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Efficient distributed moisture-ingress sensing using diamond-like carbon-nanocoated long-period gratings

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ABSTRACT

We have demonstrated the possibility of efficient distributed water ingress sensing by making use of LPGs nanocoated with diamond-like carbon (DLC). Two long-period gratings (LPGs) with different coating thicknesses were tested. A portion of each LPG was soaked and the responses were measured by tracking both the center-wavelength shift and the LPG resonance minimum depth and by simulating a two-detector sensing arrangement in combination with a diffraction grating. The responses exhibit large linear sections and thus allow for a simple distributed sensing over the grating length.

1. Introduction

Detection of moisture in a variety of structures from large civil engineering constructions to smaller aircraft is an important niche for optical fiber sensing technology. The conventional and fiber-optic sensing techniques for measuring moisture have been addressed at length in an extensive overview paper [1] and the major application areas that have been clearly outlined are construction, medicine, motor vehicles, food processing, meteorology, and semiconductor production. An important class of optical fiber humidity sensors is that of fiber grating sensors employing either fiber Bragg gratings (FBGs) [2–5] or long-period gratings (LPGs) to convert humidity changes to wavelength changes [6–12]. To increase sensitivity to water vapors, LPGs are coated with gelatin [7], polyvinyl alcohol (PVA) [8], hydrogel [9], a thin film of silicon dioxide (SiO_2) nanospheres [10] or nanolayers using the electrostatic self-assembly technique [11].

In this paper we report on the use of diamond-like carbon (DLC) nanocoated LPGs [12], which are found to exhibit a high sensitivity to moisture and are particularly suitable for moisture ingress sensing.

2. Theoretical considerations

An LPG is characterized by resonant center-wavelengths $\lambda_c^{(m)}$given as:

$$\lambda_c^{(m)} = \Delta n_{eff}^{(m)} \Lambda \tag{1}$$

where $\Delta n_{eff}^{(m)}$is the effective difference in the refractive index between the fundamental core mode and the m-th forward-propagating cladding LP_{0m} mode. A change of the surrounding refractive index (SRI) affects the $\Delta n_{eff}^{(m)}$ and causes a shift of the LPG's center-wavelength. The additional deposition of nanolayers with appropriate thicknesses and refractive indices has been shown [11,12] to increase sensitivity to changes in the SRI. In our experiments we measure the spectral responses of DLC-nanocoated LPGs [12].

If we denote the refractive indices of air and the ambient liquid by n_a and n_0, and the surfaces on the fiber grating exposed to air and the liquid by s_a and s_0, then the effective refractive index sensed by the grating can be written as:

$$n = \frac{s_a . n_a + s_0 . n_0}{s_a + s_0}. \tag{2}$$

Therefore if, due to moisture ingress or to evaporation, the relative proportions of s_a and s_0 are varied, the changes in the effective refractive index will be sensed by the nanocoated LPG.

3. Experiments and results

The experimental set-up used to measure the LPG response to water ingress is shown in Fig. 1. We use a piece of Kimwipe paper to wrap the fiber grating and thus create a blanket that can easily absorb liquids and allow evaporation to take place. When the paper blanket is soaked with a given liquid, a change in the effective refractive index occurs in the area around the grating and changes are then observed in both the center wavelength (in nm) and the transmission minimum

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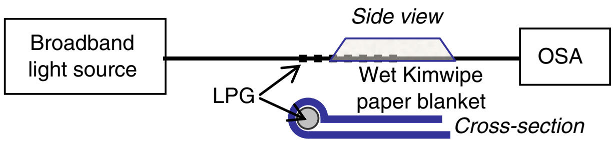

Fig.1. Experimental set-up for measuring the response to water ingress.

