Long-Period Grating Thermal Sensitivity Dependence on the External Medium Refractive Index

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Abstract **— We report the thermal sensitivity dependence of long period gratings on the surroundings refractive index. For external 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, respectively. The presented results point to the important behavior that must be considered when the device is intended to operates as a temperature sensor for different external media, or as a refractometer working in different temperatures.**

Keywords **— Long period grating, optical sensor, temperature sensor, refractive index.**

I. Introdução

LPGs are formed by inducing a periodic refractive-index modulation in the core of an optical fiber. The phase-matching condition causes light from fundamental guided mode to be coupled to forward-propagating cladding modes at distinct wavelengths, given by the following relation [1]:

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

where n_{co} and n_{cl}^m represent the refractive-index of the guided mode and a LP_{0m} cladding mode, respectively. The n_{co}, n_{cl}^m and the grating period Λ can be affected due to changes in the external medium, 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 are strongly affected by fiber imperfections, micro and macro bending, and by boundary condition at the cladding-external medium interface. Thus, the light coupled from 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).

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For resonant wavelengths the transmission T though the core is [2]:

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

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

In accordance with Quin *et al* [3] the thermal sensitivity of LPG is due two factors: the thermal expansion effect and the thermo-optic effect. The thermal-expansion coefficient for silica is about 10^{-7} ºC^{-1} [4], while the thermo-optic coefficient, α, is about 10^{-5} ºC^{-1} [3]. Therefore the thermal sensitivity of LPG mainly depends on the thermal-optic coefficient given by [3]:

$$\alpha = \frac{1}{n_{co} - n_{cl}^m}\frac{\Delta\left(n_{co} - n_{cl}^m\right)}{\Delta T} \tag{3}$$

Temperature sensitivities of LPGs produced in single mode fibers are rather low, reaching only values between 0.04 and 0.1 nm/ºC [5]. Some techniques have been adopted to improve this temperature sensitivity. A significant enhanced sensitivity of 3.4 nm/ºC was achieved with a bare LPG inscribed in commercial Boron/Germanium co-doped fiber operating in the dispersion turning-point region [6]. 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 and index of refraction close to that of fiber cladding [7]. He *et al* [8] achieved a wavelength shift of 60 and 0.6 nm to temperature changes from 0 to 100 ºC, using acrylate-based polymer and silicone resin as recoating materials surround LPG, respectively. Recently Chormát *et al* [9] obtained sensitivities of 0.56 nm/ºC for the bare LPG fabricated in a graded-index optical fiber and 0.86 nm/ºC when the same grating is recoated with a polymer layer. In these works the temperature sensitivity change was obtained by properly doping the fiber core, by altering the fiber structure and geometry and by coating the LPG with a polymer layer or surround it with a temperature-sensitive liquid.

In this work long period gratings were produced by the use of a point-by-point writing method, applying on a bare fiber an electrical arc discharge from a fusion splicer. The relation between the number of discharges in each point and the coupling strength was analyzed. The LPG thermal-sensitivity when the surrounding medium changes was studied. Thermal sensitivities from 0.040 ± 0.001 nm/ºC to 0.393 ± 0.015 nm/ºC were obtained for external media with refractive indexes ranging from 1.000 to 1.447. Besides, a non-linear behavior of the LPG thermal sensitivity was observed for surrounding media with refractive index above 1.404.

II. Experimental Set-up

A. LPG fabrication

The experimental set-up used to fabricate the long period grating is the same used by Rego *et al* [10]. A bare fiber without is protective coating is placed between the electrodes of a fusion splice machine. To keep the fiber under constant longitudinal tension, a small weight is suspended in one of the fiber end while the other end is mounted on a computer controlled translation stage. An electrical arc is applied with an electric current of 12 mA during 0.5 seconds exposing a short length of the fiber. After the discharge, the translation stage displaces de fiber by a distance that represents the grating period (Λ). After a suitable number of point-by-point discharges, a periodic pattern is engraved in the refractive index profile of the fiber, because of heating activated process. The gratings spectra were recorded using an optical spectra analyzer (OSA) set to a resolution of 1.0 to 0.07 nm. The light source was provided by a LED (MRV Communications, central wavelength 1547.1 nm and half bandwidth of 54.8 nm).

Three gratings were produced modifying the number of the electric arcs applied to each point (1, 2 and 3 electric arcs). The other fabrications parameters were used to produce the LPG are: weight of 30 g and a period of 595 µm.

B. LPG characterization

To measure the temperature sensitivity, the LPG, produced with one discharge, is inserted into a specially designed glass recipient 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 sample with different refractive indexes. With the LPG inserted into the recipient, the fiber ends are immobilized to avoid fiber-bending interference on the sensor response. We characterized the thermal response of the LPG by heating the recipient, filled with one of sample, from about 20 ºC to about 55 or 60ºC in incremental steps of about 5 ºC. The used samples and their refractive indexes are: air (n = 1.000), water (n = 1.333), alcohol (n = 1.365), naphtha (n = 1.404), thinner (n = 1.432), turpentine (n = 1.439) and kerosene (n = 1.447). The refractive indexes of the samples, after being drained from the glass recipient, are measured with an Abbe refractometer.

