Temperature influence of an air-conditioner in refractive index measurements using long-period fiber gratings

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ABSTRACT

The influence of temperature in the measurements of surrounding refractive index using long-period fiber gratings is studied for room temperature variations. For temperature changes close to 2 ºC it is verified wavelength shifts lower than 0.1 nm for the grating immersed in air and as high as 1.1 nm for a hydrocarbon sample whose refractive index is 1.4530. Sensitivity evaluations of long-period fiber gratings and evanescent fiber sensors require a temperature system control that keeps the temperature constant. Otherwise, it should be considered compensation systems that consider not only the temperature changes but also the refractive index and the thermal-optical coefficient of the materials under analysis.

Keywords: long-period gratings, optical fiber sensors, refractive index, temperature

1. INTRODUCTION

Industrial and laboratory environments often use an air conditioning system to keep their equipments close to the work temperature, or to avoid the temperature influence during experimental measurements. Since each application has different acceptable limits of room condition variations, there are different control systems of air-conditioners. Close temperature control at all times requires a more complex and expensive control system than that ones with some tolerable limits. The choice for a less expensive air-conditioning system, however, brings detriments since temperature variations could interfere with the measurands under study.

Refractive index sensors are very susceptible to temperature variations because materials alter its properties when the temperature changes and, therefore, its refractive index (RI). Evanescent fiber sensors and fiber Bragg gratings (FBG) have their refractive index sensitivity given by the evanescent core mode, which could result in brittleness and careful handling of these sensors [1]-[3]. On the other hand, long-period fiber gratings (LPFG) are optical fiber gratings with original fiber dimensions that are sensitive to surrounding refractive index due to coupling occurs between the forward propagating core mode into forward propagating cladding modes [4]. The central wavelengths of the LPFG resonance λ^m in the transmission spectrum are given by [4]:

$$\lambda^m = \left(n_{eff\_co} - n^m_{eff\_cl}\right)\Lambda \qquad (1)$$

where n_{eff_co} is the effective refractive index of fundamental fiber mode, $n^m_{eff\_cl}$ is the effective refractive index of the m–th cladding mode, and Λ is the grating pitch. The main difference between the RI sensors related before and LPFG is that the latter works with the core and cladding modes interaction. The cladding modes have their effective refractive indexes dependent on the core, cladding and external medium refractive index, whilst the core mode has its effective refractive index dependent on the fiber core and cladding refractive indexes. Chiang *et al* presented an analytical expression to determinate the LPFG resonance shift when the refractive index of the surrounding medium is changed from n_{si} to n_s [5]:

$$\Delta\lambda_0 \approx \frac{u_\infty^2 \lambda_0^3 \Lambda}{8\pi^3 n_{cl}\rho^3}\left[\frac{1}{\left(n_{cl}^2 - n_{si}^2\right)^{1/2}} - \frac{1}{\left(n_{cl}^2 - n_s^2\right)^{1/2}}\right] \qquad (2)$$

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As can be seen from equation (2), the grating refractive index sensitivity depends on the following parameters: the grating pitch Λ, the resonance position of the m-th mode at air λ_0, the m-th root of the first kind and order zero Bessel function u_∞, cladding radius ρ, and cladding refractive index n_{cl}. Although implicit, equation (2) also establishes how the grating differently responds for same variations of both temperature and refractive index, but different surrounding material refractive indexes. The closest the refractive index of the surrounding medium to $n_{cl,}$ the larger is the wavelength shift. As a result, it is expected a nonlinear behavior for LPG thermal sensitivity when the surrounding medium has refractive index ranging from 1.000 to 1.460 refractive index unit (RIU). Furthermore, studies in lower refractive index sensitivity regions or with small refractive index ranges can use a linear approximation for the temperature coefficient of surrounding medium $\partial n_s / \partial T$ and can also use simultaneous measurement techniques of temperature and refractive index to decouple these measurands [3], [6]-[7]. On the other hand, for large surrounding refractive index and temperature changes as well as for measurements with refractive indexes close to n_{cl}, one should consider the nonlinear nature of the thermal sensitivity and linear methods could not be applied.

Kamikawachi *et al* [8] have shown how temperature and strain sensitivities can be influenced by the surrounding refractive index. For the temperature case, they have proved such influence using a temperature range from about 20 to 55 ºC. In this work, we analyze the temperature influence in the RI measurements with LPFG. It is demonstrated that small temperature variations as those supplied with an air-conditioner are enough to provide a wrong interpretation of RI response of LPFG. Therefore, the RI measurements with LPFG should be carefully taken to avoid incorrect results.

2. METODOLOGY

To verify the grating responses for low temperature variations when it is immersed in different surrounding refractive indexes, we firstly have determined resolution of the two independent and automatic systems used in this work, one for temperature measurements and another for grating shift measurements. Then, we have measured the refractive index sensitivity of LPFG at 20 ºC. After that, we apply these systems, on a synchronized way, to obtain the grating responses for different surrounding RI when room temperature variation close to 2 ºC is offered with an air-conditioning system.

