stability of ± 5 pm) set to a resolution in the range from 0.07 nm to 0.1 nm, and a LED (MRV Communications, central wavelength 1547.1 nm and half bandwidth of 54.8 nm). Three gratings are produced with a suspended mass of 30 g and a different number of electrical arcs applied to each point (1, 2 and 3 arcs). To produce the other five gratings, only one electrical arc is applied to each point and suspended masses of 20, 25, 30, 35 and 40 g are employed.

B. LPG Characterization

The LPG thermal sensitivity dependence on the surrounding medium refractive index is measured with the LPG produced with one discharge per point and the 30 g mass. The LPG is inserted into a specially designed glass container with four openings, two of them used to insert the optical fiber with the LPG and the two others to insert and to drain the samples with different refractive indexes. With the LPG positioned inside the container, one of the fiber tips is immobilized and the other one is fixed

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to a small mass by means of a pulley. This procedure is adopted during the thermal characterization to avoid bend and stress crossed sensitivities. The thermal response of LPG is determined by heating the container, filled with each sample, within the temperature range from 20 ºC to 60 ºC in incremental steps of about 5 ºC. In the experiments are used samples of air (n = 1.000), water (n = 1.333), ethanol (n = 1.365), naphtha (n = 1.404), thinner (n = 1.432), turpentine (n = 1.439) and kerosene (n = 1.447). After being drained from the glass container, an Abbe refractometer is used to measure the refractive indexes of the samples.

III. RESULTS AND DISCUSSIONS

The normalized transmission losses versus grating length for the produced devices with different numbers of electrical arcs per point are shown in *Fig*. 1. It is also shown the best fit of the analytical curve given by (2), and the related parameters are summarized in Table I. It is observed that the application of 2 or 3 electrical arcs in the same point increases the refractive index modulation. As result, these gratings present a better coupling strength and a smaller number of periods are necessary to achieve the maximum coupling.

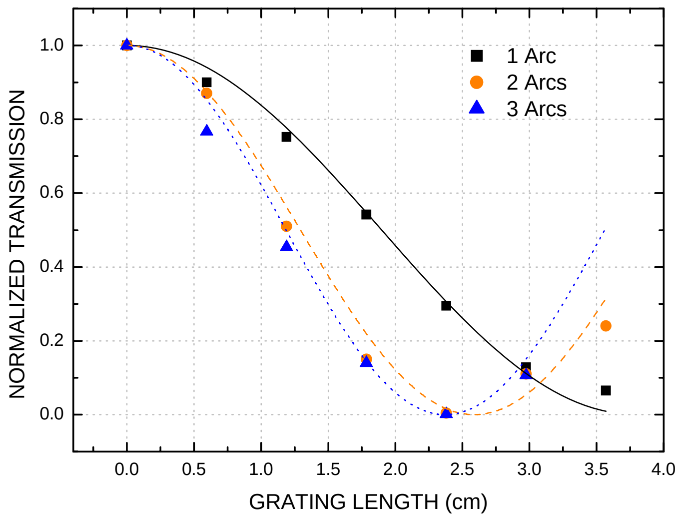

Fig 1. Normalized transmission loss versus grating length for the gratings produced with 1, 2 and 3 electrical arcs per point. The marks show the experimental values, the lines depict the correspondent best fit.

TABLE I. PARAMETERS OF THE GRATINGS PRODUCED WITH A DIFFERENT NUMBER OF APPLIED ELECTRICAL ARCS

Arcs per point	Coupling coefficient, *D* (rad/cm)	Transmission loss (dB)	Correlation coefficient, *r*
1	0.82 ± 0.02	-11.9	0.99305
2	1.21 ± 0.03	-23.5	0.98204
3	1.32 ± 0.03	-31.7	0.98620

The transmission losses versus grating length for the produced devices with different suspended masses are shown in *Fig*. 2. It is also shown the best fit of the analytical curve given by (2), and the related parameters are summarized in Table II. An increment of the suspended mass causes an increase in the coupling coefficient. This effect may have its origin in the periodic fiber tapering

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reported by other authors when employing the same writing process used in this work [17]. The grating produced with a mass of 35 g presents a coupling coefficient smaller than that one produced with 30 g. It can be caused by changes on the ambient conditions (e. g. humidity), electrodes degradation, dust on the fiber or on electrodes, or by changes on the relative position between the fiber and the electrodes.