III. Results and Discussions

The transmission losses versus grating length to the three gratings produced are shown in Fig. 1. It also shows the best fit of the analytical curve given by (2). The parameters of LPG are shown in Table I. The application of 2 or 3 electric arcs in the same point increase the refractive index modulation. As result gratings produced have a better coupling strength and the number of period necessary to achieve the maximum coupling is smaller.

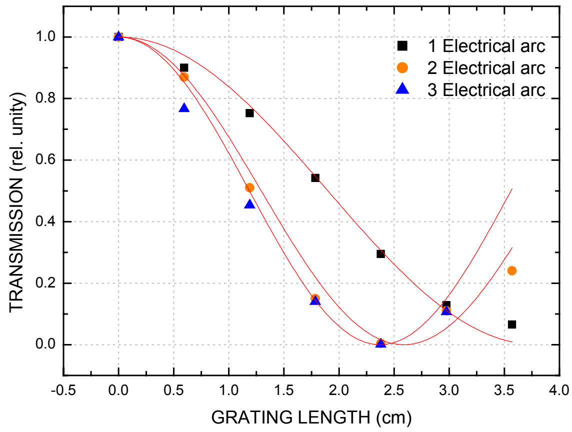

Fig 1. Transmission loss versus grating length to the gratings produced with 1, 2 and 3 electric arcs applied.

TABLE I. Parameters of the gratings produced

Electric arc numbers	Coupling coefficient (*D*)	Transmission Loss	Correlation Coefficient *r*
1	0.82740 ± 0.01739	-11.9 dB	0.99305
2	1.21388 ± 0.02545	-23.5 dB	0.98204
3	1.32384 ± 0.03394	-31.7 dB	0.98620

The LPG response to medium with different external refractive index is shown in Fig. 2. With these data the average external refractive index sensitivity was calculate in the 3 ranges. The first from 1.000 (air) to 1.365 (alcohol), the second from 1.365 (alcohol) to 1.432 (thinner) and the last one from 1.432 (thinner) to 1.447 (kerosene). The values obtained was –10.30, -92.53 and –510.66 nm/RIU (refractive index unity), respectively.

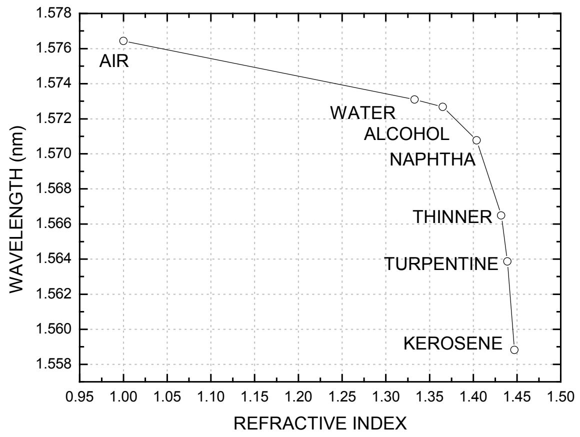

Fig. 2. Response of resonance wavelength with external refractive index.

Fig. 3 shows the thermal responses of the LPG dip to different samples. As expected a red shift is observed when the temperature increases. Além disso, o aumento no índice de refração causa um aumento na sensibilidade térmica. To the air, water, alcohol and naphtha an approximately linear behavior was found and a linear-regression was used to determine the sensitivity. The sensitivity values are shown in the Table II.

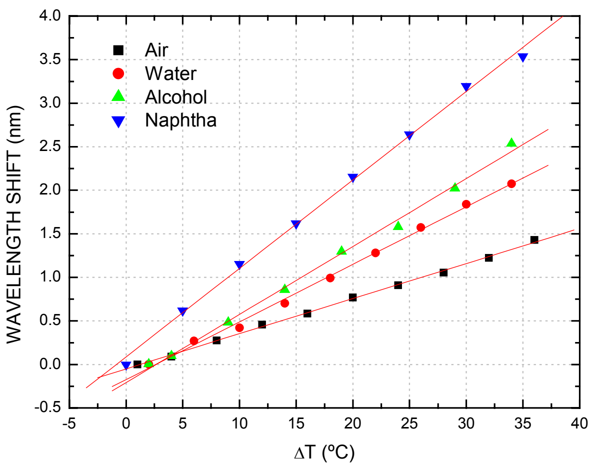

Fig. 3. Responses of the wavelength to temperature when the external mediums are air, water, alcohol and naphtha.

