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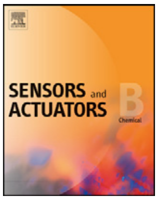

Fiber humidity sensors with high sensitivity and selectivity based on interior nanofilm-coated photonic crystal fiber long-period gratings

Shijie Zheng, Yinian Zhu*, Sridhar Krishnaswamy

Center for Quality Engineering and Failure Prevention, Northwestern University, 2137 Tech Drive, Evanston, IL 60208-3020, USA

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ABSTRACT

A photonic crystal fiber (PCF) long-period grating (LPG) humidity sensor has been developed with high sensitivity and selectivity for nondestructive detection of moisture ingression into structures that can potentially lead to corrosion. We have proposed two types of nanofilms to be coated on the surface of air channels in the grating region by electrostatic self-assembly deposition processing. The primary nanofilm does not affect LPG properties such as resonance wavelength or transmission intensity which can impact sensing characteristics; however it increases the sensitivity by changing the refractive index of the surrounding material. The secondary nanofilm is used for selectively adsorbing analyte molecules of interest. The experimental results reveal that, compared to the conventional fiber LPGs and exterior nanofilm-coated PCF-LPG, the interior nanofilm-coated PCF-LPG humidity sensors have both the most sensitive resonance intensity change of 0.00022%/10^{-3} dBm from relative humidity (RH) of 38% to 39% and average wavelength shift of 0.0007%/pm for a relative humidity variation from 22% to 29%. The proposed sensor shows excellent thermal stability as well.

1. Introduction

One of the most critical reasons for infrastructure deterioration is corrosion of reinforced concrete, in which water plays an important role for initiating and sustaining electrochemical damage. The ingress of water acts as a transporting vehicle for aggressive agents, such as chloride and sulfate ions, to be penetrated into the concrete by capillary force. Water is also a reaction medium in destructive chemical processes, causing the corrosion of the concrete rebar. In general, the concentration of water in ambient air, which is expressed by relative humidity ($RH = P_m/P_{ms} \times 100\%$, where RH stands for relative humidity; P_m is the partial pressure of moisture; and P_{ms} is the pressure of moisture in saturation), has a significant effect on the corrosion mechanism. It is therefore important to develop a sensing tool such as a humidity sensor that can be easily integrated into the structure and which enables early detection of moisture ingression within reinforced concrete structures to remediate the situation before serious damage occurs.

Fiber-optic grating refractometers have been increasingly explored for the interrogation of refractive index change of gas or aqueous solution [1], and the long-period gratings (LPGs) as optical fiber humidity sensors have also been reported for applications in structural concrete condition monitoring to determine moisture ingress [2]. In this work, we have developed a fiber-optic humidity sensor with high sensitivity and selectivity by using two types of nanofilms coated in the surface of air channels in the LPG region inscribed in a photonic crystal fiber (PCF) using an electrostatic self-assembly (ESA) deposition processing. These sensors can potentially be used for monitoring of structural health conditions through *in situ* measurements of corrosion in the concrete reinforced structures.

2. Fabrication of the nanofilm-coated PCF-LPG fiber sensors

2.1. Modes in PCF for evanescent field sensing

It is worth noting that other fiber-optic platforms have been explored for vapor phase and/or aqueous solution sensing with evanescent field of a guided light or direct laser excitation. While simple design and implementation are carried out, the schemes utilizing conventional optical fiber with its cladding or even part of its core removed (as in the case of D-shaped fiber) are typically limited by the probe length (a couple of centimeters due to potential compromise in mechanical and structural integrity) and mechanical strength [3,4]. The specific surface is also limited for evanescent field intensity–analyte interaction in such probe geometries although relatively high field intensity overlap is possible in some D-shaped fiber designs. Compared to their conventional optical fiber counterpart, PCFs are a particularly attractive sensing platform because the vapor/fluid can be entered into the air

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* Corresponding author. Tel.: +1 847 491 5527.
E-mail address: yinian-zhu@northwestern.edu (Y. Zhu).

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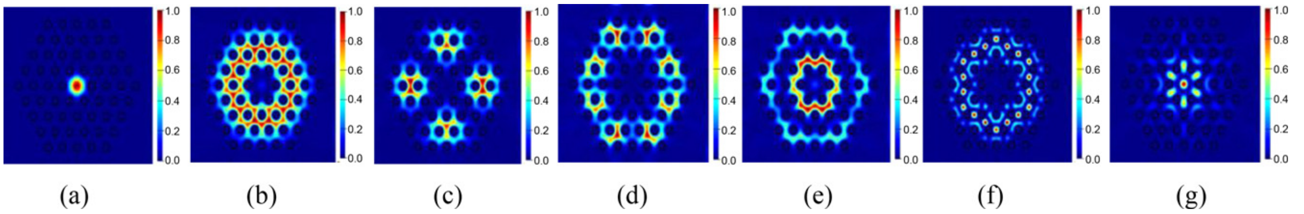

Fig. 1. Linear polarization (LP) mode field intensity distributions in a PCF with 4 rings of air-channels hexagonally arranged, calculated at wavelength of 1550 nm for: (a) LP_{01} fundamental core mode, (b) LP_{02} cladding mode, (c) one state of degeneracy in LP_{03} cladding mode, (d) LP_{04} cladding mode, (e) LP_{05} cladding mode, (f) LP_{06} cladding mode, (g) one state of degeneracy in LP_{07} cladding mode.

channels directly and, furthermore the fiber-optic characteristics can be optimized to improve sensitivity. The fundamental core mode in the PCF has been used for evanescent field sensing [5]. While this sensing modality has demonstrated its potential for sub-monolayer measurements, there exist two inherent limitations. First, the evanescent field extends only a small distance (~λ/3, λ is the operating wavelength) from the guiding core to surrounding PCF cladding air channels, restricting the analyte and light interaction region to only the innermost ring of air channels in the cladding. Secondly, the fundamental core mode is localized mostly in the PCF core and, in fact, for most designs, less than 1% power of the core mode overlap with the surrounding air channels thus providing weak light intensity–analyte interactions for spectroscopic interrogation.

