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Study of In-line Hollow Core Fiber Sensor for Uniaxial Transverse Deformation

Arturo Sanchez-Gonzalez, Daniel Leandro, Romain Dauliat, Raphael Jamier, Philippe Roy, and Rosa Ana Perez-Herrera

Abstract—This research explores the impact of cyclic uniaxial transverse deformation on an in-line hollow-core fiber etalon. The structure consists of a 6 mm long section of hollow-core fiber spliced between two standard single-mode fibers. The optical response of the structure is theoretically analyzed in spectral and transformed domains, evidencing Fabry-Perot and antiresonant interferometric mechanisms. A validation of the theoretical behavior is carried out both through simulation and experimentation. The performance of the structure for uniaxial transverse deformation is subsequently evaluated by tracking the phase of the main component in the transformed domain. Several sensors with different internal diameters underwent cycles of transverse deformation, revealing robust linear trends in every case. On average, the structure demonstrated elastic behavior under deformations up to 42 μm , with a mean sensitivity of 0.174 $\text{rad}/\mu\text{m}$, and mechanical breakage taking place at 58 μm . The results confirmed the suitability of the sensor to withstand uniaxial micro-displacements or pressures, with smaller inner diameter capillary fibers showing the best performance.

Index Terms—Antiresonant, capillary fiber, deformation, Fabry-Perot, Fast Fourier Transform, hollow core fiber, interferometer, optical fiber sensor, reflectance, phase tracking.

I. INTRODUCTION

SINCE its initial conceptualization in the late 60s [1], a decade would prove sufficient for the fiber optic sensor technology to begin an expansion that would reach the present day [2]-[4]. The basic appeal behind this development involves the capability of modulating light signals within optical fibers in response to a variety of external parameters while preserving an inherent immunity to electromagnetic interference, lightweight, miniaturizable design, and ability to cover extensive distances without significant signal degradation [5]. Among the various types of fiber optic sensors, interferometric sensors, which rely on the superposition of light waves to measure minute changes in the optical path length induced by external stimuli, stand out for their unparalleled precision and sensitivity while preserving previous listed properties [6]. Such resilience paired with

versatility has propelled their deployment in diverse critical application fields, namely defense [7], civil engineering [8], medicine [9], and seismology [10], amongst others.

From a design point of view, most fiber optic interferometric sensors can be built both by employing standard single-mode fiber (SMF) combined with classical fiber components, as well as by hybrid structures in which segments of multimode, microstructured, or tapered fibers are placed between SMFs. The latter, commonly referred to as in-line fiber optic interferometric sensors, exploit the different guiding mechanisms in each fiber segment, as well as the existence of interfaces, to replicate classical interferometric mechanisms [11]. Of the aforementioned non-standard fibers, capillary fibers, characterized by an annular cross section of variable thickness and material, excel among the microstructured ones for their simplicity and low-cost [12]. As a result, capillary fibers, also known as hollow core fibers (HCFs) given their geometry, have recently been employed in the development of in-line fiber optic interferometric sensors for the monitoring of a wide range of physical and chemical parameters. Designs tailored for strain [13], temperature [14], curvature [15], refractive index [16], microfluid [17], liquid level [18], and multiparameter [19], have been recently reported. Despite the varied nature of measurands, their application in monitoring micro-deformation, pressure, and micro-displacement of the external medium remains largely unexplored. Furthermore, in most studies measurements are constrained to uniformly distributed pressures and deformations across the inner or outer surface of the fiber [20] [21]. However, addressing a particular transverse direction becomes relevant in civil engineering applications, where the stresses suffered by the fiber may not be homogeneous or the installation could require adherence to another surface [22].

From the point of view of the measurement technique, SMF-HCF-SMF structures rely on following one or several of the valleys or peaks of the interferogram to monitor the sensing parameter. However, since the effect of the external stimuli induces a wavelength shift of the spectrum in most cases,

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another natural option is to track the phase associated with the relevant contributions of the transformed spectrum obtained by means of the Fast Fourier Transform (FFT) algorithm. This alternative has several advantages, such as providing higher accuracy of the measurements and allowing the discrimination of the different interferometric components [23] [24]. Nevertheless, this approximation requires prior identification of the underlying mechanisms in the interferogram to make the correct choice of components whose phase to track.

