



Semi-distributed interferometers fiber-optic sensors for high-sensitivity refractive index detection: Design and sensitivity analysis

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ABSTRACT

In this work, we present the design and analysis of fiber-optic refractive index (RI) sensors based on a simple semi-distributed interferometer (SDI). The SDI is a cavity formed between a cleaved fiber tip and the reflective interface between a single-mode fiber and a high-scattering fiber with core doped by Mg-silicate nanoparticles. The fabrication is rapid (~1 min) and straightforward, as only a splice and cleave of the fibers are required; the resulting spectral fingerprint is an interferometer-shaped envelope, with a stochastic distribution due to the random scattering centers of the in-cavity fiber. We fabricated 18 sensors with 6 different enhanced-scattering fibers, having different drawing temperature and speed; by analyzing the RI sensitivity of each unit, we obtain sensitivity values up to 787.0 dB/RIU (refractive index units), whereas the optimal fiber allows achieving average sensitivity of 457.9 dB/RIU.

1. Introduction

Refractive index (RI) sensors based on optical fibers are receiving wide interest in recent years, and have achieved substantial traction across the whole spectrum of chemical, biochemical, and biological applications [1–3]. The use of optical fibers enables the development of compact probes, with lightweight form factor, biocompatibility (according to ISO 10993 standard); the use of fiber-optic technologies allows also expanding the sensing units from a single device to a large-scale network of remote devices, exploiting either wavelength [4] or spatial [5] division multiplexing approaches, which enable multi-point, multi-probe detection with a single readout unit. RI sensors can be used for the measurement of unknown refractive indices of liquids, for example for the monitoring of water quality [6,7], or for the identification of gases [8,9]. Most of the applications however functionalize the surface of the sensor for the detection of a specific target [10]; this approach is commonly used in biosensors for the measurement of proteins [11], viruses [12], cells [13] using a specific bioreceptor, or in biochemical sensors for the identification of contaminations such as heavy metals in water [14,15]. Overall, compact in-fiber RI sensors are the building block of biochemical sensors.

Interferometry is a common approach for RI sensing, mainly thanks to the high potential in terms of performances [16–18], which lead to high-precision sensing [19]. The approaches based on optical fiber sensors for miniature probes resemble the main interferometric systems based on Mach-Zehnder, Sagnac, and Fabry-Perot structures [20]. The changes in the refractive index surrounding the optical fiber can be encoded in the optical path difference between the branches of the interferometer, obtaining a wavelength-sensitive spectrum; alternatively, the fiber tip can be used as a mirror having reflectivity varying as a function of the RI, obtaining large intensity variations in the reflection or transmission spectra [21].

The implementation of interferometric RI sensors and biosensors can be separated between transmission probes, which are more suitable for operating as a benchtop instrument for the analysis of different samples, and reflective sensors which can operate as compact reflective probe and have the capability of operating *in situ* [22]. Among the first type of devices, in-line interferometers and Sagnac loops have been used in biosensors for the analysis of biomolecules, while the Fabry-Perot approach has been widely employed in fiber-tip reflective sensors.

The Mach-Zehnder approach is based on the forward-propagating interference of at least two light paths. Li *et al.* [23] proposed a

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microstructured Mach-Zehnder interferometer with an inner micro-cavity, with sensitivity of 10055 nm/RIU (RIU = refractive index units); a similar design with a Mach-Zehnder inline cavity was proposed by Song *et al.* [18] achieving up to 11571 nm/RIU sensitivity. The modal interferometer extends the device to a multi-path structure, making use of multimode structures that have different effective propagation speed; Yu *et al.* [24] reported a modal interferometer based on a thin fiber core that achieves 61 nm/RIU sensitivity, while Betancur-Ochoa *et al.* [25] designed a similar interferometer based on a photonic crystal fiber cavity with 722 nm/RIU. The Sagnac interferometer exploits counter-propagating light paths arranged in a loop; besides the common use as a gyroscope, when the inner fiber exploits an open birefringent cavity the loop configuration enables RI sensing. Li *et al.* [26] proposed a Sagnac loop for the flow-cell sensing with sensitivity of 2592 nm/RIU, whereas a section of exposed-core fiber provides the birefringency; an alternative approach was reported by Gao *et al.* [27] using a microstructured high-birefringent fiber cavity, achieving sensitivity up to 13488 nm/RIU.

