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Temperature sensing with a liquid-filled hollow-core photonic crystal fiber

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Abstract—We report the realization of temperature sensing measurements using a water-filled hollow-core photonic crystal fiber. The operation of the sensor relies on the thermo-optic effect-mediated spectral shifts of the fiber transmission bands due to temperature variations. The characterization of our device allowed us to estimate a sensitivity of $(0.42 \pm 0.04) \text{ nm}/^\circ\text{C}$ and to identify the studied platform as a valid path for the development of fiber-based temperature sensors.

Keywords—*fiber optics, photonic crystal fibers, hollow-core fibers, sensing, optofluidics*

I. INTRODUCTION

Hollow-core photonic crystal fibers (HCPCFs), special fiber optics displaying a void core surrounded by a microstructured cladding, attract important interest from the photonics community. This is much due to the tremendous advancement in the HCPCF field achieved in the latest years, which encompassed, for example, the design and fabrication of optimized fibers exhibiting ultralow loss from the ultraviolet to the infrared ranges [1, 2].

Naturally, such advances propel the development of a large set of applications ranging from progress in the field of optical sources [3] to telecommunications [4]. Of particular interest are the application routes that take advantage of the possibility of inserting gases and liquids into the alveolar structure of the HCPCF. In this regard, the HCPCF acts simultaneously as a waveguide and a micro-reservoir, hence allowing direct interaction between the optical beam that travels through the fiber and the material that fills it.

While loading the HCPCF structure with gases drives strong advancements in nonlinear optics and plasma photonics [5], the infiltration of liquid samples into hollow fibers has also motivated the realization of research efforts by the HCPCF community and allowed the utilization of this class of fiber as a platform for the study chemical reactions, for example [6].

In this paper, we study the application of a liquid-filled HCPCF for monitoring temperature variations. By assessing the spectral shifts of the transmission bands of a tubular-lattice HCPCF filled with water due to temperature variations, we could demonstrate a temperature sensor with a sensitivity of $(0.42 \pm 0.04) \text{ nm}/^\circ\text{C}$. We consider that our investigation provides a valid route for the development of fiber-based temperature monitoring systems, showing itself as an alternative to other temperature fiber sensors based on, for example, fiber Bragg gratings and metal-filled fibers [7, 8].

II. TEMPERATURE SENSING WITH A LIQUID-FILLED HCPCF

Fig. 1(a) displays the HCPCF we use in this work. Its microstructure comprises eight $2.3 \mu\text{m}$ -thick tubes arranged symmetrically. The characteristic transmission spectrum of this type of fiber alternates regions of low- and high-loss guidance (namely the transmission bands and the resonances, respectively). The high-loss wavelengths (λ_m) can be approximated found by Eq. (1) [5]:

$$\lambda_m = \frac{2t}{m} \sqrt{n_2^2 - n_1^2}, \quad (1)$$

where t is the tubes' thickness; n_1 and n_2 are, respectively, the core and cladding refractive indices, and m is resonance order. Our choice of using a fiber with thick tubes is because its transmission spectrum exhibits several transmission bands in the analyzed spectral range – 450 nm to 950 nm –, being suitable for the sensing experiments we report in this paper.

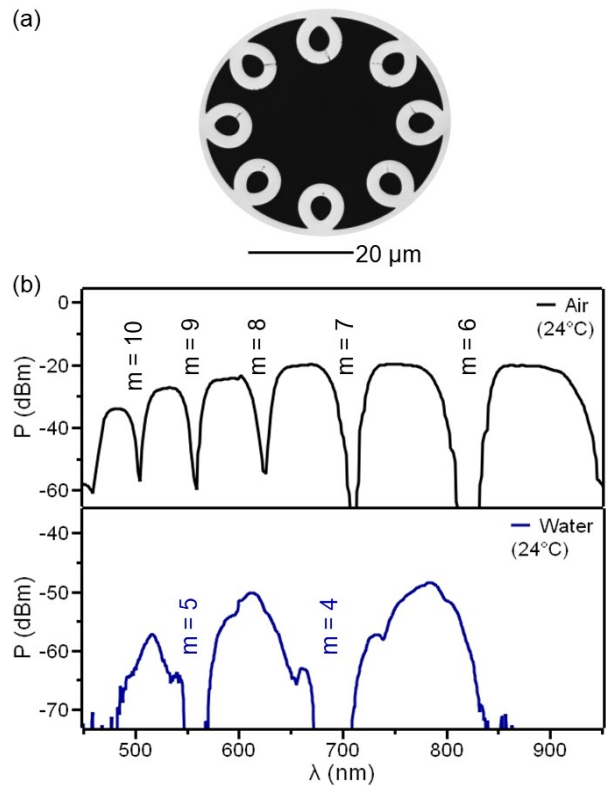


Fig. 1. (a) Cross-section of the HCPCF used herein. (b) Transmission spectra for an air-filled (top plot) and water-filled HCPCF (bottom plot). P: optical power; λ : wavelength.

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Fig. 1(b) presents two transmission spectra of our HCPCF. The plot on the top stands for the situation in which the fiber is air-filled, while the bottom plot refers to the case in which it is water-filled. As expected by Eq. (1), the variation of the core refractive index implies the shifting of the transmission bands (in Fig. 1(b), the resonances have been identified by their orders). Due to difficulties with the optical coupling to the water-filled fiber, there is a loss of the transmitted signal strength. However, it did not prevent us from characterizing our system. The spectra in Fig. 1b stand for fibers 15 cm long.

