# Optical refractometer based on large-core air-clad photonic crystal fibers

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A large-core air-clad photonic crystal fiber-based sensing structure is described, which is sensitive to refractive index. The sensing head is based on multimodal interference, and relies on a single-mode/large-core air-clad photonic crystal fiber (PCF)/single-mode fiber configuration. Using two distinct large-core air-clad PCF geometries—one for refractive index measurement and the other for temperature compensation, it was possible to implement a sensing head sensitive to refractive index changes in water as induced by temperature variations. The results indicated the high sensitivity of this sensing head to refractive index variations of water, and a resolution of $3.4 \times 10^{-5}$ refractive index units could be achieved. 

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In the past few years, multimode interference in optical fiber structures has been studied, with the aim of developing novel optical devices [1,2]. Such fiber-optic devices are usually based on a single-mode/multimode/single-mode (SMS) fiber structure and exhibit unique spectral characteristics that make them suitable for optical communications and sensing [3,4]. For instance, Wang and Farrell [5] reported a configuration of this type: by applying a numerical beam propagation method, an optimum value could be determined for the length of the multimode fiber section that makes the fiber structure feasible to operate as a refractometric sensor. For an operation wavelength of 1550 nm, this sensor presented an estimated resolution of $5.4 \times 10^{-5}$ refractive index units (RIU) for the refractive index range of 1.33–1.45. Recently, an SMS fiber structure was proposed for refractive index measurement, in which the multimode fiber branch was etched with different diameters [6]. A maximum resolution of $7.9 \times 10^{-5}$ RIU was attained for a refractive index range of 1.33–1.383.

The use of air–silica microstructured fibers for single-mode operation has earned considerable attention owing to their novel waveguide properties, which make them suitable for a large range of applications, from nonlinear effects to optical sensing [7]. Nowadays, research interests have expanded into large-core air-clad photonic crystal fibers (PCFs) due to their multimode propagation characteristics and their promising potential for laser applications [8]. In sensing applications, a Bragg grating written in the Ge-doped core of microstructured optical fibers (MOFs) has been proposed for refractive index measurement [9]. Using a two-ring triangular and a six-hole MOF, resolutions of $7 \times 10^{-4}$ RIU and $4 \times 10^{-3}$ RIU, respectively, were achieved, for a refractive index close to 1.33. Recently, Rindorf and Bang [10] reported a highly sensitive refractometer based on a long-period grating (LPG) written in a large-mode-area PCF. A maximum sensitivity of 1500 nm/RIU, at a refractive index of 1.33, was achieved with a minimum detectable refractive index change of $2 \times 10^{-5}$.

In this Letter, experimental results are presented pertaining to a large-core air-clad PCF-based sensing structure. The proposed sensing device relies on two distinct inline air-clad PCFs and is interrogated in transmission. One of the fibers, due to its large dimensions, has a ring of air holes in contact with the external medium, so it is used for refractive index measurement; the other is used as the temperature-compensation element, because the air holes are obstructed in the splice zone. A sensing head was then implemented to measure the refractive index changes in water that were induced by changes in temperature.

PCFs are generally pure silica fibers in which the refractive index contrast required to ensure guidance of light arises from the presence of air holes with a specific geometric size and arrangement rather than from using doped glasses with different refractive indices. This is an important feature, especially for large-core PCFs that are supposed to have a small index step that can be controlled only by the configuration of the air holes.

The working basis of a large-core air-clad PCF section spliced between single-mode fibers (SMFs) relies on the multimode interference principle. When the light field propagating along the input SMF enters the air-clad PCF section, high-order modes are excited, so interference between different modes occurs. Light is then coupled into the output SMF, where the coupling efficiency, for a given length of the air-clad PCF section, is wavelength-dependent. The optical power coupled out to the SMF will also depend on the amplitudes and relative phases of the various modes of the air-clad PCF at its output end. Therefore, in addition to the wavelength-dependence of the transmitted power of the air-clad PCF-based fiber structure, the sensing head also shows a spectral behavior with well-defined loss bands that are dependent on the variation of the air-clad PCF's geometry and length.