The system for automatic measurement of temperature can be divided in two different electronic parts. The first part is an electronic circuit that converts changes in resistance of the thermistor to direct temperature readings in volts with a resolution of 0.1 ºC [9]. The second part digitalizes the DC voltage signals by using an auxiliary input (resolution of 1 mV) of an Amplificador Lock-In DSP, model SR830 from Stanford Research Systems, and transmits these signals to a Personal Computer (PC). To perform the calibration of the temperature automatic measurement system (TAMS), we set an acquisition program, which is used to collect the signals from the lock-in equipment and to store the data in a text file, to make a standard mean of each set of 251 successive voltages values acquired from the lock-in, and then we characterize the temperature response of TAMS by heating the thermistor from 12.0 to 37.0 ºC, using a Peltier cooler with a temperature control accuracy of 0.1 ºC. The final function that relates the differences between the Peltier cooler and TAMS has been used in all data experiments. This procedure allowed that temperature values obtained with TAMS have an inaccuracy of about 0.04 ºC.

The spectrum of long-period fiber gratings is obtained by using the wavelength automatic measurement system (WAMS), which consists of a LED as a light source from MRV Communications (central wavelength of 1547.1 nm and half bandwidth of 54.8 nm), an optical spectrum analyzer (OSA) from Anritsu, model MS9710B, set to a resolution of 0.1 nm, minimum wavelength stability of ± 5 pm, and linearity of ± 20 pm, and a proper Labview Software which communicates to OSA to record the current spectrum, and then to obtain and record along time the central wavelengths of the LPFG resonance in the range under study.

Measurements of refractometer sensor characteristics have been performed in the 1550 nm range using the experimental setup described in [10] and four hydrocarbon samples (1.4303-1.453 RIU), ethanol (1.3328 RIU), and air (1.0000). After each refractive index measurement, realized at 20.0 °C, we have washed both the glass cell and the LPFG with the next sample to be analyzed. After that, the glass cell has been filled with a new amount of such a sample and the wavelength shift has been measured using the WAMS. With the fluid from the glass cell, we further measured the refractive index using an Abbe refractometer from Bausch & Lomb which woks at 589.3 nm and has a resolution of ± 0.0001 RIU. The LPFG used in the experiments has been fabricated using the electric arc-discharge technique with an electric current of 9.0 mA applied during 1.0 s, and Λ = 540 μm [11]. The resultant LPFG has a total length of 21.6 mm, central wavelength of 1555.6 nm at 19.6 ºC in air and amplitude of –6.62 dB.

To investigate the temperature influences in the refractive index measurements and to determine the thermal sensitivity of the LPFG, we have forced room temperature to change between 19.0 and 22.0 ºC with an air-conditioner. Such ascending and descending temperature variations along time have been recorded simultaneously with the TAMS and WAMS when the grating and the thermistor were simultaneously immersed in the samples related before.

3. RESULTS AND DISCUSSIONS

Figure 1(a) and (b) respectively shows the temporal evolution of temperature and LPFG wavelength for the surrounding refractive index at 20.0 °C equals to 1.0000 and to 1.4530, when the external temperature is changed from 19.0 to 22.0 °C. As can be seen, for a same temperature variation, different wavelength shifts are obtained. Furthermore, the wavelength shift is higher for the refractive index equals to 1.4530.

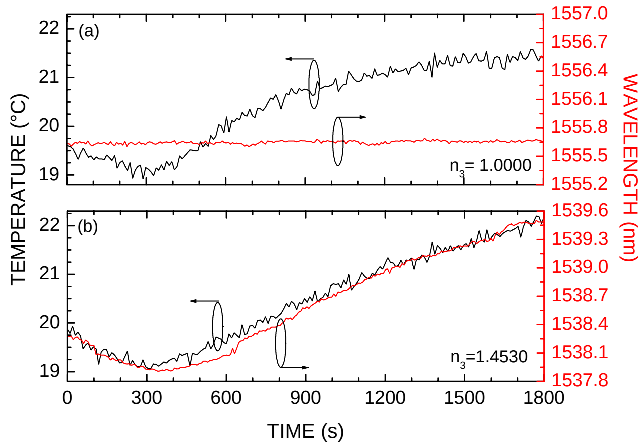

Fig. 1 – Temporal evolutions of temperature and wavelength for (a) n_s = 1.0000 and (b) n_s = 1.4530.