(in dB). To measure these quantities, we need an Optical Spectrum Analyzer (OSA) or some sort of spectrometer. However, there is another way to measure the LPG response which makes use of a diffraction grating and just two detectors spaced at an appropriate distance. The detectors measure the optical powers P_1 and P_2 over the spectral intervals $\Delta\lambda_1$ and $\Delta\lambda_2$ around two distinct center-wavelengths λ_1 and λ_2 whose values depend on the distance to the grating and its dispersion. We then can calculate the normalized differential signal as:

$$\xi = \frac{P_2 - P_1}{P_1 + P_2}. \tag{3}$$

The values of P_1 and P_2 are in absolute units and are calculated from the data as a summation over the chosen spectral intervals $\Delta\lambda_1$ and $\Delta\lambda_2$. We compare the three types of responses to water ingress – the center-wavelength shift, the transmission minimum and the normalized differential signal – for two DLC-nanocoated LPGs.

The two gratings were written in a Corning SMF28 fiber using the electric arc method [13]. With a grating period of $\Lambda = 400\ \mu m$ a resonance coming from the LP_{06} cladding mode at around $\lambda = 1460$ nm is observed. The growth of the spectral notch was monitored during the fabrication process. The gratings were cleaned in an acetone bath and then prepared for nanocoating deposition.

The nanocoatings were deposited using the radio frequency plasma assisted chemical vapor deposition (RF PACVD) process on LPGs and oxidized silicon wafers. The LPGs were kept 5 mm over the RF-biased electrode, while the silicon wafers used as a reference were placed directly on the electrode. The deposition procedure has been described in detail in [14,15]. The optical properties and thickness of the films were measured on the wafers using a Horiba Jobin-Yvon UVISEL spectroscopic ellipsometer in the spectral range of $\lambda = 250$–2050 nm following a procedure described elsewhere [15]. The refractive index (n) of the DLC films deposited on the reference samples was established to be from 2.00 to 2.07 (at $\lambda = 1460$ nm), depending on the deposition time [15]. The thickness of the film, determined by the deposition time, was 77 nm and 327 nm for deposition times of 1 and 7 min, respectively.

To take the spectral responses to moisture ingress, we cover the fiber outside the grating section with a piece of Kimwipe which we soak with water. Then we slide the moist Kimwipe paper piece along the grating and cover a section of length x with a one mm increment. The spectral response is taken at each value of x. Fig. 2 shows the spectral responses obtained from LPG S1 (18 mm in length), where the thickness and the refractive index (at $\lambda = 1460$ nm) of the DLC film on the reference sample were 181.6 nm and 2.02, respectively. From Fig. 2 we see that spectral changes are expressed in center-wavelength shifts to lower values and a decrease in the LPG depth.

Fig. 4 shows the shift in center wavelength with the Kimwipe position along the LPG, i.e., the length of the moist region for the two resonance wavelengths, 1460 nm and 1250 nm. As is evident, the center-wavelength shifts track the moisture ingress very accurately and can be used to precisely measure how deep into a given structure the moisture has advanced.

A total wavelength-shift range of 31 nm was observed for the 1460 nm resonance wavelength and of only about 16 nm for the 1250 nm resonance. This is about four times more than the 8 nm center-wavelength shift for a non-coated LPG when fully wetted as shown in Fig. 3.

Fig. 5 presents the simulated responses that can be obtained if two detectors are used over the spectral ranges shown in the shaded areas in Fig. 2. Two sub-cases are considered, namely a 10-nm and a 20-nm integration spectral range, and the responses in both cases are practically the same. Clearly, relatively wide spectral ranges can be used to sense spectral shifts with a simplified detection scheme using a low-cost diffraction grating and two detectors instead of far more costly OSAs or interrogation units based on CCD arrays.