Taking all this into consideration, this work focuses on the analysis and design of a transverse deformation sensor based on capillary fibers that employs the phase tracking technique for an enhancement in accuracy. For this end, the research begins with the analysis of the multiple interferometric phenomena involved in a conventional SMF-HCF-SMF structure, subsequently focusing on those whose influence is predominant in the designed sensors. This study is performed both theoretically and through simulation, validating the conclusions reached with experimental results. Once the underlying interferometric phenomena have been thoroughly explained, the design and manufacturing process of the structure are optimized to minimize propagation losses while preserving a lengthy operating surface. After the experimental setup employed for the uniaxial transverse deformation study is presented, the measured interferogram and transformed spectra are studied to identify which parameter yields the best results. Sensors with different geometries are characterized under uniaxial transverse deformation cycles, achieving highly linear trends and sensitivities. Their performance is subsequently analyzed both globally and comparatively in terms of sensitivity, linearity, repeatability, and resilience.

II. THEORETICAL ANALYSIS AND SIMULATION

Initially, a theoretical analysis supported by simulations have been performed in order to optimize and improve the design of the sensing structure. As a first approximation, a phenomenological approach to the different interferometric mechanisms supported by a SMF-HCF-SMF structure can be fulfilled by applying ray optics to any symmetry plane in which the optical axis of the system is contained [26]. For this purpose, once the light has travelled through the first SMF-HCF interface, each mode is replaced by a plane wave characterized by a wave vector k with an angle with respect to the optical axis ranging from 0 to that associated with the numerical aperture of the SMF. In this way, four different interferometric phenomena can be identified, as shown in the schematic illustration in Fig. 1 [12]. In the first place, the Fabry-Perot (FP) etalon associated with the existence of two interfaces facing each other (air-silica transition) is observed. As depicted by the solid green ray of Fig. 1, this phenomenon arises from the phase shift accumulation between consecutive roundtrips. Since the effective propagation along the optical axis can be conducted with a non-parallel k , simultaneous waves with different wave vectors will accumulate phase shifts depending on the difference in optical paths travelled, i.e., the difference in effective propagation constants. This indicates the existence of multimodal interference (MM), which can arise between waves

traveling through the inner hollow core (solid rays in Fig. 1), between those traveling through the silica cladding of the capillary (dashed rays in Fig. 1), or between any combination of the two. In accordance with the literature [12] [19] [25] [26], the latter mechanism is referred to as Mach-Zehnder (MZ), given that each wave travels through a different physical medium. Finally, beyond a certain capillary length threshold [27], certain waves cross the cylindrical core-cladding interface of the HCF and, after returning to the hollow core, interfere with those remaining inside as illustrated by the dotted rays (yellow) in Fig. 1. This phenomenon results in a transverse confinement via destructive interference, in which wave attenuation coefficients go through periodic flat minima (antiresonances), reminiscent of the reflectance of a Fabry-Perot cavity with rotational symmetry [28]. Given that the actual propagation arises from an antiresonance (AR) mechanism instead of a proper guiding, this type of confinement, as well as the waveguide itself, receive the name of “leaky” [29].

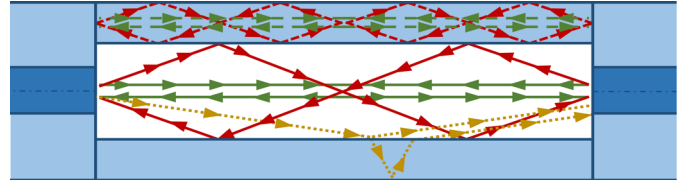


Fig. 1. Schematic illustration of the four interferometric phenomena supported by a SMF-HCF-SMF structure.

Once the distinct phenomena have been described, the particular influence of each mechanism on the overall performance of the structure highly depends on the dimensions of the HCF under consideration, requiring more precise models for their exploration. For this purpose, a complete electromagnetic model was considered through numerical computation. To begin with, the PhotoDesign[®] suite of Fimmwave was employed for the simulation of the waveguide cross section in the semi-analytical derivation of its modes. Once achieved, the determination of the SMF-HCF coupling matrix and mode propagation along the structure was carried out by means of Fimmprop, a numerical tool based on the EigenMode Expansion method [30]. Considering the dimensions of the experimental manufacture, which will be detailed in the next section, the study analyzes structures with a capillary length (L) of 6 mm and an internal diameter (ID) ranging from 52.8 μm to 75 μm .