 

To demonstrate the proposed configuration, a sensing head structure was implemented as shown in Fig. 1. It consists of two inline sections of large-core air-clad PCFs, spliced between SMF-28 single-mode fibers and interrogated in transmission. In this simple approach, a broadband source (BBS) in the 1550 nm spectral range was used with a bandwidth of 100 nm and an optical spectrum analyzer (OSA) as the interrogation unit. The detail of each PCF implemented in the experiment is also depicted in Fig. 1.

Two air-clad PCFs with different dimensions were used: the air-clad $PCF_1$ had 79 $\mu$m for core and 127 $\mu$m for cladding diameter, whereas the silica core was surrounded by one ring of air holes with a ratio of hole diameter, $d$, to pitch, $\Lambda$, given by $d/\Lambda = 0.5$; the air-clad $PCF_2$ had 129.8 $\mu$m for core and 200.7 $\mu$m for cladding diameter, and the silica core was surrounded by two rings of air holes, with $d/\Lambda$ ratios of 0.54 and 0.2. Furthermore, the bridge width for the air-clad $PCF_1$ was 2.2 $\mu$m, and those for the air-clad $PCF_2$ were 5.6 $\mu$m and 3.1 $\mu$m for the outer and inner air hole rings, respectively. Because of the multimode propagation characteristics of the large-core air-clad PCFs, an optimized length was found for each air-clad PCF section, namely, 4.2 and 4.3 cm for air-clad $PCF_1$ and $PCF_2$, respectively. An important feature is that the bridge thickness had a strong dependence on the numerical aperture [11]. The distance between the air-clad PCFs was ~2 m, in order to eliminate modal interference between fibers.

Conventional splices between SMFs and air-clad $PCF_1$ were done to obstruct the air holes, in order to further use this fiber section as a temperature-compensation element. However, to ensure that the air holes of air-clad $PCF_2$ are uncollapsed, a simple splice technique was used [12]. It consisted of applying an electric arc discharge in the SMF region, with low power current (13.7 mA) and a short arc duration (300 ms).

Each air-clad PCF was characterized individually, and the corresponding optical spectra are available in Figs. 2(a) and 2(b); the transmission spectrum of the proposed sensing structure, where the two air-clad PCFs are in line and spliced between SMFs, is depicted in Fig. 2(c).

Using the aforementioned configuration, it can be observed that the optical power transmitted exhibits two wavelength loss bands (centered at $\lambda_1$ and $\lambda_2$), which, in principle, will be sensitive to different physical parameters, viz., refractive index and temperature.

The response of the sensing head to temperature variations was duly characterized, as shown in Fig. 3. The structure was placed in a tube furnace and submitted to increasing values of temperature in the range [0–100] °C, at 10 °C steps. Our results indicate that the loss bands centered at $\lambda_1$ and $\lambda_2$ have linear responses to temperature variations characterized by similar sensitivities, viz., $(10.5 \pm 0.01)$ and $(11.1 \pm 0.01)$ pm/°C for $\lambda_1$ and $\lambda_2$, respectively. This means that the temperature variation does not change the single-mode/air-clad PCF launching conditions. Instead, the length variation of both air-clad PCFs (due to thermal expansion) and the air-clad PCF core refractive index variation (due to the silica thermo-optic effect) only change the optical path length, thus causing the wavelength shift of each resonance peak.

When this sensing structure was placed in water and heated, the shift behavior of the two loss bands [Fig. 2(c)] was different, as shown in the inset in Fig. 3, unlike what happened when the sensing head was heated in air [Fig. 3]. In view of the dimensions of the air-clad $PCF_2$, the water infiltrates along the air holes, thus changing the refractive index of this region, which behaves as the cladding of the fiber, and, consequently, the effective index of the modes guided in the core. This did not happen with the air-clad $PCF_1$ because the air holes in the splice zone were obstructed. Consequently, the distinct behavior can be related to the presence of water in the holes and to the

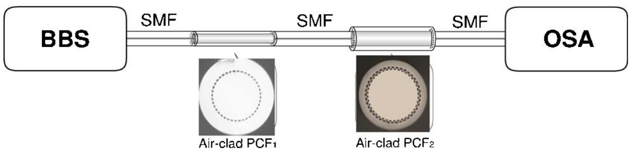

Fig. 1. (Color online) Experimental setup of the air-clad PCF-based sensing structure and detail of each PCF implemented.