The second DLC-nanocoated LPG S2 (43 mm in length), whose thickness and refractive index (at $\lambda = 1460$ nm) were determined to be 285 nm and 2.07, respectively, showed a different spectral response to water ingress characterized by a 2.5-nm increase in the

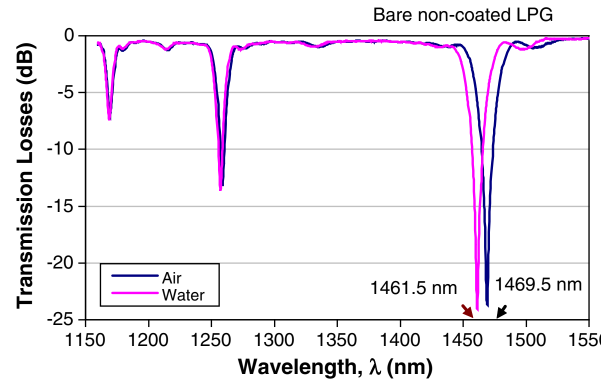

Fig. 3. Wavelength shift caused by wetting in a bare non-coated LPG.

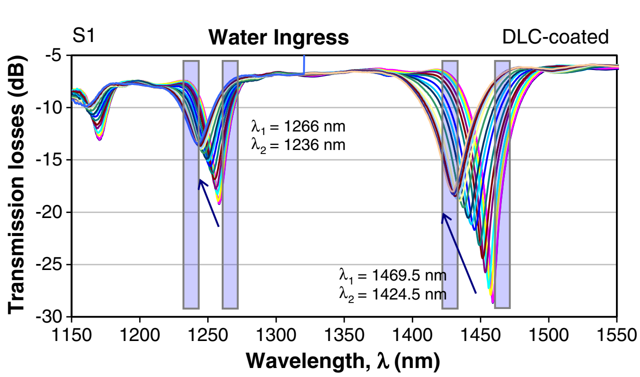

Fig. 2. Evolution of spectral responses to water ingress for DLC-nanocoated LPG S1. The observed spectral changes are center-wavelength shifts to lower values and reduction of the grating depth.

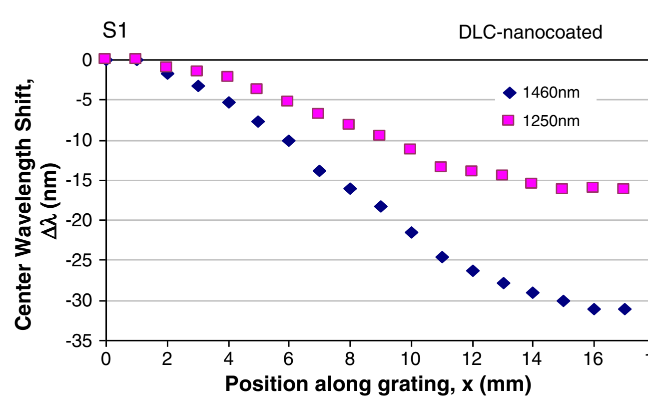

Fig. 4. Center-wavelength shifts of the two resonance minima caused by water ingress for DLC-nanocoated LPG S1.

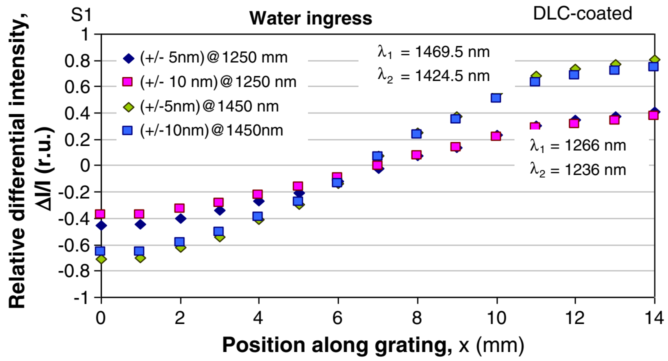

Fig. 5. Relative differential intensity changes as a function of position along grating reached by moisture for DLC-nanocoated LPG S1.