As the first remarkable result of simulation, the total power coupled from the SMF to the silica cladding of the HCF in the first interface remains well below $10^{-4}\%$ in every case and over the entire S+C+L infrared band, making MZ and cladding MMI mechanisms negligible. Consequently, virtually all light is injected into modes confined mainly in the hollow core, which are therefore leaky as they present effective refractive indexes lower than the unit [28]. Regarding the field distribution of these leaky modes, it closely resembles that of a guided mode found in a conventional waveguide [28]. For this reason, the mode numbering used henceforth refers exclusively to core modes, and it is specifically associated with the number of zeros of modal fields in the core, regardless of the field distribution

in the claddings [29] [31]. Considering that the structure is enclosed between two SMFs, with fundamental guided mode HE_{11} , only those leaky modes preserving symmetry could present coupling in the absence of axis mismatch or additional perturbations [32], i.e., $HE_{1n} \forall n \in \mathbb{N}$. Simulation revealed that the first five modes HE_{11} to HE_{15} are enough to translate over 90% of the power injected into the HCF section of the structure in the spectral range from 182 to 207 THz (1450 to 1650 nm), with individual couplings varying between 5% and 35% depending on the particular mode, ID, and interrogation frequency. At the same time, being a leaky waveguide, propagation capabilities are highly limited by leakage loss, which greatly increases with modal index. To provide a sense of scale, the confinement loss incurred in propagation through a wavelength distance is over an order of magnitude greater for the second HE_{12} leaky mode than for the fundamental HE_{11} mode [31]. Therefore, and taking into account that the length of the leaky section of the sensor is 5 orders of magnitude greater than any operating frequency, it can be considered that the structure behaved as a single-mode waveguide (ignoring 2-fold polarization degeneracy). Note that the fundamental HE_{11} mode varied in nature from guided to leaky as SMF to HCF interfaces were crossed.

Consequently, of the four interferometric mechanisms initially proposed, only two retain significant impact: AR due to the leaky nature of the hollow waveguide, and FP as a consequence of performing the sensor characterization in reflection. In terms of its effect over reflectance, FP results in a spectral periodicity $\Delta\nu_{FP} = c/(2L)$ defined by the phase shift accumulation between successive roundtrips, $\phi_{FP} = 4\pi L\nu/c$ [33]. Similarly, AR leads to abrupt losses over the entire spectrum with periodicity $\Delta\nu_{AR} = c/(2d\sqrt{n_{cl}^2 - 1})$ related to the transverse geometry of the hollow waveguide and an accumulated phase shift $\phi_{AR} = 4\pi d\nu\sqrt{n_{cl}^2 - 1}/c$ [34]. In every case, c refers to the vacuum speed of light, ν is frequency, d is the thickness of the HCF silica cladding, and n_{cl} the refractive index of the HCF silica cladding. It is assumed that the latter matches the SMF cladding, therefore, being lower than SMF core refractive index n_{co} .

Figure 2 (a) shows the main magnitude components in the transformed domain of the reflectance, obtained both experimentally and by simulation for an SMF-HCF-SMF structure of $L = 6$ mm and $ID = 52.8$ μm . As can be seen, contributions outside baseband of both experimental and simulated spectra perfectly matches. On the one hand, the main component in both cases corresponds with the FP behavior, $t_{FP} = \Delta\nu_{FP}^{-1} = 4 \cdot 10^{-11}$ s. On the other hand, the AR contribution is present at evenly spaced intervals of $t_{AR} = \Delta\nu_{AR}^{-1} = 2.6 \cdot 10^{-13}$ s. Only one contribution associated with FP is observable because, as a consequence of its low finesse, its effect can be fully described by a first-order Maclaurin series expansion without any loss of generality [35]. In contrast, this approximation is not applicable to the case of AR, where the transfer function is somewhat more intricate [12], promoting the presence of multiple spectral bands. This result is sometimes attributed to the multimodal nature of the structure

[26]. However, this interferometric mechanism is not necessary for its derivation since the simulation shown here considers exclusively the fundamental HE_{11} mode, whose field distribution in the HCF is depicted in Fig. 2 (b). Finally, contributions observable near DC in a wider temporal range as depicted in Fig. 2 (c) reduce to the baseband replica of anti-resonance components, providing no additional information.

