U.Porto Journal of Engineering, 8:3 (2022) 2-6
ISSN 2183-6493
DOI: 10.24840/2183-6493_008.003_0002

Received: 8 April, 2022
Accepted: 26 April, 2022
Published: 30 May, 2022

Long-Period Fiber Gratings Coated with Poly(ethylene glycol) as Relative Humidity Sensors

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Abstract

Relative humidity is an important parameter in controlled environments and is typically monitored using low-cost electrochemical sensors with low resolution and accuracy. This kind of sensors cannot not be implemented in harsh or explosive environments (as in pyrotechnic facilities) due to electrical discharges, or in marine structures where the oxidation of the sensing probe materials changes the sensing response). In these cases, fiber optic sensors can provide solutions due to their intrinsic properties, such as immunity to electromagnetic interference and resistance in harsh environments.

This work presents preliminary results regarding the steps of the fabrication of Long-Period Fiber Gratings, the coating processes with a thin layer of poly(ethylene glycol) (PEG) and its sensing performance to relative humidity, displaying a from 60 to 100%sensitivity of 0.6 nm/%RH in the range of 80 to 100%RH.

Author Keywords. Long-period Fiber Gratings, Relative Humidity Sensors, Optical Sensors.

Type: Research Article

1. Introduction

Long Period Fiber Gratings (LPFGs) consist of a refractive index (RI) periodic modulation of the fiber core, which can be achieved by various methods, such as femtosecond laser writing or electric arc discharges. This structure results in a rejection band along the optical spectrum, which is sensitive to changes in the surrounding environment, due to the penetration of the evanescent field in the external environment. By coupling this configuration with a relative humidity responsive polymer (that changes its RI and/or its thickness), a measurable change in the rejection band is observed, enabling the usage of the compound structure as a relative humidity sensor (Wang 2019; Wang 2006).

The effect of the polymer on the variation of the wavelength of the attenuation band (λ) is well explained by Erdogan (1997) (Equation (1)), in which the effects of thickness and RI variation are encoded in the change of the effective index of the cladding modes (n_eff^cl).

$$\lambda = (n\_eff\hat{}co - n\_eff\hat{}cl\ )\Lambda \tag{1}$$

This work presents the preliminary results regarding the fabrication and performance testing of the poly(ethylene glycol) (PEG) coated LPFGs, along with the experimental setup devised to create a controlled relative humidity environment, which may allow for further testing of other sensors and/or humidity sensitive polymers.

2. Materials and Methods

2.1. Fabrication and characterization of long-period fiber grating sensors

A set of similar LPFGs was fabricated using the setup available at the Centre for Applied Photonics – INESC TEC, through the induced electric arc discharges technique (Rego 2016) along its longitudinal axis, with real-time monitorization using a broadband light source and an Optical Spectrum Analyzer (OSA) in a transmission configuration. After this process, each fiber is coated with the polymer by horizontal dip coating with a small angle and with a constant velocity, ensuring that a uniform layer of the polymer is deposited. Different concentrations of PEG were used to produce distinct thickness polymer layers in the different LPFGs, after which their performance was analyzed.

An experimental setup (Figure 1) was devised to test the performance of the multiple sensors at high relative humidity ranges (60 to 99%RH). This setup consists of a tightly sealed plastic container connected by a valve to a humidity source (which is a separate container with air directly in contact with water) allowing the increase of internal relative humidity. Another valve connects the container to the external environment, which oscillates between 40 and 50%RH.

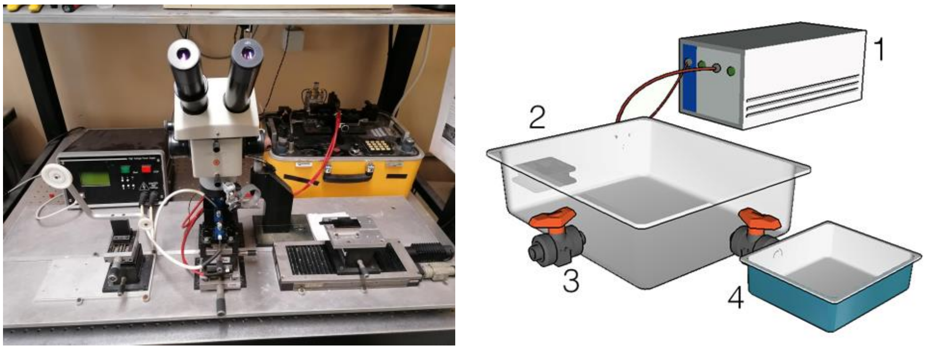

Figure 1: Left: Experimental setup for the fabrication of the LPFGs, displaying the electric-arc setup and the step motor for periodic discharges. Right: Experimental setup for the varying humidity measurements, displaying the interrogation unit (1), the controlled environment container (2) and the interrogation unit connected to the sensor, placed inside the container the external valve (3) and the water container (4)

