Influence of External Medium Refractive Index on the Waveguide Dispersion Factor and Thermo-Optic Coefficient of Cascaded Long-Period Gratings

Ricardo C. Kamikawachi, Gustavo R. C. Possetti, Márcia Muller and José L. Fabris
Federal University of Technology-Paraná, Av. Sete de Setembro, 3165, 80.230-901, Curitiba-PR, Brazil
canute@cpgei.cefetpr.br

Abstract: We report the thermal sensitivity dependence of a cascaded long period grating on the external medium refractive index. The device thermal sensitivity, waveguide dispersion factor and thermo-optic coefficient in the presence or air, water and alcohol are obtained. Changes in the thermo-optic coefficient due variations in the external refractive index are the main cause of changes in the thermal sensitivity.

OCIS codes: (060.2370) Fiber optic sensor and (060.2310) Fiber optic;

1. Introduction

Long period gratings (LPGs) are formed by inducing a periodic refractive-index modulation in the core of an optical fiber with long spatial periods (50-700 μm). The LPG transmission spectrum shows distinct resonant loss bands that result from the coupling of the fundamental core mode (LP_{01}) to the forward-propagating cladding modes (LP_{0m}). The resonant wavelengths λ^m of an LPG with period Λ are determined by the phase matching condition [1]:

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

where n_{co} and n_{cl}^m are the effective indexes of the core guided mode and the *m*-th 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 result, the coupling wavelength (λ^m) experiences a shift that can be used to measure the parameter being changed. Two LPG can be cascaded to perform a device similar to a Mach-Zehnder interferometer [2]. A first grating induces the coupling of the power propagating in the core mode to the cladding modes. The second grating re-couples the light in the cladding modes to the core mode at each resonance and an interference pattern is observed. The light propagation in the core and the cladding of the fiber along the length separating the two gratings will result in a phase-shift. The phase shift is wavelength dependent and the transmission spectrum is characterized by several narrow-dips. One cascaded LPG can be performed by the deposit of a layer of silver in one of the extremities that contain only one LPG [3]. Figure 1 illustrates the cascaded long period grating (CLPG) besides the related parameters. The thermal sensitivity of a LPG is given by [4]:

$$\frac{d\lambda^m}{dT} = \gamma(\alpha + \beta)\lambda^m \tag{2}$$

where α is the thermal-expansion coefficient of the fiber, β is the thermo-optic coefficient and γ is the waveguide dispersion factor. For a silica-based fiber, α (about 10^{-7} ºC^{-1}) [5] is much smaller than β (about 10^{-5} °C^{-1}), and can be neglected. Therefore the thermal sensitivity of LPG depends on the coupling thermo-optic coefficient given by [6]:

$$\beta = \frac{1}{n_{co} - n_{cl}^m}\left[\frac{\partial\left(n_{co} - n_{cl}^m\right)}{\partial T}\right] \tag{3}$$

The waveguide dispersion factor of a LPG is given by the following expression [6]:

$$\gamma = \left\{1 - \Lambda\left[\frac{\partial\left(n_{co} - n_{cl}^{m}\right)}{\partial\lambda}\right]\right\}^{-1} \tag{4}$$

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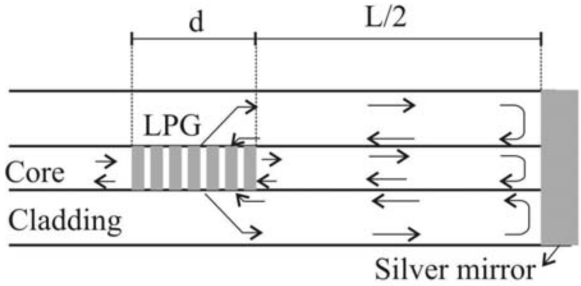

Fig. 1. Schematic diagram of CLPG.

and the distance between the fringes in the interference pattern is dependent on the waveguide dispersion factor [6]:

$$\Delta\lambda = \frac{|\gamma|\lambda\Lambda}{L + (4/\pi)d} \tag{5}$$

Using the above equation, the temperature sensitivity of the cascaded long period grating can be found [6]:

$$\frac{d\lambda^{m}}{dT} = \gamma\beta\lambda^{m}\frac{L_1}{\left[L + (4/\pi)d\right]} \tag{6}$$

where the thermal expansion effect is omitted and L_1 represents the length of the cascaded LPG.

