Simultaneous Measurement of Humidity and Temperature Based on an SiO_2-Nanospheres Film Deposited on a Long-Period Grating In-Line With a Fiber Bragg Grating

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***Abstract*—A novel configuration able to measure simultaneously relative humidity and temperature is proposed. The sensing head is based on a long-period fiber grating (LPG) coated with silica nanospheres in-line with a fiber Bragg grating. The polymeric overlay that changes its optical properties when exposed to different humidity levels is deposited onto the LPG using the electrostatic self-assembly technique (ESA), resulting into a humidity-induced shift of the resonance wavelength of the LPG. Considering the humidity range from 20% to 50% RH, a system resolution of 1.6% RH and 2.5 °C was achieved. At higher humidity, from 50% to 80% RH, the corresponding resolution values were 2.4% RH and 0.4 °C.**

***Index Terms*—Electrostatic self-assembly (ESA), fiber Bragg grating (FBG), fiber sensors, humidity sensor, long-period grating (LPG), nanospheres, simultaneous measurement.**

I. Introduction

The simultaneous measurement of humidity and temperature is a critical issue in several areas such as medical or industrial food processing. In some of these applications, in which small size and electromagnetic noise immunity are required, optical fiber sensors have advantages over the conventional electronic ones due to their electromagnetic immunity. Moreover, due to their reduced dimensions, specific environments that require small-size sensors can also benefit from reliable optical fiber humidity sensors. Many different types of optical fiber sensors have been proposed to measure temperature, and several others have been also demonstrated to measure humidity [1], [2]. Different sensing fiber designs, such as hollow core fibers, tapered optical fibers, side-polished fibers, U-bend fiber structures, and fiber Fabry-Pérot cavities, have been reported for humidity measurement based on refractive index change of the external medium [3]–[6]. Also, different kinds of long-period fiber gratings (LPGs) [7], [8] have been exploited as humidity-sensing transducers due to their high sensitivity to the surrounding medium.

In previous works, humidity sensors based on polymeric overlays have been developed [9], [10]. However, some of them exhibit modest performance in terms of sensitivity and time response. Additionally, temperature cross sensitivity is quite often a problem. This scenario motivated the research of an innovative sensing head for simultaneous measurement of humidity and temperature. It consists of an LPG with a polymeric overlay incorporating silica nanospheres in-line with a fiber Bragg grating (FBG). Humidity changes give rise to a variation of the overlay refractive index that is detected through the shift of the LPG resonant peak. The sensitivity and time response can be optimized by adding an intermediate layer that increases the total effective refractive index of the sensitive coating [11], [12]. The LPG resonance is also temperature-dependent, and discrimination is effectively achieved through the extra information provided by the resonant peak of the FBG. A similar temperature-compensation configuration was already demonstrated by Patrick *et al.* [13] for simultaneous measurement of temperature and strain and by Jesus *et al.* [14] in a refractive index and temperature simultaneous measurement. The proposed sensing structure also incorporates self-referencing characteristics, providing compensation to undesirable optical losses along the system that often plague intensity-based designs.

II. Experimental

The LPG was coated with polymeric layers exploiting the electrostatic self-assembly (ESA) method [15]. In this work, the materials involved were poly(diallyidimethyl ammonium chloride) (PDDA), PolyR-478, Poly(allylamine hydrochloride (PAH), and LUDOX SM-30 SiO_2 water colloidal. In this case, the PAH and PDDA acted as polycation, and PolyR-478 and SM-30 were the anionic species. The pH value of all solutions was adjusted to 4.0 just by adding either HCl or NaOH. The LPG substrate was thoroughly cleaned by oxygen

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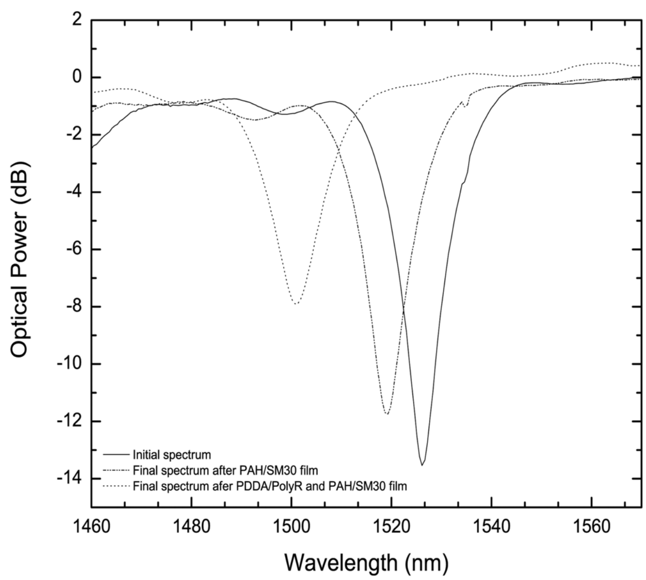