To analyze such RI response of LPFG with the temperature changes, the wavelength response of the LPFG for different surrounding refractive index have been measured, figure 2(a). The dotted curve fitted in figure 2(a) is the analytical expression given by equation (2) where we have fixed $\Lambda = 540\ \mu$m, $\rho = 62.5\ \mu$m and $n_{exi} = 1.0000$, and variable $u_\infty = 11.60 \pm 0.76$, $\lambda_0 = (1555.6 \pm 0.4)$ nm, and $n_{cl} = (1.4647 \pm 0.0038)$ RIU. From this result, we conclude that the characterized resonance is the cladding mode of fourth order is since the 4th Bessel root is 11.79. Figure 2(a) also shows a dashed curve representing the refractive index sensitivity (RIS), which has been obtained by numerical derivative of the analytical curve. For samples with high refractive index the RIS is greater. In this case, when the surrounding refractive index increase from 1.0000 to 1.4530 the RIS changes from 2.86 to 718.93 nm/RIU.

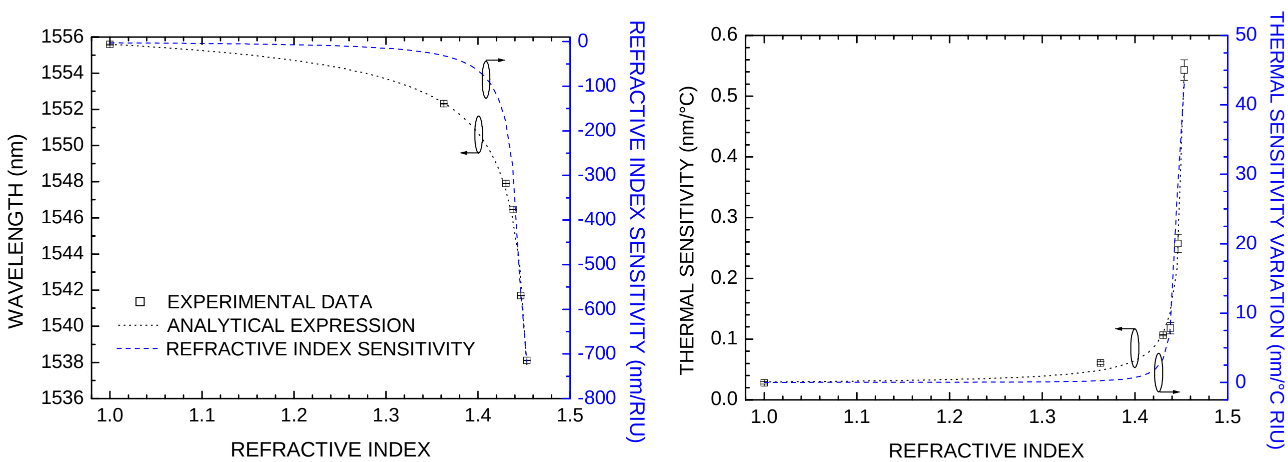

Fig. 2 – (a) LPFG responses with surrounding RI, (dotted curve) fitting result obtained from equation (2), and (dashed curve) LPFG refractive index sensitivity. (b) Thermal sensitivities obtained for air, ethanol and hydrocarbons samples and (dashed curve) temperature influence with RI. Dashed and dotted curves are just a visual guide.

In the figure 2(b) one can verify how many the influence of temperature is when the surrounding refractive index increases. Temperature variations close to 1.0 °C causes wavelength shifts from 0.03 to 0.54 nm for the refractive index range from 1.0000 to 1.4530. Such temperature influence is explained through the thermo-optic coefficient of surrounding material. Because the thermo-optic coefficient of these samples is negative, the temperature increase causes a decrease in the surrounding refractive index and then an additional and positive contribution in the wavelength shift. For that reason, the wavelength shift for the same temperature variation is more significant for refractive index above 1.42 RIU since in this range the RIS is greater, see figure 2(a). To better characterize the temperature influences, we have made a numerical derivative of the thermal sensitivity curve with respect to RI, dashed curve in figure 2(b). In fact, the high slope of the thermal sensitivity variation indicates that a nonlinear wavelength shift is expected for temperatures changes in the range of the refractive index higher than 1.43 RIU. As a result, the refractometer based on LPFG is very sensitive to the surrounding temperature. This means that the use of LPFG for this purpose must be carefully though in both air-conditioning environment and field applications where temperature changes are higher than 0.5 °C.

4. CONCLUSIONS

We show that refractive index measurements with LPFG can be strongly influenced by surrounding temperature changes. The refractive index region where temperature changes are more critical is that one where the refractive index sensitivity is greater. Wavelength shifts as high as 0.54 nm have been obtained for a temperature change close to 1.0 °C for a refractive index of 1.4530. These results indicate that measurements with LPG or with any sensor based on evanescent wave should be made with a close temperature control or than this temperature influences must be characterized with before with materials which one intend to use with the sensor. Another way that could solve this problem is by using such temperature influence to characterize materials with different compositions.

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