The comparison between experimental measurement and simulation was extended to structures with all four capillary diameters, presenting similar correspondence.

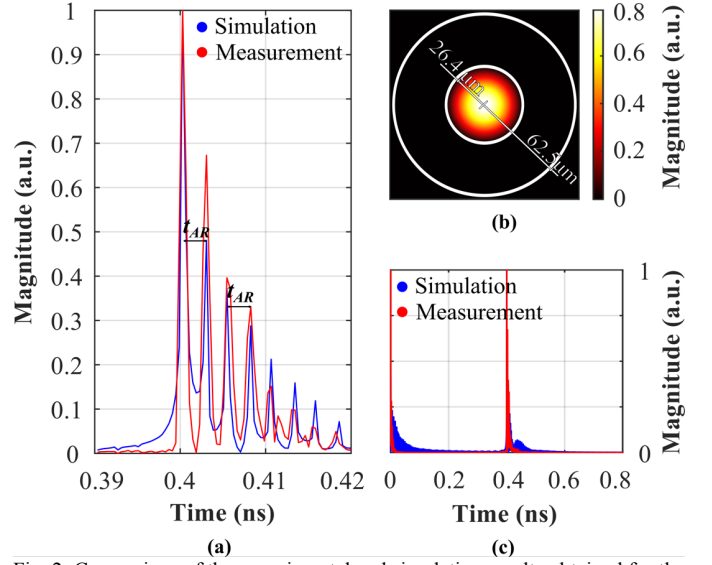


Fig. 2. Comparison of the experimental and simulation results obtained for the reflectance FFT magnitude in the range of the main contribution (a), with a wider span (c), and field distribution of the leaky HE_{11} mode obtained by semi-analytical computation (b).

III. EXPERIMENTAL SETUP

A. Sensor Design

Regarding the sensor configuration, a dimensioned diagram is illustrated in Fig. 3 (a). The core element comprised a 6 mm long soft-glass high-silica capillary fiber segment spliced between two SMF sections. This length constraint, which defines the effective length of the sensor itself, was imposed to ensure that a mean reflectance exceeding 1% was experimentally achieved across the spectral range from 1450 nm to 1650 nm, while maximizing the dimension over which transverse deformation would be applied. In reference to the silica capillary cross-section, the outer diameter (OD) was set at 125 μm , aligned with the cladding diameter of the SMF. Concerning the ID, different values were explored on the basis of three considerations. First of all, by significantly exceeding the mode field diameter of the employed SMF, insertion loss could be reduced in the SMF-HCF transition [12]. Secondly, given that the operating principle of the sensor relies mainly on the mechanical properties of capillary fibers, those associated with solid ring propagation and most affected by hollow core collapse during splices (MM and MZ) could be minimized by choosing a fairly large ID [36]. As a result, optical power would be mainly confined to the Fabry-Perot mechanism, albeit with the inherent influence of anti-resonance as a consequence of the

large capillary segment, well above the associated cut-off length [25]. Thirdly, the attenuation coefficient of any leaky mode in an HCF scales with ID^{-4} [29], requiring substantial IDs to achieve non-negligible mean reflectance over millimeter-in-length capillary section. As a trade-off between every constrain and manufacturing capabilities, sensors with HCFs characterized by IDs ranging from 50 to 75 μm were subjected to testing, namely 52.8, 55, 66 and 75 μm .

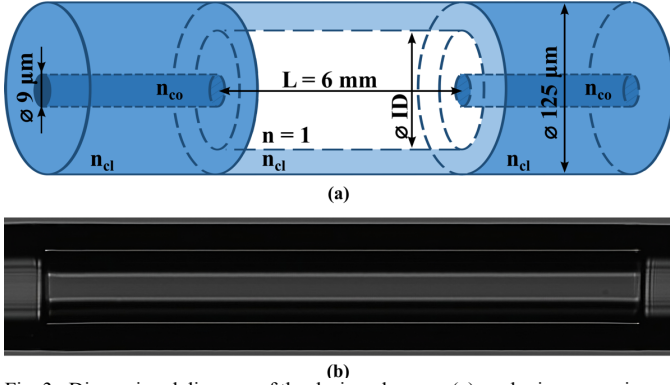


Fig. 3. Dimensional diagram of the designed sensor (a), and microscope image of one of the manufactured structures (b).