Fig. 1. LPG spectra before and after deposition of PAH/SM30 (single coating) and after deposition of PDDA/PolyR-478 + PAH/SM30 (double coating: intermediate layer and sensing coating).

plasma etching, and afterwards it was immersed into the solutions, applying the procedure further explained. The number of overlays of PDDA/PolyR-478 and PAH/SM30 was 14 in both cases, which confer a total film thickness smaller than 300 nm. Although the film thickness is difficult to measure due to the fiber geometry, in previous works [16], [17], it has been demonstrated that each layer of PDDA/PolyR-478 and PAH/SM30 had thicknesses of approximately 12 and 7 nm, respectively. Throughout all of the fabrication process and after each immersion step, a 3-min rinsing bath into gently stirred ultrapure water was carried out. All of the fabrication process was carried out using a dipping robot (R&K GmbH) in order to minimize experimental errors. The thickness overlay is chosen to ensure that the attenuation band of the LPG is located where there is good sensitivity and where it does not vanish. Two different sensing devices were tested. One consists of a single sensing coating and the other one is based on a double coating composed of an intermediate layer between the fiber and the sensing coating. As was advanced before, the introduction of an intermediate layer (PDDA/Poly-R) can enhance the sensor response because the LPG resonance is shifted to a more sensitive region, as shown in [12]. In this work, this region appears around 1500 nm, as can be seen in Fig. 1. The LPG used on the experiment performed was fabricated using the electrical-arc technique and has a length of 25 mm and a refractive index modulation period of ∼395 nm. The FBG utilized has a length of 10 mm and a Bragg wavelength of ∼1560 nm.

Fig. 2 shows the sensing head configuration and the experimental setup used to characterize it. The sensing head is composed of an FBG—sensitive to temperature—and the LPG coated with the SiO_2-nanospheres film sensitive to humidity. The combined transmission spectrum of the FBG and LPG was acquired through a broadband source and an optical spectrum analyzer. Several experiments were implemented changing the relative humidity from 20% to 80% at distinct temperatures in a range of 10 °C to 40 °C. These experiments were made using a commercial climatic chamber (Binder Climatic Test Chamber APT. Line, model MKF240). Both the range of humidity and temperature are the ones supported by this equipment.

III. Results and Discussion

Several humidity cycles were made from 20% to 80% at a constant temperature of 25 °C. The dependence of the LPG resonance wavelength on the relative humidity is depicted in Fig. 3. The wavelength shift of the peak of the LPG is represented by the solid line, and the humidity variation is represented by the dashed line. Notice that, when the humidity increases, the LPG resonance wavelength peak shifts to lower wavelengths. This effect is due to the changes accomplished in the refractive index of the SiO_2-nanospheres film. The introduction of the intermediate layer, PDDA/Poly-R film, increases the sensitivity of the sensor, as was expected and already demonstrated in previous works [11], [12].

With the purpose of studying the response time of the sensors, these were submitted to higher speed dynamic conditions of humidity and under more aggressive conditions. The experiment consists of breathing near the sensor to measure the time that it takes to sense the increase of the moisture in the environment. Fig. 4 shows the response to human breathing. This is not suitable to quantify the amount of humidity that the sensor is measuring, but is an effective way to change drastically the moisture in the environment. The sensor time response to increasing humidity is around 30 ms. The recovery time, when the relative humidity level decreases, is around 150 ms.

In order to measure the response of the sensor due to humidity and temperature changes as well, the sensor was exposed in the climatic chamber to several cycles of humidity and temperature. Figs. 5 and 6 show the evolution of the wavelength shifts of the FBG and LPG when the sensing head is subject to temperature and humidity variations, respectively.

Considering the temperature response (see Fig. 5), it can be observed that the FBG and LPG spectral resonances shift in opposite directions when temperature changes. As expected, the FBG presents a small variation when compared with the LPG. The negative slope of the temperature sensitivity of the LPG can be explained by the effect of the silica nanospheres coating (PAH/SM30). In what concerns humidity, the FBG resonance wavelength is, logically, insensitive to humidity.