The shifting of the fiber transmission bands due to the core refractive index variations allows us to propose a temperature sensor based on our HCPCF. To do so, we infiltrate water into the HCPCF structure and, by exploring the thermo-optical effect, we can change the water core's refractive index by imposing different temperature conditions on it. This, in turn, allows us to attain shifting of the fiber transmission bands as we vary the temperature of the liquid contained in the fiber.

Fig. 2(a) illustrates the experimental setup we used herein. A supercontinuum source (SC) has been employed as the light source and an optical spectrum analyzer (OSA) detected the fiber transmission spectra. A pair of mirrors (M1 and M2) has been used to align the laser beam. In turn, we used lenses to focus the light on the fiber core (L1), collimate the output beam (L2), and couple the light to a multimode fiber connected to the OSA (L3). Finally, we used a Peltier plate as a thermal source to regulate the fiber temperature by feeding it through a current source. Additionally, we attached a thermocouple to the Peltier plate to measure the temperature.

To fill the HCPCF, we developed a liquid cell. It has three parts: an optical window, which allows the light transmission towards the OSA; a platform, which internally fixes the fiber in the cell and facilitates its alignment; and a reservoir, which stores the liquid that will be inserted into the fiber. To fill the reservoir, we applied pressure to a water-filled surgical syringe, through which the water has been compelled towards the HCPCF, filling its core. It is worth mentioning that, to avoid forming air bubbles in the fiber's core, we gently pressed the syringe following a quasi-static process.

Fig. 2(b) shows the spectra of the water-filled HCPCF between 555 nm and 690 nm for different temperatures. Within this spectral range, we note the fiber transmission band bounded by the resonances of orders $m = 4$ and $m = 5$. Observation of Fig. 2(b) allows noting that the studied transmission band redshifts as the temperature increases. This is because the thermo-optic coefficient of water is negative, while that of silica – the fiber cladding material – is positive. Thus, by raising the temperature, these refractive indices move apart, and the resonances and transmission bands are expected to shift towards longer wavelengths. We clarify that we analyzed the region between 555 nm and 690 nm as the fiber transmission was well-defined in this range. Also, it lies within the low-absorption region of the water spectrum.

To detect the central wavelength of the transmission band and measure its spectral shifts, we used quadratic function fits for the points with power greater than -60 dBm. We then used the wavelength of the vertex of each fitted curve to associate the band position with the temperature in question. Fig. 2(c) displays the points obtained by following this procedure. The spectral shift ($\Delta\lambda$) is calculated with respect to the band position at $41^\circ\text{C} - 613$ nm. From there, we performed a linear fit and obtained a sensitivity of $(0.42 \pm 0.04) \text{ nm}/^\circ\text{C}$, which is consistent to what we can predict from our analytical analyses.

For completeness, we followed a similar procedure for studying the impact of temperature variations on the spectrum

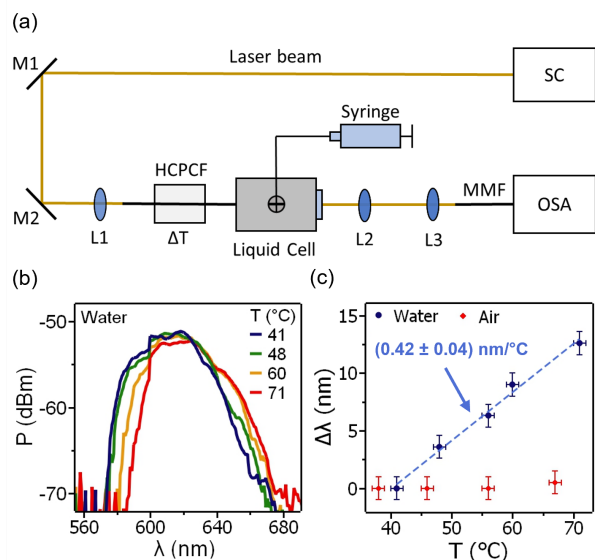


Fig. 2. (a) Diagram of the experimental setup. SC: supercontinuum source; M1 and M2: mirrors; L1, L2 and L3: lenses; MMF: multimode fiber; OSA: optical spectrum analyzer. ΔT : temperature variation. (b) Transmission spectra of the water-filled HCPCF for different temperatures between 555 nm and 690 nm. (c) Wavelength shift ($\Delta\lambda$) of the transmission band as a function of the temperature (T).

of an air-filled fiber. In this case, however, as the wavelength shift is tiny due to the lower thermo-optic coefficient of air with respect to that of water, we monitored the shift of the transmission band left edge (for a band of the same order as in the water-filled case). We hence obtained the points shown in red in Fig. 2(c). We see that the tested temperature variations for the air-filled fiber implied a minor change in the transmission band spectral position, as expected. Therefore, filling the HCPCF with liquids with higher thermo-optic coefficients increases the fiber's sensitivity to temperature variations, allowing it to act as a temperature sensor.

III. CONCLUSIONS

In this investigation, we showed the applicability of HCPCF as a temperature sensor, reaching a sensitivity of $(0.42 \pm 0.04) \text{ nm}/^\circ\text{C}$. We believe the reported platform can be an alternative to other fiber-based temperature sensor schemes.

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