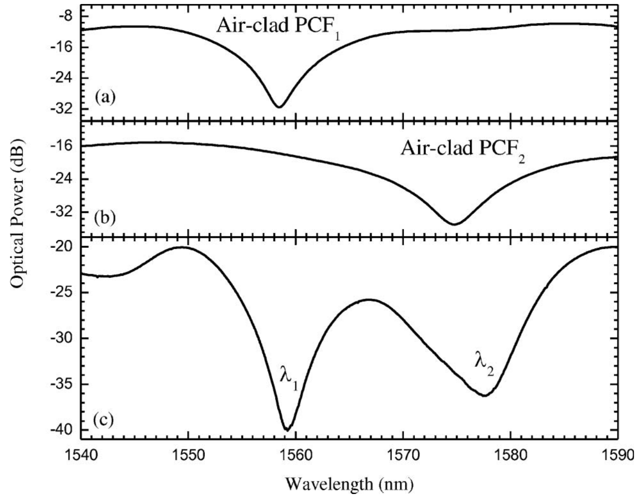

Fig. 2. Optical spectra of (a) air-clad $PCF_1$, (b) air-clad $PCF_2$ and (c) air-clad PCF-based sensing structure.

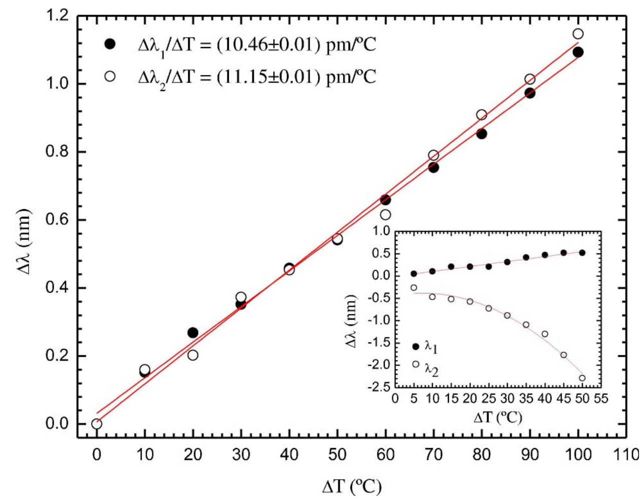

Fig. 3. (Color online) Temperature response in air of the two loss bands centered at $\lambda_1$ and $\lambda_2$, for the air-clad PCF-based sensing structure. Inset, wavelength shift of the sensing head to temperature variations of the water.

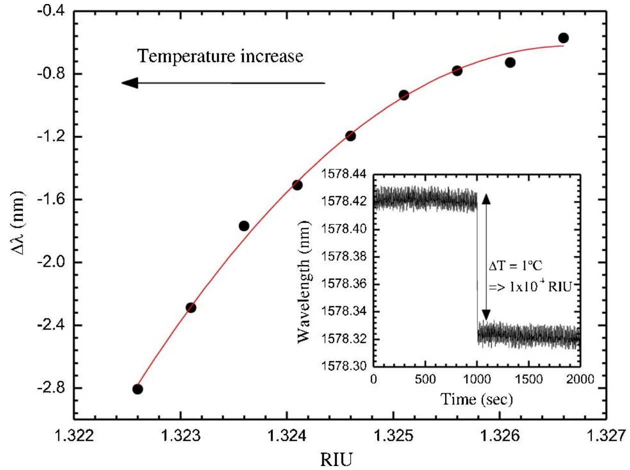


Fig. 4. (Color online) Refractive index response of the sensing head to temperature variations of water. Inset, variation of the wavelength resonance peak, $\lambda_2$, induced by a step change of the temperature of the water.