The performance of the sensor is analyzed by placing it in the container and setting the relative humidity to the maximum value (99%RH). After this process, the valve connected to the humidity source is closed and the one connected to the external environment is opened, allowing a slow and controlled variation of the relative humidity inside the chamber in the response range of this polymer. The sensor is connected to a Braggmeter (HBM Fibersensing FS22 Braggmeter), collecting the variation in the transmission spectra with every 1%RH variation. For the monitorization of the internal relative humidity, a DHT22 (Adafruit Industries LLC, USA) capacitive sensor controlled by an Arduino was placed, updating the internal humidity and temperature values every 12 seconds with typical ±3%RH precision. The RH chamber was tested with the DHT22 sensor and it was confirmed that the container was properly sealed.

2.2. Long-period fiber grating simulations

In order to interpret the results obtained from the PEG coated LPFGs subjected to relative humidity variations, numerical simulations involving a three-layer model of LPFGs were implemented, following the theoretical work developed by Erdogan (1997). In this model, three different layers are considered, namely the core of the fiber, the cladding and an infinite external medium. Firstly, the simulations implement numerical routines that calculate the propagation constant of the core and cladding modes, respecting the boundary conditions set by the fiber geometry and the RI of the media. Secondly, the coupling coefficients between the core and various cladding modes are calculated, establishing the optical power transferred away from the core mode, creating the typical LPFG rejection bands (Figure 2). Lastly, coupled-mode theory equations are formulated, which are then simplified due to the phase-matching and co-propagating conditions imposed by the LPFG structure. This is the process by which the LPFG spectra are simulated, allowing for the variation of parameters such as the RI of the external medium.

Given the sensor performance obtained in the experimental results, the comparison with numerical simulations allows for a deeper comprehension and eventual optimization of its behavior. The used humidity responding polymer (PEG) displays a RI variation from 1.455 to 1.413 in the sodium line (Acikgoz et al. 2008). By placing these RI values in the numerical simulations, it is possible to predict the theoretical response of the LPFG under ideal conditions, and the comparison with the experimental results can be carried.

3. Discussion

The variation of the spectra for three different PEG concentrations solutions (in water) with different concentrations were analyzed, namely 50, 75 and 100% wt/wt (Figure 2). The results show that this optical device can potentially be used as a humidity sensor in the 80 to 100%RH range by tracking variations in the optical power, showing a sensitivity of 0.55dBm/%RH for the 50% wt/wt coated LPFG and in the wavelength shift showing a sensitivity of 0.6nm/%RH, which is similar to other optical sensors developed in this RH range (Wang 2019). Regarding the variations in the wavelength of the minimum of the attenuation band, a transition from guided to radiative modes was observed (Coelho et al. 2014), explaining the blueshift verified at low humidity values and rendering the wavelength shift as an unsuitable figure of merit for relative humidity measurement.

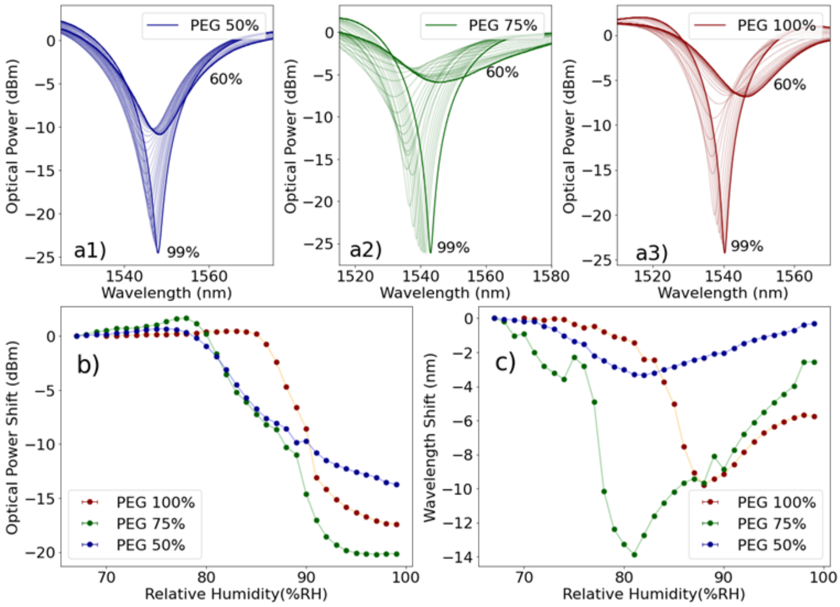

Figure 2: Variation of the spectra of the three coated LPFG sensors and their measured response: a1) PEG 50%wt/wt; a2) PEG 75%wt/wt, a3) PEG 100%wt/wt; b) Optical Power Shift response; c) Wavelength Shift Response

The wavelength shift response of the fabricated sensors can be compared with the theoretical response obtained via the numerical simulations implemented; this is displayed in Figure 3. It can be noticed in Figure 3 that there is an inverse relation between the refractive index of the external medium and the relative humidity, which is to be expected due to the fact that water absorption will decrease the polymer's RI.