TABLE II. THERMAL SENSITIVITY TO AIR, WATER , ALCOHOL AND NAPHTHA EXTERNAL MEDIUM

Samples	Thermal sensitivity (nm/ºC)	Correlation Coefficient *r*
Air	0.040 ± 0.001	0.9988
Water	0.066 ± 0.002	0.9984
Alcohol	0.078 ± 0.002	0.9964
Naphtha	0.102 ± 0.002	0.99873

To the other ones a non-linear behavior was found Fig. 4. Same authors [7,8] have reported this non-linear temperature sensitivity; is due the thermo-optic effect of the medium (α_s) causes an external refractive index variation. This change contributes with the wavelength shift. In the case of the air, water, alcohol this effect can be ignored because these sample are in the low sensitivity range. In this situation the wavelength shift due refractive index changes is two or three magnitude order smaller than the ones caused by temperature changes. To the case of naphtha the external refractive index is between high and low sensitivity range and the wavelength shift caused by changes in this parameter and the ones caused by the temperature changes are the same magnitude order, but an approximately linear behavior still was found. It's happens because variations in the refractive index due temperature changes not cause greater modifications in the refractive index sensitivities. In the cases where the external medium is thinner, turpentine and kerosene the external refractive index is in the high sensitivity range. These sensitivities have a greater contribution with the wavelength shift when the refractive index varies due temperature changes. A linear regression was used in two ranges of temperature, 20 to 40 °C and 45 to 60 °C, to determine the thermal sensitivities. The sensitivity values are showed in Table II, where (a) indicate the temperature range from 20 to 40 °C and (b) from 45 to 60 °C. The increase of the temperature causes a refractive index decrease and the wavelength shifts due the variation of this parameter are smaller. This effect causes a decrease in the wavelength shift due the temperature increase.

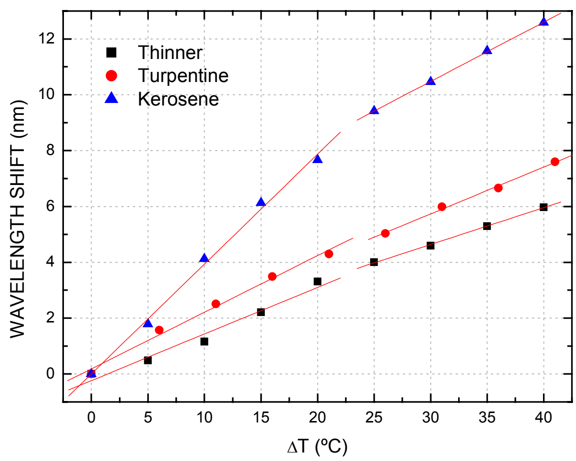

Fig. 4. Responses of the wavelength to temperature when the external mediums are thinner, turpentine and kerosene.

One of the contribution to the thermal sensitivity enhanced observed with the external refractive index could be explained by the thermo-optics coefficient dependence with the external refractive index, as observed in (3). In (3) n_{cl}^{m}

depends on the external refractive index. And another contribution is due the refractive index variation resulted of the thermo-optics effect of external medium.

TABLE III. THERMAL SENSITIVITY TO THINNER, TURPENTINE AND KEROSENE EXTERNAL MEDIUM.

Samples	Thermal sensitivity (nm/ºC)	Correlation Coefficient *r*
Thinner (a)	0.167 ± 0.016	0.9866
Thinner (b)	0.132 ± 0.003	0.9993
Turpentine (a)	0.203 ± 0.011	0.9956
Turpentine (b)	0.168 ± 0.008	0.9978
Kerosene (a)	0.393 ± 0.015	0.9979
Kerosene (b)	0.213 ± 0.002	0.9998

IV. CONCLUSIONS

The increase of electric discharge applications in each point results in gratings with better coupling strength. This effect is due to higher index modulations on the fiber exposed to electrical discharge local. The gratings produced with 2 and 3 electrical discharges achieved the maximum coupling of -23.5 and –31.7 dB, respectively, with about 2.5 cm grating length. In contrast with this results, the grating produced with one electrical discharge and grating length of 3.5 cm, has the maximum coupling (-11.9 dB). Therefore, technique allows fabricating LPG with small size length and high amplitude loss at the resonant wavelength.

Temperature sensing experiments with LPG written in a single mode optical fiber were done. The LPG response was analyzed when the grating is immersed in different mediums. The results show that the LPG thermal sensitivity can be 0.040 ± 0.001 nm/ºC when the external medium is air and 0.393 ± 0.002 nm/ºC (approximately ten times greater), when the same grating is immersed in kerosene. Furthermore, samples in the high index sensitivity range a non-linear behavior was observed. Furthermore, samples with refractive indexes close to cladding refractive index presented a non-linear behavior when temperature is increased. In fact, the some external medium can produced two different thermal sensitivities since for temperature ranges from 20 to 40 ºC and 25 to 60 ºC, the obtained thermal sensitivities for kerosene are 0.213 ± 0.002 and 0.393 ± 0.002, respectively.

These results shows that for measurements of refractive index where temperature variations are compensated by another grating [11, 12] it is essential analyze carefully thermal sensitivity dependence on external medium. Another important aspect is the thermal sensitivity change with temperature increase when the same external medium is used. For external mediums with high refractive index this effect can cause wrong interpretations when LPG are used for refractometer purposes [13, 14].

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