A variety of LPG temperature sensors with several compositions, dimensions and structures and with different sensitivities have been reported [7].Temperature sensitivities of LPGs produced in single mode fibers are rather low, reaching only values between 0.04 and 0.1 nm/ºC [8]. Some techniques have been adopted to improve this temperature sensitivity. 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 refractive index close to the fiber cladding one [9]. He *et al* [10] measured wavelength shifts of 60 nm and 0.6 nm within the temperature range of 0 ºC to 100 ºC, using acrylate-based polymer and silicone resin as recoating materials on the LPG, respectively. Recently, Chormát *et al* [11] 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 is recoated with a polymer layer.

In this work the thermal behavior of a CLPG in different external media is investigated. The changes in the waveguide dispersion factor and in the thermo-optic coefficient are measured, and its influence in the thermal sensitivity is analyzed.

2. Experimental set-up

The long period grating is produced using a technique similar to that described by Rego *et al* [12]. A bare fiber without its protective coating is inserted between the electrodes of a fusion splice machine. A small weight is suspended in one of the fiber's extremities to keep a constant longitudinal tension. The other extremity of the fiber is mounted on a computer controlled translation stage. The fusion splicer arc parameters used in the writing process are a current of 12 mA and fusing time of 0.5 s. Three electrical arcs are applied in each point to increase the index modulation. After the discharges, the fiber is moved by the required period of the grating, before the application of other electrical arcs. After a suitable number of point-to-point discharges, a periodic pattern is engraved in the refractive index profile of the fiber, because of heating activated processes. After this, one fiber extremity far away 1 cm of the LPG is coated with a silver mirror, obtained by the reaction:

$$RCHO_{(aq)} + 2Ag(NH_3)_2OH_{(aq)} \rightarrow RCO_2NH_{4(aq)} + 3NH_{3(aq)} + H_2O_{(l)} + Ag_{(s)} \tag{7}$$

To produce the mirror, a length approximately 2 mm long of the fiber extremity is kept into the solution during 10 minutes.

The monitoring optoelectronic set-up uses a broadband superluminescent LED operating at 1547.1 nm with 54.8 nm FWHM (full width half maximum), a directional 3 dB coupler to collect the reflected spectrum from the sensor and an OSA (Anritsu MS9710B), set to a resolution in the range between 0.07 nm to 0.1 nm with ±5 pm of wavelength stability.

To measure the LPG dispersion factor and thermo-optic coefficient, the grating is inserted into a glass container filled with one of the used samples. The container is heated up within the temperature range from 29 ºC to 40 ºC in incremental steps of about 1 ºC. In the experiments are used samples of air (n = 1.000), water (n = 1.333) and alcohol (n = 1.365). The refractive indexes of the samples are measured by an Abbe refractometer.

3. Results and Discussion

The CLPG is performed using a LPG with pitch of 595 μm and 20 interaction points and attenuation loss about −3 dB at 1509.36 nm produced in a SMF fiber. The LPG and CLPG spectra are shown in the figure 2, when the external medium was air. The CLPG spectrum shows four fringes in the range from 1450 nm to 1625 nm. The high insertion loss, about −8 dB, is due to losses in the coupler used and in the CLPG mirror. The absolute values of waveguide dispersion factor (γ) are calculated for each sample, with the help of equation (5) and the average measured distance between the interference fringes. The thermal response of the CLPG fringe centered in 1537 nm is shown in figure 3 to the different samples.