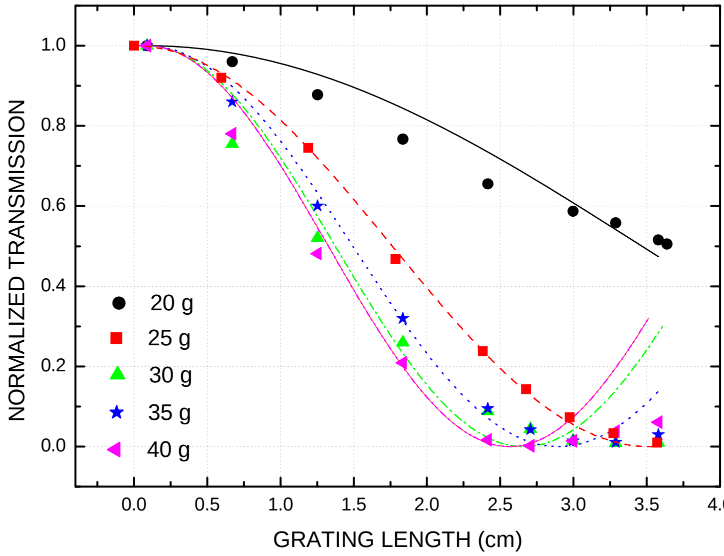

Fig. 2. Transmission loss versus grating length for the gratings produced with suspended masses of 20, 25, 30, 35 and 40 g and 1 electrical arc per point. The marks show the experimental values, the lines depict the correspondent best fit.

TABLE II. PARAMETERS OF THE GRATINGS PRODUCED WITH DIFFERENT SUSPENDED MASSES

Mass (g)	Coupling coefficient, D (rad/cm)	Transmission loss (dB)	Correlation coefficient, r
20	0.46 ± 0.01	-2.9	0.93395
25	0.89 ± 0.01	-19. 7	0.99890
30	1.20 ± 0.05	-20.5	0.97088
35	1.10 ± 0.02	-19.7	0.99570
40	1.24 ± 0.04	-28.3	0.98364

Fig. 3 shows the shift in the grating resonance wavelength for the seven different samples used in the experiments (left axis), and the best fit of the analytical curve given by (3) for $n_{ex} < n_{cl}$, which agrees well with the experimental data. The parameters used for the fitting are $\Lambda = 595$ µm, $n_{ex0} = 1.000$ (air), $\rho = 62.5$ µm, $n_{cl} = 1.460$ (fixed parameters) and $u_\infty = 11.58 \pm 0.10$, $\lambda_0 = (1576.3 \pm 0.1)$ nm (variable parameters). These results allow finding the order of the m-th cladding mode for which the coupling occurs. The J_0 root closest to the u_∞ is 11.79, corresponding to the fourth order mode [8]. As can be seen from that figure, higher wavelength shifts, and consequently higher sensitivities, are obtained when the external medium has a refractive index close to the refractive index of the cladding ($n_{cl} = 1.460$). To determine the specific external refractive index sensitivity for the different samples it was used (4), which curve is also depicted in *Fig*. 3 (right axis). Table III summarizes the refractive index sensitivities S (measured in nm/RIU, nanometers per refractive index units) of the LPG in the presence of different external media. As can be verified, when the refractive index is changed from 1.000 to 1.447, an increase in the refractive index sensitivity about 348 times is observed.

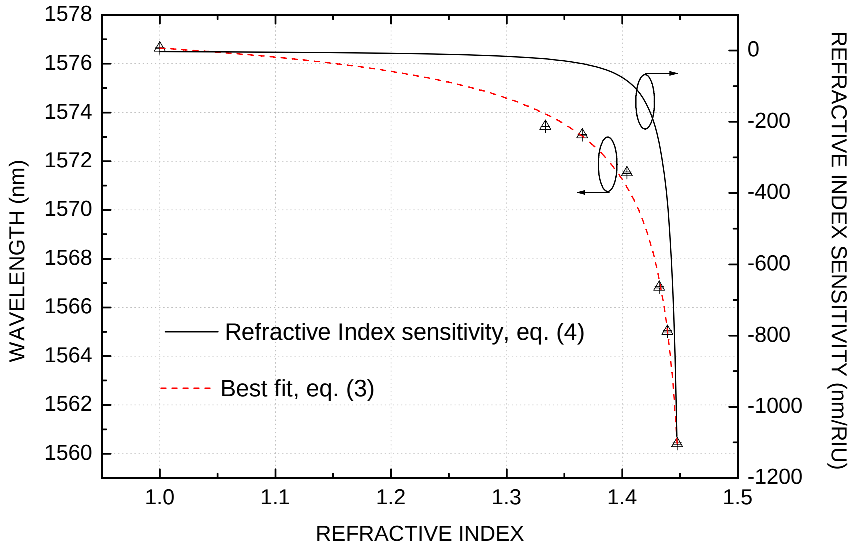

Fig. 3. Shift in the resonance wavelength (left) and the theoretical refractive index sensitivity (right) for changes in the external refractive index.

