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Large-core hollow fibers for speckle-based displacement sensing

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Abstract—We study the application of a large-core hollow fiber as a platform for displacement sensing. The sensor is assembled by inserting and appropriately moving a single-mode fiber in the empty core of the hollow fiber. Such a construction allows attaining a speckled intensity profile at the hollow fiber output, which is evaluated while one controllably displaces the single-mode fiber in its interior. Our results allow identifying this scheme as a promising means for exploring the multimode characteristics of hollow fibers in sensing contexts.

Keywords—*fiber optics, photonic crystal fibers, hollow-core fibers, fiber sensors, speckle*

I. INTRODUCTION

The striking recent advancements in the hollow-core photonic crystal fibers (HCPCFs) field place this family of waveguides in a prominent position among the currently available enabling technologies in photonics. Indeed, roughly after 30 years after their proposition, HCPCFs now stand out as the lowest-loss optical fibers working all along from the ultraviolet to the infrared [1, 2], and establish themselves as building blocks for several applications such as the development of optical sources and sensors [3, 4].

While high-order modes (HOMs) are omnipresent in the modal content of HCPCFs, in typical applications, the fiber design and the corresponding experimental setups are tailored so that, in practice, the fiber exhibits an effective single-mode operation. In this regard, HCPCF architectures can be designed to efficiently filter families of HOMs that might contaminate the fiber modal content, hence reaching a very high extinction ratio between HOMs and the core fundamental mode [5]. Similarly, the light launching setups can be set to afford appropriate alignment and mode-matching conditions to circumvent the multimode behavior of these fibers. This is particularly acute in high-power beam delivery applications using, for example, large-core HCPCFs (here referring to those exhibiting core diameters larger than 100 μm) [6].

Alternatively, we here explore the multimodal behavior of a large-core HCPCF and investigate its application for detecting micrometric displacements. The sensor is built up by

inserting and controllably moving a single-mode fiber (SMF) inside the HCPCF and has its operation assessed by evaluating the speckled output beam emerging from the system. We consider that our results widen the framework of HCPCF applications and offer a promising path for the exploration of their multimode behavior in the realm of fiber sensors.

II. SPECKLE-BASED DISPLACEMENT SENSING WITH A LARGE-CORE HCPCF

Fig. 1a exhibits the cross-section of the HCPCF we use in this investigation. It consists of a silica tubular-lattice HCPCF whose microstructure is formed by a set of 12 tubes (with a thickness of 680 nm), which delineates a 140 μm -diameter hollow core. Fig. 1b shows the fiber's transmission spectrum between 480 nm and 1300 nm – measured for a fiber with a length of 4 m –, where one can discern two transmission bands, namely between 510 nm and 630 nm, and between 740 nm and 1230 nm. In the measurements to be described in the following, we used a laser source emitting at 543 nm. The vertical dashed line in Fig. 1b readily informs that this wavelength lies within one of the fiber's transmission bands.

Fig. 2a shows the experimental setup we employed for characterizing our sensing platform. By appropriately adjusting two alignment mirrors (M1 and M2) and an objective lens L1, light from a 543 nm laser source has been launched into a commercial SMF with operation in the visible

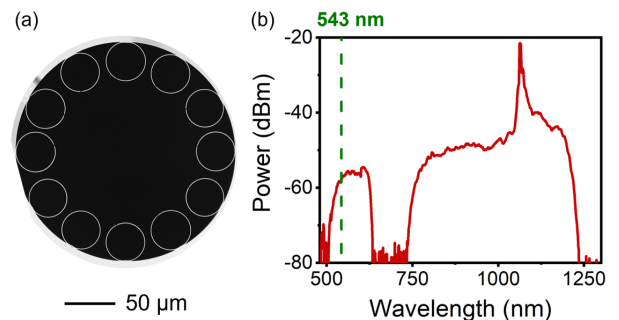


Fig. 1 (a) HCPCF cross-section and (b) its transmission spectrum between 480 nm and 1380 nm. The vertical dashed line indicates the wavelength of 543 nm.

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range (Newport FSA, 125 μm external diameter), which had been in turn previously and cautiously introduced in the core of the HCPCF. We sequentially affixed the SMF to a motorized translation stage so it could be controllably moved inside the HCPCF during the displacement sensing measurements.

To collimate the beam emerging from the HCPCF and project it onto a camera, one placed an objective lens (L2 in Fig. 2a) at the HCPCF output. Fig. 2b shows the HCPCF output beam intensity distribution measured by the camera when the SMF end was 3 mm apart from the HCPCF extremity (an illustration of the fiber microstructure has been superposed to the image for eye guidance). We can observe that, due to the very dissimilar HCPCF and SMF core sizes, a highly multimode beam is attained at the HCPCF output, which makes it adequate for the realization of the speckle-based sensing tests we will describe in the following. We inform that we run in-depth numerical and experimental studies on the evolution of the multimode propagation inside our large-core HCPCF and that the corresponding analyses will be reported in a forthcoming publication [7].