Soft-glass high-silica optical capillaries were designed and manufactured by means of conventional stack-and-draw technique, employing a pulling tower assembled for classical optical fibers and a single preform, where the different dimensional series were obtained following the premises set out in [37]. It is noteworthy that ID uniformity is not a limiting factor in the manufacturing process, as confinement losses remain within a factor of 2 under a 50% uncertainty in cladding thickness [31].

To ensure the creation of mechanically robust HCF-SMF interfaces without the occurrence of core collapse, axis misalignment, or fiber bending, a commercial specialty fiber fusion splicer (Fujikura FSM-100P) was employed. Among the different fusion parameters to be precisely set (discharge intensity profiles, number of cycles, and gap between the fiber ends), the influence of arc discharge location was particularly noteworthy to avoid core collapse. Thus, in order to consistently achieve homogenous and well-defined interfaces, the discharge had to take place from 15 to 25 microns over the SMF segment for internal diameters ranging from 50 to 75 μm . Similarly, to consistently achieve capillary fiber cleaves with angles below 0.5° and length uncertainties under the micrometer, a motorized microscopy-assisted electric cleaver station was employed (3SAE TMS). In this case, pre-strain the capillary before cleaving proved essential for straightness and uniformity, requiring a load range of 180 to 209 grams as ID decreased. The 1 μm movement resolution of the motorized clamps responsible for cleaving point alignment ensured that the uncertainty in the length of the HCF sensor section remained below the interrogation wavelength. Thus, considering the 6 mm length of the capillary sensor section imposed by reflectivity constraint, this resolution translated to a length error under 0.02%.

An optical microscope image of one of the manufactured devices can be partially observed in Fig. 3 (b), focusing on the

SMF-HCF interface abruptness.

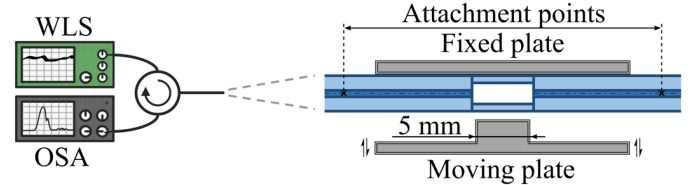


Fig. 4. Experimental setup employed during SMF-HCF-SMF sensor characterization.

B. Interrogation Scheme

In order to test the interferometric structure as transverse deformation sensor, the interrogation scheme depicted in Fig. 4 was employed in the experiments. As illustrated, a broadband white light source (WLS) providing an integrated output power of 7.55 mW from 1450 to 1650 nm and an optical spectrum analyzer (OSA, Anritsu MS9740A) with a spectral resolution of 0.03 nm were employed. Given that sensor monitoring was performed in reflection, a conventional C-band circulator was introduced to redirect the light coming from the source once reflected from the sensor back to the OSA. However, considering the wide range of interrogation and the narrow bandpass and insertion losses of the circulator, measurements were referenced to the response of a calibration mirror with a flat reflectance in the S+C+L band. Furthermore, to prevent undesired reflections, the free end of the SMF section of the sensor remained immersed in an index-matching gel.

In reference to the actuator used to apply uniaxial transverse deformation, a pair of grips, positioned at a fixed distance of 25 cm from each other, were employed to secure and center the sensor onto a flat polished sheet. The sensing fiber was pre-strained before fixing with a 0.15 N load. Facing it, another 5 mm-long flat surface approach and withdraw from the sensor in predefined patterns, applying cyclic uniaxial transverse deformation to the sensors. The motorized unit employed for surface spacing control exhibited a resolution of $204 \pm 17 \text{ nm}$, which established the step resolution for the progressively increased consecutive deformation and relaxation cycles.

Given the length of moving plate and sensor, the deformation was purposefully confined to the capillary section of the structure, avoiding any disturbance of the SMF cross section that could interfere with the measurement process. Additionally, this limitation in stress applied to the splices served to minimize the risk of structural failure, thereby mitigating potential shortening of the measuring range.

IV. RESULTS AND DISCUSSION

A. Spectral Response and Transformed Domain

At each step within each deformation-relaxation cycle, reflectance data from the sensor was captured within the spectral range of 182 to 207 THz (1450 to 1650 nm). Following, FFT was directly applied over the frequency axis spectrum. Upon obtaining reflectance in the Fourier-transformed domain, its evolution with incremental values of uniaxial transverse micro-deformation was studied.