realization that the temperature-induced refractive index variation of water is orders of magnitude larger than that of air. The aforementioned result raised the possibility of using the sensing head in Fig. 1 as a refractometer—in the present case, to detect temperature-induced refractive index variations in water. The air-clad $\mathrm{PCF}_1$ section was used as the temperature-compensation element. The second section (air-clad $\mathrm{PCF}_2$) was sensitive to both physical parameters (i.e., the temperature and the refractive index of the surrounding medium). Therefore, in the wavelength shift of the loss band associated with the air-clad $\mathrm{PCF}_2$, one can remove the temperature component. In first-order systems, the influence of temperature arises only from the temperature-induced change of the liquid refractive index, with the thermo-optic coefficient of distilled water being $\simeq 1 \times 10^{-4}\ \mathrm{K}^{-1}$ [13]. The wavelength shift dependence on the refractive index of water is presented in Fig. 4: the results indicate a high sensitivity of this sensing head to refractive index variations of water; even considering that no optimization was attempted for temperatures below 20 °C, the sensitivity was ~230 nm/RIU, and, in the most linear region, a sensitivity of 800 nm/RIU was attained.

This characteristic, coupled with the temperature-compensation feature, unfolds a high potential for this optical fiber sensing structure to be used as a temperature-compensated optical fiber refractometer. The relationship between the wavelength shifts $\Delta\lambda_1$ (air-clad $\mathrm{PCF}_1$) and $\Delta\lambda_2$ (air-clad $\mathrm{PCF}_2$), as induced by changes in temperature ($\Delta T$) and refractive index ($\Delta n$), may thus be expressed in matrix form as:

$$\begin{bmatrix}\Delta\lambda_1\\ \Delta\lambda_2\end{bmatrix} = \begin{bmatrix}K_{T_1} & K_{n_1}\\ K_{T_2} & K_{n_2}\end{bmatrix}\begin{bmatrix}\Delta T\\ \Delta n\end{bmatrix} \Rightarrow \begin{bmatrix}\Delta T\\ \Delta n\end{bmatrix} = \begin{bmatrix}K_{n_2} & 0\\ -K_T & K_T\end{bmatrix}\begin{bmatrix}\Delta\lambda_1\\ \Delta\lambda_2\end{bmatrix}, \quad (1)$$

where $K_{T_1}$ and $K_{T_2}$ denote temperature sensitivities, whereas $K_{n_1}$ and $K_{n_2}$ denote refractive index sensitivities. Considering that $K_{n_1} = 0$ and $K_{T_1} \approx K_{T_2} = K_T$, the values for the measurands can then be obtained via inversion of the matrix, where one may thus obtain $\Delta T = \Delta\lambda_1/K_T$, which confirms that temperature measurements are dependent only on the air-clad $\mathrm{PCF}_1$, and $\Delta n = (\Delta\lambda_2 - \Delta\lambda_1)/K_{n_2}$, which implies that refractive index measurements are dependent on both sensing fibers.

To ascertain the system sensitivity to refractive index variations, the change in wavelength ($\lambda_2$) associated with a step change of 1 °C was measured in water; the results are shown in the inset in Fig. 4. Based on the step changes and rms fluctuations, one could calculate a refractive index resolution of $3.4 \times 10^{-5}$ RIU. Note that this is just an average performance; it is believed that it can be further improved by using other interrogation techniques not based on the use of the OSA. Therefore, further studies are warranted to address such issues as identification of the origins of the nonlinearity observed in Fig. 4 and estimation of the response time of the sensor (directly associated with the diffusion rate of the liquids into the $\mathrm{PCF}_2$ holes, as well as with the time period required to reach homogeneity inside the holes).

A large-core air-clad PCF-based sensing structure relying on multimode interference was presented in this research effort. Using two distinct large-core air-clad PCF geometries, one for refractive index measurement and another for temperature compensation, it was possible to implement a sensing head that is sensitive to refractive index changes induced by temperature variations in water as a base matrix. Our results indicated a high sensitivity of this sensing head to refractive index variations of water, having achieved a resolution of $3.4 \times 10^{-5}$ RIU.

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