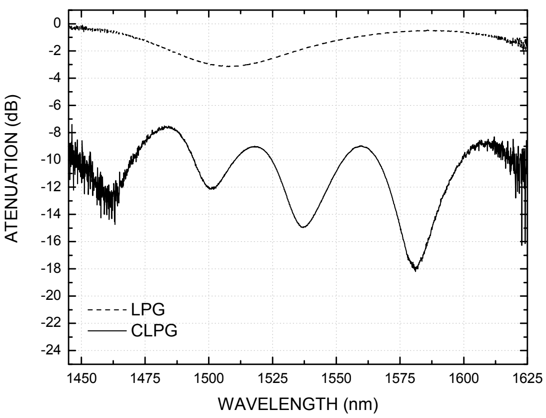

Fig. 2. The spectra of LPG and CLPG.

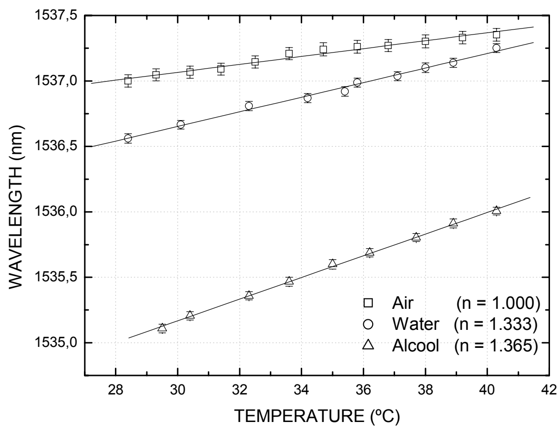

Fig. 3. Response to temperature changes of the 1537 nm fringe when the external medium was air, water and alcohol.

As expected, a red shift in the fringe position is observed when the temperature increases. Besides, the thermal sensitivity rises as the refractive index of the used sample increases. A linear-fit is used to determine the thermal sensitivities, and by using equation (2) the thermo-optic coefficient is calculated to each external medium. Table I shows the measured $\Delta\lambda$ and thermal sensitivity, besides the calculated values of dispersion factor γ and thermo-optic coefficient.

Table I – Experimental and calculated parameters of the CLPG for different external medium

External medium	$\Delta\lambda(nm)$	γ	$d\lambda/dT$ (nm ºC $^{-1}$)	β (10^{-5} ºC $^{-1}$)
Air	40.30 ± 0.01	1.68 ± 0.02	0.030 ± 0.004	0.97 ± 0.28
Water	40.04 ± 0.01	1.67 ± 0.02	0.056 ± 0.003	1.82 ± 0.27
Alcohol	40.03 ± 0.01	1.67 ± 0.02	0.083 ± 0.002	2.70 ± 0.27

During the fabrication process a red shift is observed and the sign of γ is positive [13]. The distance between the fringes and consequently the waveguide dispersion factor (γ) present approximately the same value in the presence of the 3 different samples. However, the thermo-optic coefficient (β) and the thermal sensitivity increase with the external medium refractive index.

4. Conclusions

The CLPG thermal sensitivity is determined when the grating is immersed in three different media air, water and alcohol. For each external medium the CLPG showed a different sensitivity. The waveguide factor and thermo-optic coefficient is calculated for these media. Small changes in the external refractive index (from 1.333 to 1.365) cause changes in the thermal sensitivity from 0.056 ± 0.003 to 0.083 ± 0.003 nm/ºC and in the thermo-optic coefficient from 1.82 ± 0.27 to 2.70 ± 0.27 $ºC^{-1}$, while the waveguide dispersion factor present approximately the same value. This behavior indicates that the observed changes in the thermal sensitivity in the presence of different external media are mainly due to the thermo-optic coefficient. The thermo-optic coefficient increases with the external refractive index as indicated in equation (3). As result, a thermal sensitivity tuning can be obtained by changing the external refractive index. Besides, when the CLPG is employed as a refractive index sensor, this behavior must be considered in the measured values in the presence of temperature changes.

5. References

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