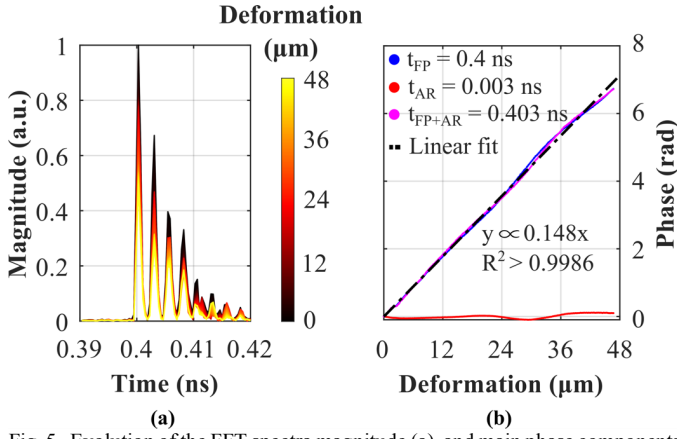


Fig. 5. Evolution of the FFT spectra magnitude (a), and main phase components (b), with applied uniaxial transverse deformation. Example of the sensor with ID = 52.8 μm .

Concerning the magnitude of the FFT spectra, it can be observed in Fig. 5 (a) (ID = 52.8 μm), that FP and AR components maintained a constant profile, suffering exclusively from attenuation as the fiber geometry was altered. Therefore, their phase could be reliably monitored as a source of information, resulting in Fig. 5 (b). As depicted, both FP and FP+AR main components exhibited remarkable phase linearity with transverse deformation, with a determination coefficient $R^2 > 0.9986$. Consequently, the sensitivities measured are for FP and FP+AR $1.48 \cdot 10^{-1} \pm 1.0 \cdot 10^{-3} \text{ rad}/\mu\text{m}$ and $1.48 \cdot 10^{-1} \pm 1.2 \cdot 10^{-3} \text{ rad}/\mu\text{m}$, which can be considered statistically indistinguishable [38]. This result extended to the remaining replicas of AR over FP, since they all inherited the sensitivity of FP because of the negligible sensitivity of AR with applied stress, remaining two orders of magnitude below the FP case. This experimental independence of AR with uniaxial transverse deformation is in agreement with theoretical results, whereby the spectral response depends exclusively on the thickness of the circular ring [28], unaltered during measurements.

The study was repeated for structures with all four capillary diameters, yielding consistent results in every case between the interferometric contributions and their phase evolution.

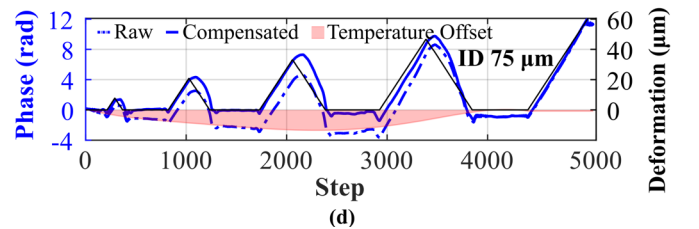
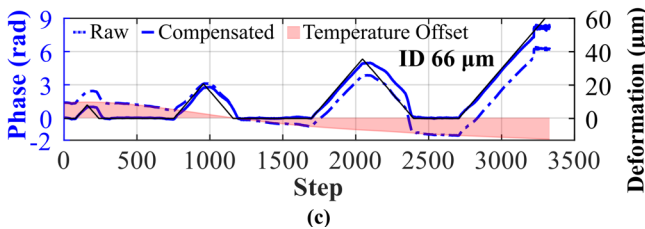
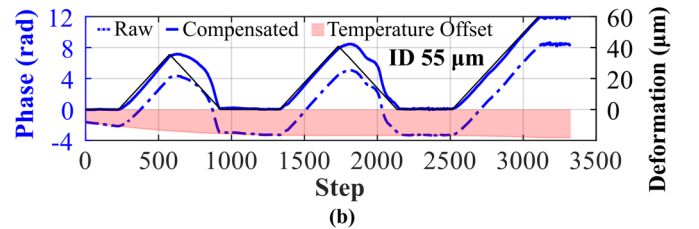
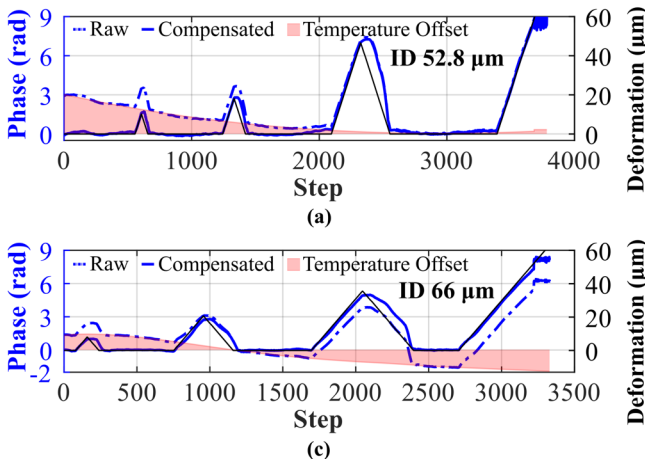