As can be also seen in Fig. 6, the LPG response to humidity can be split into two fairly linear regions with different slopes, one that goes from 20% to 50% of relative humidity, while the second one extends from 50% to 80%.

The LPG and FBG spectral dependences enable the simultaneous measurement functionality of relative humidity and temperature [18]. The basis is the following equation:

$$\Delta\lambda_i = k_{Ti}\Delta T + k_{Hi}\Delta R_H, \qquad i = \mathrm{FBG, LPG}. \quad (1)$$

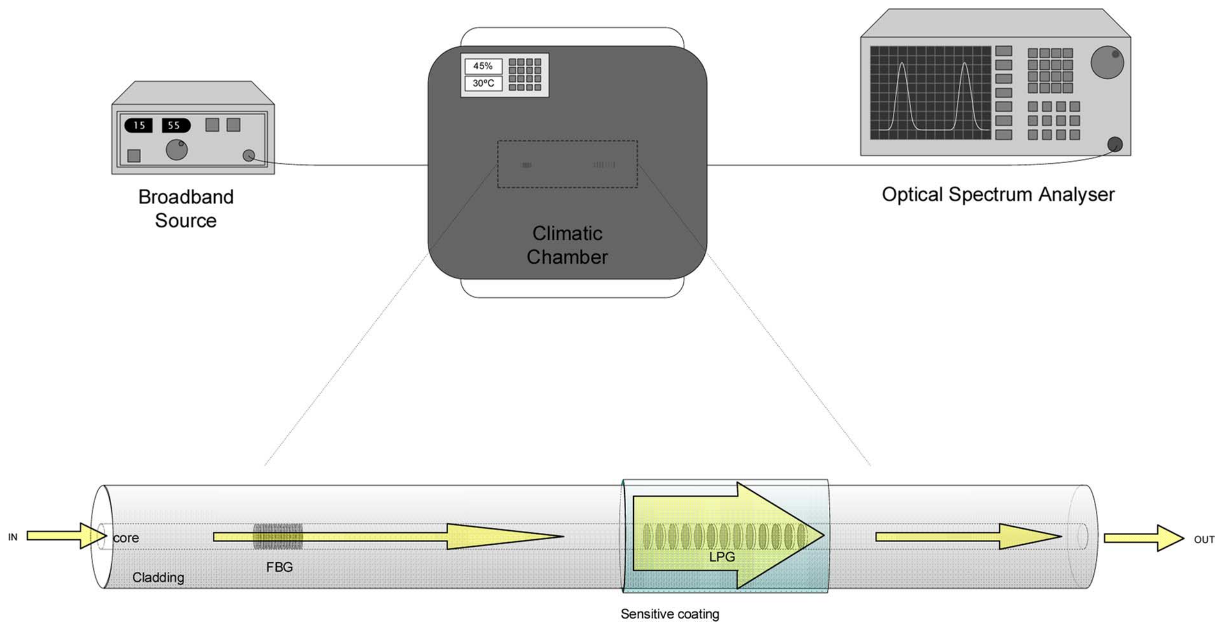

Fig. 2. Experimental setup.

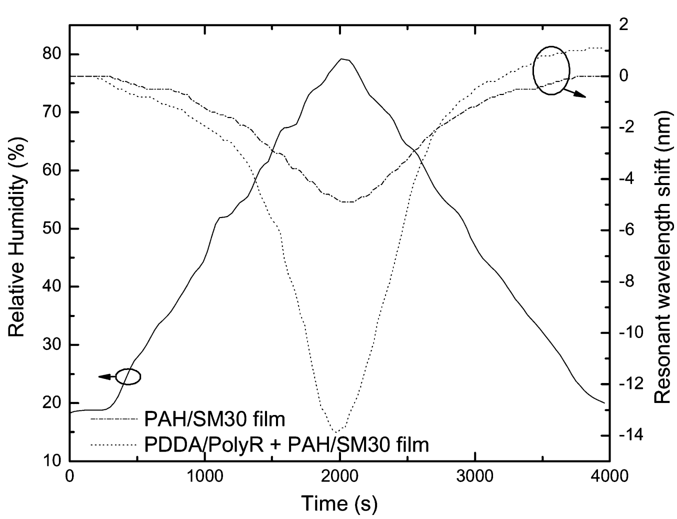

Fig. 3. LPG resonance wavelength shift for different relative humidity levels considering two films with different sensitivities.