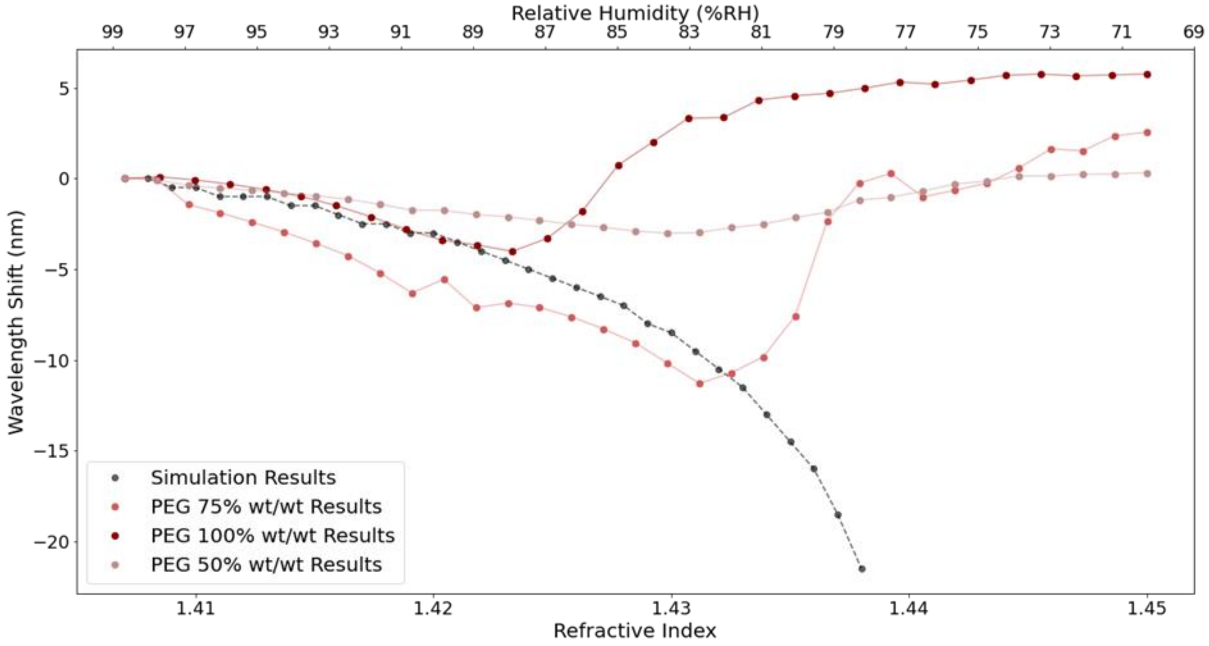

Figure 3: Comparison between the wavelength shift response of the fabricated LPFG sensors coated with PEG and the theoretical response obtained with the numerical simulations using the RI values reported in Acikgoz et al. (2008)

By analyzing the results presented in Figure 3, it is possible to verify that the theoretical results given by the simulations are in agreement with the experimental results until a specific RH value (for each concentration), in which the sensor's wavelength shift response increases. This change in the response of the sensors corresponds to the transition from guided to leaky modes with the increase of RI caused by the decrease of the relative humidity of the environment. The reason why this transition happens at lower indices (it should be seen approximately at 1.44, which is the cladding RI) is most likely due to the fact that the layer deposited on the LPFG is too thin to fully contain the evanescent field of the cladding modes, thus lowering the effective index. It can be concluded that increasing the thickness of the PEG layer (which can be achieved by coating with a more concentrated solution) will lead to a sensor performance closer to the theoretical results, which displays high sensitivity in the 80-90%RH.

4. Conclusions

The performance of a PEG coated LPFG structure was analyzed and its fabrication methods were described. These devices may be applied in high RH contexts, such as concrete curing monitoring. It was determined that the 50% wt./wt. PEG coated sensor had the best overall performance, leading to a 0.55dBm/%RH sensitivity in the 80 to 100%RH. The experimental results also determined that the variation of RI of the polymer occurs near the cladding RI, leading to an extremely sensitive behavior in a region of high humidity, but whose working range cannot yet be tuned.

By establishing a comparison with the theoretical response given by numerical LPFG simulations, it can be shown that increasing the thickness of the polymer layer will most likely lead to a better performance regarding the sensor's wavelength shift, with a working range from 80 to 100%RH but with high sensitivity in the 80 to 90%RH range.

Possible next steps in this work include the optimization of the sensor's performance and working range by studying the properties of different mixes of humidity sensitive polymers, as well as tuning the LPFG parameters such as the cladding thickness (which can be reduced by etching processes), leading to custom made sensors with maximized the sensitivity and working range.

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