Fig. 6. Phase variation of the reflectance main spatial frequency contribution as a result of progressive uniaxial transverse deformation cycles for the sensor with an HCF characterized by an ID of 52.8 μm (a), 55 μm (b), 66 μm (c), and 75 μm (d).

B. Phase Tracking during Deformation Cycles

Based on the previous findings, the main FFT component of each sensor was chosen for tracking its phase response under applied deformation. The outcome is presented in Fig. 6, where the consecutive and progressively increased deformation-relaxation cycles are depicted in black. The reference line at 0 μm marks the contact between the motorized flat surface and the outer surface of each sensor. Consequently, positive values correspond to progressive transverse deformation, leading to a reduction in the capillary fiber diameter along that specific transverse axis while increasing its eccentricity. For each sensor and cycle, the background of the blue dashed curve reveals that the phase was notoriously influenced by variations in room temperature, consistent with observations in similar hollow-core fiber (HCF) structures of a certain length [39]. However, owing to its slowly varying nature, it could be compensated through a polynomial fit fed with the measurement time intervals without deformation. The results are depicted in dotted blue, showing that the phase of the main central frequency component of every sensor faithfully tracked the upward deformation ramps, displaying marginally longer relaxation times during the downward ramps. In each cycle, the phase ultimately returned to its initial resting value until the last ramp, where sensors were subjected to a stress test until breakage. These observations are similarly depicted in Fig. 7, illustrating the various hysteresis cycles undergone by the sensor. As it is summarized in Table I by means of the different coefficients of determination, each monitored phase component exhibited a strong linear trend with progressively applied deformation. These findings surpassed those recently reported by authors on similar structures [40], showcasing a fourfold increase in mean uniaxial transverse deformation sensitivity, \bar{S} . Furthermore, the sensitivity remained consistently stable across cycles, independently of the HCF employed, with a maximum coefficient of variation (CV) of 6% for the 66 μm scenario.

Several significant conclusions can be drawn by comparing the different results obtained for each sensor in Table I. Firstly, the sensitivity of the structure did not appear to exhibit a direct dependence on the internal capillary diameter, attaining analogous values for both the largest and almost smallest ID cases. Secondly, the repeatability of measurements with