Shown in Fig. 1 are the numerical simulations for the linear polarization (LP) mode field intensity distributions of a PCF LP_{01} fundamental core mode and cladding modes from LP_{02} to LP_{07} at wavelength of 1550 nm, including states of degeneracy, as shown in Fig. 1(c) and (g). As shown in Fig. 1(a) in the case of LP_{01}, the mode field overlap with air channels is limited to only 0.13% of the core mode for the traditional approach of evanescent field sensing using PCF. The overlap becomes weaker and weaker from LP_{03} to LP_{07} cladding mode (Fig. 1(c)–(g)). The LP_{02} cladding (Fig. 1(b)), however, exhibits the strongest and broadest intensity field overlap, ~4.40%. Should the LP_{02} cladding mode be selectively excited using a LPG and utilized for sensing, it would drastically enhance the sensitivity of evanescent field interaction, and this is the approach taken here.

2.2. Phase-matching condition and coupled-mode theory

A LPG couples the fundamental core mode to several co-propagating cladding modes in a single mode fiber, resulting in a sequence of attenuation resonances in the transmission spectrum. The LPG is an intrinsic and passive device that can be induced by a periodic refractive index modulation in the fiber core with a typical period of a few hundred micrometers. Four parameters in a LPG can be described as follows: $\lambda_{(i)}$, the resonance wavelength of the *i*th linear polarization cladding mode (LP_{0i}); $n_{\text{eff,core}}$ and $n_{\text{eff,clad}(i)}$, the effective indices of the fundamental core mode and the *i*th cladding mode; and $\Lambda_{(L)}$, the periodicity of the grating, and the relationship of which can be expressed by

$$\lambda_{(i)} = (n_{\text{eff,core}} - n_{\text{eff,clad}(i)})\Lambda_{(L)} \tag{1}$$

and their transmission spectra are characterized by resonance bends at wavelengths that satisfy the phase-matching condition. The LPGs in both conventional optical fibers and PCFs have been used as transducers for environmental sensing such as temperature, strain, vibration, and chemical measurements.

Coupled-mode theory can be applied to calculate the intensity of resonance in LPGs, which is determined by the coupling coefficient κ and the grating length L [6,7]. The minimum transmission is proportional to $\cos^2(\kappa L)$, while the coupling coefficient is a function of the effective index change and the mode overlap between the guided core mode and the coupled cladding mode over the region of refractive index change. The surrounding material will affect the coupling.

2.3. Fabrication of LPGs in both conventional optical fiber and PCF

The fibers which we used to inscriber LPGs are both the standard single mode optical fiber (SMF-28) and the endlessly single mode PCF (ESM-PCF, simply called as PCF). The specifications for those two types of fibers are: (1) SMF-28, the core and the cladding diameters are 8.2 μm and 125 μm, respectively; refractive index difference is 0.36%; numerical aperture is 0.14; attenuation is 0.19 dB/km at wavelength of 1550 nm, and (2) PCF, the center-to-center distance between the air channels (Λ) is 6.4 μm; the average air-channel diameter (d) is 3.1 μm; the d/Λ is 0.48. The channels are arranged in a hexagonal pattern, extending to a diameter of 65 μm. Defining the core diameter (D_{core}) as $D_{\text{core}} = \Lambda(2 - d/\Lambda)$ leads to a value of 10.4 μm. The outer diameter of the PCF matches the typical value of 125 μm for most of SMF fibers.

A melt fiber preform (both conventional fiber preform and PCF preform) is drawn into the size of a normal fiber diameter during the fiber drawing process. Tension, which is called mechanical residual stress, is accumulated in the fiber core with frozen silica in the cladding by radial variations of viscoelasticity and thermal expansion because of temperature gradient in the fiber drawing furnace. The residual stress in the fiber core influences the refractive index of that area by the photoelastic effect, and it can be released at the softening temperature of silica by a focused pulsed beam from a CO_2 laser. Periodic irradiation of CO_2 laser beams on the fiber results in the stress relaxation with the desired grating-pattern. A change of refractive index (~10^{-3} to 10^{-4}) in the core can be achieved to form the LPGs in the fiber.

Shown in Fig. 2 is the experimental setup for fabrication of LPGs. The insets of this figure are the cross-sectional optical micrograph of PCF and the outlook of PCF-LPG, respectively. The LPG fabrication system includes a CO_2 laser with a 1-D galvanometer. The laser beam is passed through a ZnSe cylindrical lens with a focal length of 198 mm, and located on the 1-D galvanometer that focuses and

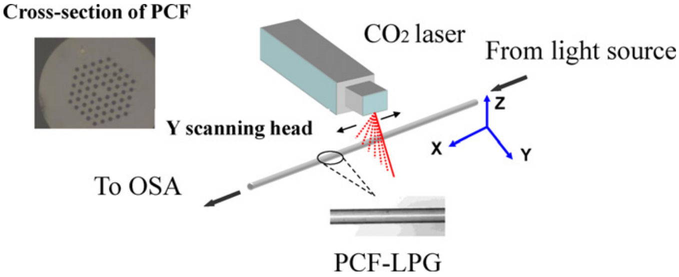

Fig. 2. Schematic diagram of experimental setup for LPG inscribed in PCF by focused beam of CO_2 laser with a 1-D galvanometer (the insets are the cross-sectional optical micrograph of PCF and the outlook of PCF-LPG).