While the intensity distribution of a speckle pattern $I(x, y)$ results from the interference of M modes, it can be algebraically described by Eq. 1, where $a(x, y)$ and $\phi(x, y)$ represent, respectively, the amplitude and phase distributions of the optical modes contributing to $I(x, y)$. The subscripts m and n represent the m -th and n -th fiber modes.

$$I(x, y) = \sum_{m=1}^M \sum_{n=1}^M a_m a_n \exp[i(\phi_m - \phi_n)] \quad (1)$$

If the system from which the speckle pattern arises is disturbed by an external stimulus, the specklegram is expected to change from $I_0(x, y)$, namely the specklegram related to the initial state, to a different state $I(x, y)$. This variation between the specklegrams is typically quantified by the zero-mean normalized cross-correlation (ZNCC) metric, which is given by Eq. (2), where $0 \leq Z \leq 1$ is the ZNCC coefficient and the overlines specify the average values of I and I_0 [8]. Eq. (2) readily informs that Z decreases as I differs from I_0 .

$$Z = \frac{\iint (I - \bar{I})(I_0 - \bar{I}_0) dx dy}{[\iint (I - \bar{I})^2 dx dy \iint (I_0 - \bar{I}_0)^2 dx dy]^{1/2}} \quad (2)$$

Although the ZNCC metric is intrinsically robust and able to provide the framework for the realization of sensing measurements, one may calculate the extended ZNCC (EZNCC), which is able to enlarge the system measurement range [9]. It is computed by Eq. (3), where EZ is the EZNCC coefficient, EZ_0 is a reference level, Z is the ZNCC between I and I_0 , and $\tau = 0.7$ is an empiric threshold parameter [8].

$$EZ = EZ_0 - [Z(I, I_0, \tau) - 1] \quad (3)$$

Here, we employ the EZNCC metric to characterize our displacement sensing platform. This is done by computing the EZNCC coefficient as we controllably move the SMF inside the HCPCF towards the z -axis positive direction (as shown in Fig. 2a). The SMF departing point has been chosen to be that when its extremity was 3 mm apart from the HCPCF end-face. We mention that the specklegram images have been recorded using a low-cost webcam (800 \times 600 pixels) and that the EZNCC has been calculated through MATLAB routines. It allows identifying our setup as a cost-effective platform.

Fig. 2c shows the graph of the EZNCC coefficient as a function of the SMF displacement inside the HCPCF.

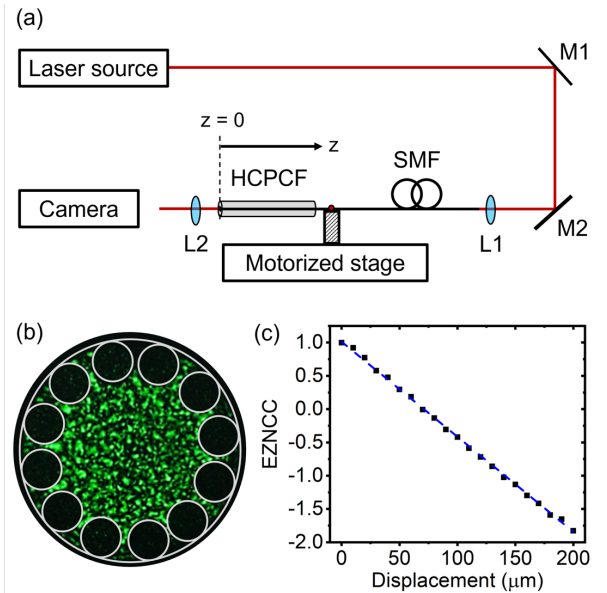


Fig. 2 (a) Diagram of the experimental setup. (b) Measured HCPCF output profile for the case in which the SMF extremity is 3 mm apart from the HCPCF tip (a representation of the HCPCF cladding has been superposed to the image for eye guidance). (c) EZNCC versus the SMF displacement inside the HCPCF. The dashed blue line indicates a linear curve fitted to the experimental data ($R^2 = 0.9996$).

Observation of the data allows recognizing a linear trend between the EZNCC and the SMF displacement. By linear fitting the experimental data, one can estimate a value of $14.27 \pm 0.07 \text{ mm}^{-1}$ for our device's sensitivity ($R^2 = 0.9996$). Additionally, if one considers the maximum random uncertainty as 0.01 (EZNCC units), one can reckon our system resolution at $0.7 \mu\text{m}$. We can hence identify our platform as a valid path for the development of new displacement sensors and evaluate that this study has the potential of disclosing a set of other speckle-based sensing applications based on the multimode characteristics of large-core HCPCFs.

III. CONCLUSIONS

We studied the use of a large-core HCPCF as a platform for speckle-based displacement sensing. We understand that our investigation identifies a promising avenue for exploring the multimode behavior of HCPCFs in the sensing field.

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