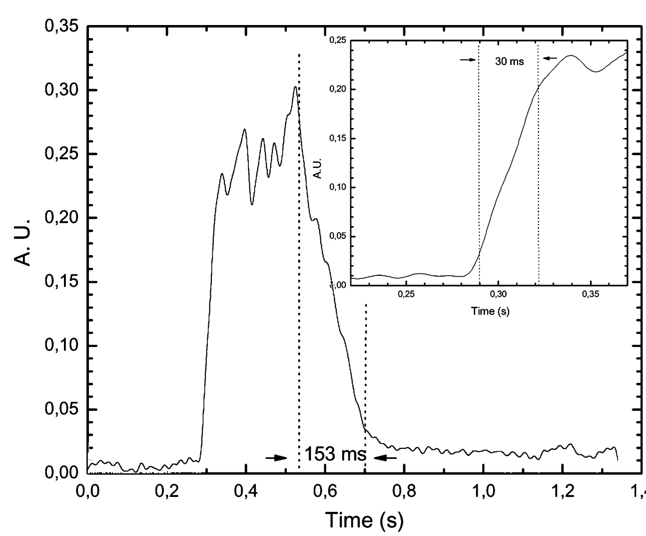

Fig. 4. Response of the sensor to human breathing.

This equation can be written in the matrical form as

$$\begin{bmatrix} \Delta\lambda_{\mathrm{FBG}} \\ \Delta\lambda_{\mathrm{LPG}} \end{bmatrix} = \begin{bmatrix} k_{\mathrm{TFBG}} & k_{\mathrm{HFBG}} \\ k_{\mathrm{TLPG}} & k_{\mathrm{HLPG}} \end{bmatrix} \begin{bmatrix} \Delta T \\ \Delta R_H \end{bmatrix} \tag{2}$$

where k_{TFBG}, k_{HFBG}, and k_{TLPG}, k_{HLPG} are the sensitivities to temperature and humidity of the FBG and LPG resonances, respectively. The temperature and humidity variations are $\Delta\mathrm{T}$ and $\Delta\mathrm{R}_H$, respectively, while $\Delta\lambda_{\mathrm{FBG}}$ and $\Delta\lambda_{\mathrm{LPG}}$ are the Bragg wavelength shift and the wavelength shift of the LPG resonance, respectively.

This equation must be specified for each of the two linear regions in Figs. 5 and 6. The corresponding coefficients are shown in the Table I.

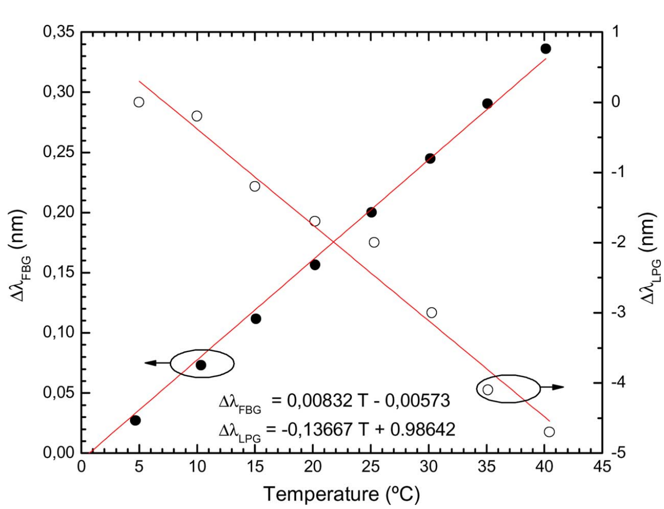

Fig. 5. LPG and FBG resonance shift with temperature variation.

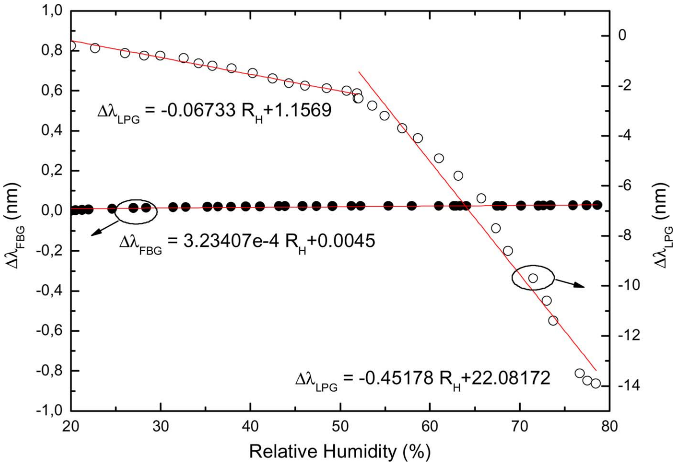

Fig. 6. LPG and FBG resonance shift with variation of the relative humidity.