TABLE III. EXTERNAL REFRACTIVE INDEX SENSITIVITY OF THE LPG FOR DIFFERENT REFRACTIVE INDEX RANGES

Samples	Refractive index sensitivity, S (nm/RIU)
Air	-3.0 ± 0.1
Water	-22.4 ± 0.1
Ethanol	-36.5 ± 0.1
Naphtha	-84.2 ± 0.1
Thinner	-261.3 ± 0.1
Turpentine	-428.2 ± 0.1
Kerosene	-1035.6 ± 0.1

Fig. 4 shows the LPG thermal response for the four samples with the lowest indexes among the used substances. As expected, a red shift is observed when the refractive index of the sample increases. For the air, water, alcohol and naphtha an approximately linear behavior is found and a linear-regression can be used to determine the thermal sensitivities, shown in the Table IV.

For the other three samples (with the highest refractive indexes) a noticeable non-linear behavior of the thermal sensitivity is found (*Fig*. 5). Previous works [13], [14] related this non-linear behavior to the external medium thermo-optic coefficient (α_s). The observed thermal sensitivity of the LPG mainly results from the combined effects:

– The changes in the refractive index of both the core (n_{co}) and the cladding (n_{cl}^{m}) modes that result from the rearrange in the field distributions of these modes, see (5).
– The changes in the external refractive index due to the thermo-optic effect, see (5).

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– The dependence of the grating sensitivity with the external medium refractive index, see *Fig*. 3.

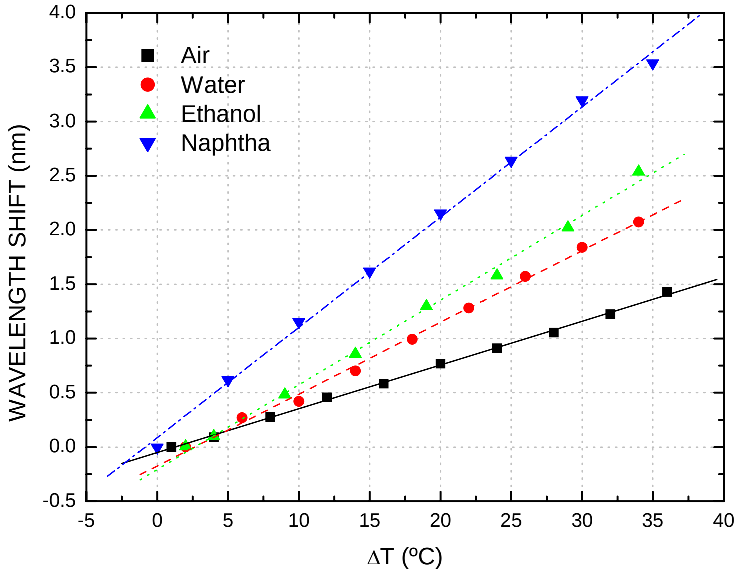

Fig. 4. LPG responses for temperature changes when the external medium is air, water, ethanol and naphtha.

TABLE IV. THERMAL SENSITIVITY FOR AIR, WATER, ALCOHOL AND NAPHTHA SAMPLES

Samples	Thermal sensitivity (nm/ºC)	Correlation coefficient, *r*
Air	0.040 ± 0.001	0.99880
Water	0.066 ± 0.001	0.99840
Ethanol	0.078 ± 0.002	0.99640
Naphtha	0.101 ± 0.002	0.99870

For the air, water and ethanol samples the grating external refractive index sensitivity (*S*) presents the lowest average values, –3.0 ± 0.1, –22.4 ± 0.1 and –36.5 ± 0.1 nm/RIU, respectively. In these cases the wavelength shift due to external refractive index changes, which results from the sample thermo-optic effect ($\alpha_s \approx -10^{-4}$ ºC^{-1}), is smaller than that one caused by the coupling thermo-optic coefficient. Consequently, a linear behavior is observed for the LPG thermal sensitivity in the presence of these samples (see *Fig*. 4). For naphtha sample the grating sensitivity assumes an intermediate value (–84.2 ± 0.1 nm/RIU). The wavelength shifts caused by the sample thermo-optic effect and by the coupling thermo-optic effect present the same magnitude order and an approximately linear behavior is still found (*Fig*. 4). When the external medium is thinner, turpentine and kerosene, the external refractive indexes are in the high sensitivity range (–261.3 ± 0.1, –428.2 ± 0.1 and –1035.6 ± 0.1 nm/RIU, respectively). As result, changes that occur in the sample refractive index, due to the sample thermo-optic effect will contribute much more to the wavelength shifts increasing the thermal sensitivities. At the same time the decrease in the sample refractive index with the temperature increase (the sample thermo-optic coefficient is negative) also causes significant

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changes in the refractive index sensitivity, witch deviates towards lower values (see *Fig*. 3). This effect will result in a smaller contribution to the thermal sensitivity as can be seen in the *Fig*. 5, and a non-linear behavior can be observed. To determine the average thermal sensitivities a linear regression is used in two ranges of temperature, 20 to 40 ºC and 45 to 60 ºC. The sensitivity values are shown in the Table V, where (a) indicates the temperature from 20 to 40 ºC and (b) from 45 to 60 ºC.