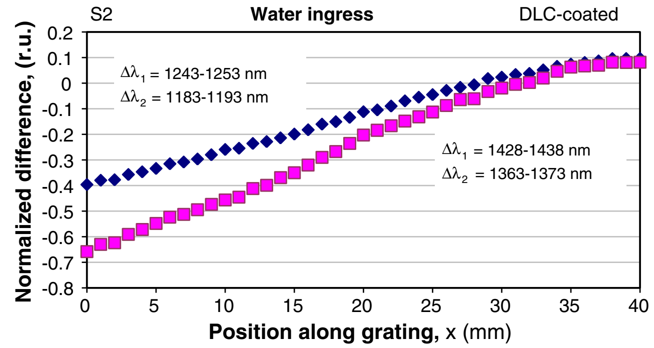

Fig. 7. Responses of DLC-nanocoated LPG S2 to the length of the LPG section covered with soaked paper blanket.

higher resonance wavelength, in contrast to the 31-nm decrease for S1, and the appearance of new resonances as shown in Fig. 6. The decrease of the resonance minimum is 7.4 dB. So we find that for all practical purposes, water ingress cannot be detected using center-wavelength tracking, while measurement of the resonance depth is still an option. In the case of LPG S2, due to the greater thickness and higher refractive index of the nano-film, one of the cladding modes starts to propagate in the film, inducing a shift of all other cladding modes to lower ones. The transition conditions can be seen in Fig. 6. Resonances previously observed at 1430 and 1250 nm reappear at 1350 and 1270 nm, respectively, with an increase in the external refractive index (water ingress). This second grating shows a different type of behavior — changes of notch depth rather than center-wavelength shifts. The reason for that type of behavior is the proportion between thickness and value of refractive index of the nanolayer. Depending on the thickness the grating's sensitivity can be fine-tuned to different RI values [16,17].

Simulation of the differential signal response based on the two-detector set-up provides a much better solution. Fig. 7 shows the simulation of the normalized differential signals obtained with two pairs of detectors in the spectral bands indicated in Fig. 6. It is clear that this LPG allows moisture ingress with an almost linear response using a simple cost-efficient two-detector scheme. Unlike a previously suggested sensor construction that detects moisture or vapor presence in a single point [13], this nanocoated LPG allows for simple and efficient distributed sensing of moisture ingress. The experiments presented here show that instead of using a pair of gratings as in [2] to sense the moisture ingress in a concrete block, just one DLC-nanocoated LPG placed along the direction of moisture penetration is sufficient not only to detect the presence of water and the direction of ingress, but to locate the leading edge of water penetration. Use of more than one such LPG placed in a sequence can easily extend the sensing length. If LPGs are installed orthogonally to each other, water ingress in a plane can be sensed. For example, three mutually orthogonal LPGs will provide information on the spatial distribution within a concrete block. A spatial resolution of 0.5 mm is readily achievable over a 35-mm LPG sensing length, giving better than 1.5% accuracy.

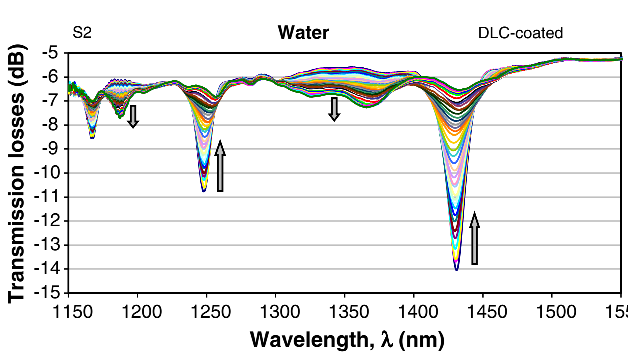

Fig. 6. Spectral responses of the second DLC-nanocoated LPG (S2) to water ingress.

4. Conclusion

In conclusion, we have demonstrated that DLC-nanocoated LPGs can successfully be used to measure the penetration depth of moisture ingress by measuring the wavelength shifts in the changing spectral distribution of the grating transmission. The spectral response of the LPGs can be successfully modified by deposition of a coating with a pre-determined thickness and refractive index. We have also shown that a simple and cost-efficient differential system based on two detectors in combination with a diffraction grating can be used to interrogate the LPG. Combinations of larger numbers of gratings can either increase the sensing length in one dimension or locate water penetration in two- or three-dimensional structures.

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