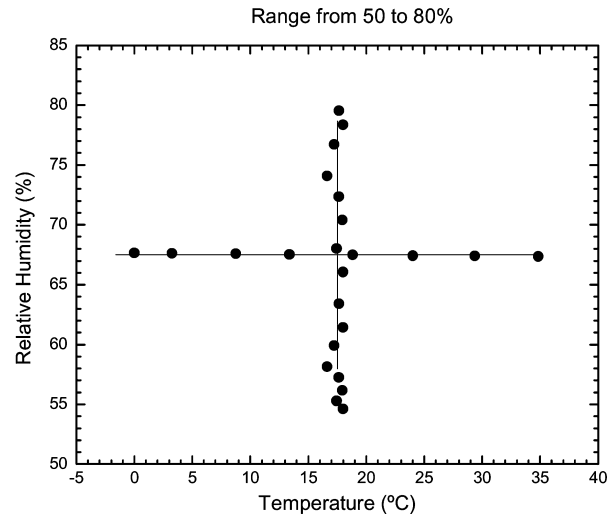

Fig. 7. Sensor output as obtained from (3) for relative humidity variation at constant temperature and for temperature variation at constant humidity level.

TABLE I
HUMIDITY AND TEMPERATURE DEPENDENCE

		Humidity range from 20% to 50%	Humidity range from 50% to 80%
Temperature Dependence	k_{TFBG}	8.32pm/ºC	8.32pm/ºC
	k_{TLPG}	-136.67 pm/ºC	-136.67 pm/ºC
Humidity Dependence	k_{HFBG}	0.32 pm/%R_H	0.32 pm/%R_H
	k_{HLPG}	-67.33 pm/%R_H	-451.78 pm/%R_H

From the previous equation, it is possible to obtain

$$\begin{bmatrix} \Delta T \\ \Delta R_H \end{bmatrix} = \frac{1}{D} \begin{bmatrix} k_{\mathrm{HLPG}} & -k_{\mathrm{HFBG}} \\ -k_{\mathrm{TLPG}} & k_{\mathrm{TFBG}} \end{bmatrix} \begin{bmatrix} \Delta\lambda_{\mathrm{FBG}} \\ \Delta\lambda_{\mathrm{LPG}} \end{bmatrix} \quad (3)$$

where $D = k_{\mathrm{TFBG}} k_{\mathrm{HLPG}} - k_{\mathrm{HFBG}} k_{\mathrm{TLPG}}$. Using the coefficients of the above table, for both humidity ranges, the dependence is written as

Humidity range from 20% to 50%

$$\begin{bmatrix} \Delta T \\ \Delta R_H \end{bmatrix} = 10^{-2} \begin{bmatrix} 13.05 & 0.06 \\ -26.48 & -1.61 \end{bmatrix} \begin{bmatrix} \Delta\lambda_B \\ \Delta\lambda_{\mathrm{LPG}} \end{bmatrix} \quad (4)$$

Humidity range from 50% to 80%

$$\begin{bmatrix} \Delta T \\ \Delta R_H \end{bmatrix} = 10^{-2} \begin{bmatrix} 12.16 & 0.01 \\ -3.68 & -0.22 \end{bmatrix} \begin{bmatrix} \Delta\lambda_B \\ \Delta\lambda_{\mathrm{LPG}} \end{bmatrix}. \quad (5)$$

The system performance was checked when the sensing head undergone relative humidity and temperature changes. Fig. 7 shows the obtained results considering the humidity range from 50% to 80%.

The spread of the obtained points from the actual measurand values indicate a system resolution of 2.4% and 0.4 °C for relative humidity and temperature, respectively. A similar procedure was implemented for the relative humidity range 20% to 50%, resulting into corresponding resolution values of 1.6% and 2.5 °C.

IV. CONCLUSION

An innovative fiber-optic sensing head based on an LPG coated with an SiO_2-nanospheres film and an FBG suitable for simultaneous measurement of humidity and temperature was demonstrated. Resolutions of 1.6% and 2.5 °C in the humidity range of 20% to 50%, and of 2.4% and 0.4 °C in the humidity range of 50%–80% were reported over a temperature variation interval close to 40 °C. The response time of the sensing head for relative humidity variation is around 30 and 150 ms for humidity increase and decrease, respectively. The performance reported indicates the potential of this fiber-optic structure for humidity/temperature measurement in a wide range of applications.

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