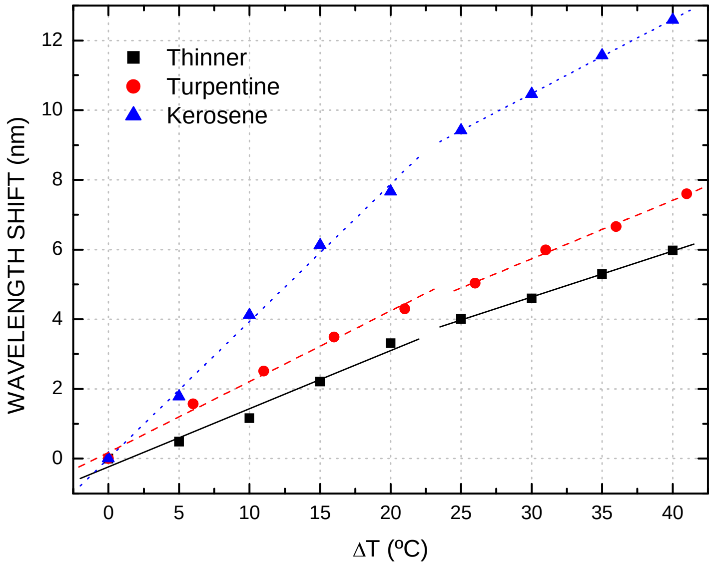

Fig. 5. LPG responses for temperature changes when the external medium is thinner, turpentine and kerosene.

TABLE V. THERMAL SENSITIVITY FOR THINNER, TURPENTINE AND KEROSENE SAMPLES

Samples	Thermal sensitivity (nm/ºC)	Correlation coefficient, *r*
Thinner (a)	0.167 ± 0.016	0.98660
Thinner (b)	0.132 ± 0.003	0.99930
Turpentine (a)	0.203 ± 0.011	0.99560
Turpentine (b)	0.168 ± 0.008	0.99780
Kerosene (a)	0.393 ± 0.014	0.99790
Kerosene (b)	0.213 ± 0.002	0.99980

IV. CONCLUSIONS

The gratings written with 2.5 cm length and 2 and 3 electrical discharges per point produced devices with attenuation losses of –23.5 dB and –31.7 dB, respectively. In contrast, the grating produced with one electrical discharge and length of 3.5 cm, presents an attenuation loss of –11.9 dB. Increasing the number of the applied electrical arcs in each point results in gratings with higher coupling coefficients what accounts for higher index modulation and attenuation losses. The higher the tension applied to the fiber during the writing process, the better the coupling coefficient of the obtained grating. Gratings produced with 20 g produced devices with attenuation losses of –2.9 dB and 3.5 cm long while gratings produced with 40 g produced devices with attenuation losses of –28.3 dB and 2.7 cm long. In these cases the increase in the coupling coefficient may have its origin in the fiber tapering [17]. Therefore, the application of 2 or 3 discharges per point or the increase in the suspended weight allows writing a LPG with smaller lengths and higher attenuation losses.

The LPG thermal sensitivity is determined when the grating is immersed in different media. The grating sensitivity is found to be 0.040 ± 0.001 nm/ºC when the external medium is the air and 0.393 ± 0.014 nm/ºC when the same grating is immersed in kerosene within the temperature range from 20 to 40 ºC. Furthermore, for samples in the high index sensitivity range (close to the cladding refractive index) a non-linear behavior is observed. As a result, two different average thermal sensitivities are obtained when the grating is immersed in thinner, turpentine and kerosene. In the case of kerosene, these two sensitivities are 0.393 ± 0.014 nm/ºC (for temperatures between 20 and 40 ºC) and 0.213 ± 0.002 nm/ºC (for temperatures between 45 and 60 ºC). If this non-linear behavior is not properly considered, the error in the measurement of the grating resonance wavelength is 3.16 nm for temperatures about 40 ºC. The presented results indicates that the non-linearity in the thermal sensitivity response is an important behavior that must be considered when a long period grating device is intended to operates as a temperature sensor in the presence of different external media, or as a refractometer working at different temperatures.

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