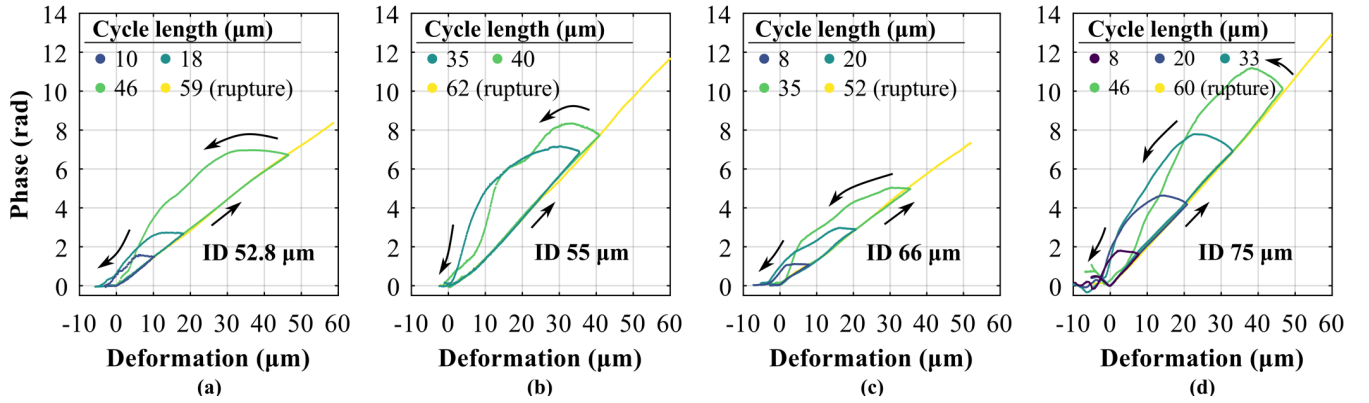


Fig. 7. Phase hysteresis cycles after temperature compensation as a result of increasingly uniaxial transverse deformation cycles for the sensor with an HCF characterized by an ID of 52.8 μm (a), 55 μm (b), 66 μm (c), and 75 μm (d).

consecutive deformation cycles seemed to worsen with the capillary diameter, as indicated by the coefficient of variation (CV). This could be related to the emergence of micro-fractures in the HCF structure as induced stress accumulated, with sensors becoming more susceptible as the solid circular crown diminished. The example that best illustrates this behavior is precisely the sensor with an ID of 75 μm , whose sensitivity increased by 3% between successive cycles from the second onwards. It is finally noteworthy that, although every HCF underwent a deformation over 50 μm before rupture, the cases with 52.8 and 55 μm withstood deformations up to a 112% of their ID, involving the complete hollow core collapse. All these results underscore the highly elastic nature of the structure and its suitability as a robust transverse micro-deformation sensor, but mostly for those cases with a smaller ID.

TABLE I
SENSOR CHARACTERIZATION RESULTS

ID (μm)	\bar{S} (rad/ μm)	CV (%)	R^2_{\min}
52.8	0.147	1.2	0.9952
55	0.202	0.5	0.9950
66	0.137	3.1	0.9937
75	0.209	6.0	0.9988

ID is the capillary internal diameter. \bar{S} is the sensitivity averaged over the different deformation cycles. CV is the coefficient of variation of the mean sensitivity. R^2_{\min} is the minimum coefficient of determination obtained between every linear regression of each sensor.

Since all interferometric mechanisms seemed to remain static in response to transverse uniaxial deformation, the measuring technique could also be performed on the wavelength-dependent spectra. In this regard, the transformed domain would lack the previous neatness, which is to be expected given the nonlinearity dependence of wavelength on frequency. However, by tracking the phase of the main spatial frequency in the spatial FFT spectra, analogous results in terms of linearity could be obtained, albeit a change of sign caused by the inverse dependence of wavelength on frequency [40].

V. CONCLUSIONS

This work has studied the impact of cyclic uniaxial transverse deformation on an in-line hollow-core fiber etalon. The structure comprises a 6 mm long hollow-core fiber spliced to standard single-mode fiber at both ends. Multiple capillary

fibers with different inner diameters were considered, optimizing the manufacturing process to achieve a mean reflectance exceeding 1% within the 1450 nm to 1650 nm interrogation range for every case. The expected optical response in the spectral and transformed domains were theoretically analyzed, emphasizing in the Fabry-Perot and antiresonant interferometric mechanisms experienced by the waveguide, as well as its mainly single-mode nature. This analysis was verified both experimentally and by simulation, characterizing its behavior in time-dependent Fourier-transformed domain by means of the FFT algorithm. Finally, the phase of the central main FFT component of the reflectance was continuously monitored through successive uniaxial transverse deformation and relaxation cycles of progressively increasing magnitude, up to the point of sensor breakage. The outcomes revealed robust linear trends with consistent sensitivities in each deformation cycle, reliably returning to the same initial resting value during the relaxation phase of each cycle. Ultimately and on average, the developed structure demonstrated elastic resilience to deformations of up to 42 μm , exhibiting a mean sensitivity of 0.174 rad/ μm , before reaching rupture at 58 μm . Thus, the capability of the structure to robustly endure uniaxial micro-displacements or pressures was proved. Although every capillary fiber among those considered resulted in a reliable sensor, the performance of those with a smaller inner diameter excelled.

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