As previously stated, the main drawbacks of these interferometers is that the configuration is inherently a transmission device, which requires light to propagate across the sensing region; *in situ* sensing devices demand a reflective probe which can be manufactured on the fiber tip. The Fabry-Perot interferometer is a common configuration, particularly in its extrinsic format which is fabricated on the fiber tip [28]. Among others, Yang *et al.* [29] reported a Fabry-Perot interferometer with an off-centered fiber that achieves 11368 nm/RIU sensitivity. A different approach is proposed by Wu *et al.* [30] making use of an arc discharge to form a cavity terminated by fiber tip with RI sensitivity of 72.6 dB/RIU, and by Zhang *et al.* [31] that propose a multi-fiber Fabry-Perot fiber tip with 9.1 dB/RIU sensitivity. More recently, fiber-tip ball resonators have been proposed by Bekmurzayeva *et al.* [21] with sensitivity up to 107.8 dB/RIU; while this structure is not a cavity in the strict sense, it forms a multi-path shallow reflection fringes that resemble a fiber-tip interferometer.

In this work, we design and experimentally analyze a new type of interferometer, labeled semi-distributed interferometer (SDI) that is originated from a Fabry-Perot structure but with an extreme simplification of the fabrication process. Rather than forming a two- or multi-mirror structure through successive splicing of various fiber types, which requires non-standard splicing recipes and therefore requires a complex process, all the structure is based on single-mode fibers (SMFs). The key is that the reflections needed to form an interferometer are provided by the use of an enhanced backscattering fiber (EBF) [32], which however is fused to a standard SMF by a standard splice. By cleaving the tip, one can form an interferometer that resembles a shallow Fabry-Perot structure; the inner reflections of the EBF due to the presence of scattering centers generates distributed reflections, and for this reason the resulting device behaves as a cavity with deterministic length interleaved by an array of distributed random reflections.

We present the result of the fabrication of 18 SDI sensors made with this process, based on 6 different types of EBFs doped with Mg-silicate nanoparticles, drawn at different temperature and speed. The results show that the spectral fingerprints change with the type of fiber defects; the maximum sensitivity for each sensor varies from 71.6 dB/RIU to 787.0 dB/RIU, providing a high-sensitivity platform capable of resolving average RI changes down to 6.7×10^{-5} RIU. The simplicity of fabrication and interrogation of the SDI, together with a sensitivity enhancement of 6–10 times with respect to Fabry-Perot sensors [30] and ball resonators [21] provides a great platform for *in-situ* refractometry and biosensing [33].

2. Methods

2.1. Fabrication of the SDI sensors

The process for the fabrication of the SDI sensors is illustrated in Fig. 1, and has been applied to all the sensors presented in this work. The

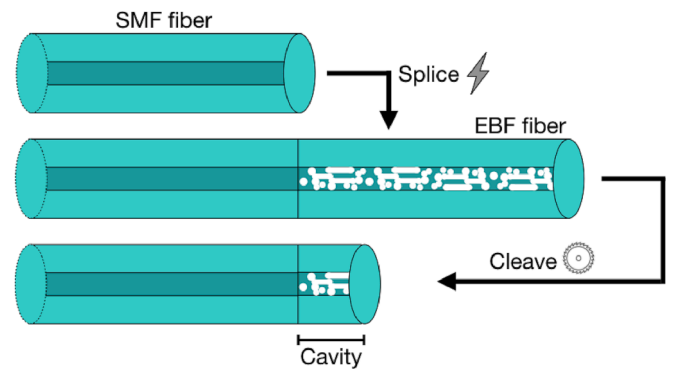


Fig. 1. Fabrication and interrogation of the SDI interferometer for RI sensing, highlighting the splice-and-cleave operation.

process is based on two simple operations, and can be labeled as “splice-and-cleave”. At first, the enhanced backscattering fiber (EBF) that acts as a reflector is spliced to a standard single-mode fiber (SMF; Corning SMF-28), using a standard telecom splicer (Fujikura 12-S; SMF-SMF recipe). The EBF fiber is designed in order to match the core/cladding size of SMF fibers. Due to the presence of scattering centers, the interface between the SMF and the EBF provides a tiny reflectivity ($\sim 10^{-5}$). In order to form a cavity, the EBF is manually cleaved with a fiber cleaver (Fujikura CT-08) at a short distance (< 1 mm) from the splice section, forming a tip mirror due to the Fresnel reflection at the interface between the EBF and the outer medium.

The resulting device acts as a cavity formed between the tip and the SMF/EBF mirrors, which can be regarded as a deterministic spectrum, corresponding to a low-finesse Fabry-Perot interferometer. However, the inner reflections occurring in the EBF due to the large presence of scattering centers causes a set of distributed reflections, whose intensity and phase is random due to the inhomogeneous distribution of defects [34]. This set of reflections provides a stochastic variation of the Fabry-Perot spectrum, and depends on the type of EBF, which leads to a semi-stochastic spectral fingerprint. Hence, the SDI has a very simple fabrication process, all carried out in ~ 1 min with telecom-grade components and operating as a compact reflective probe on the tip of the fiber, suitable for *in situ* operation.

It is important to recall that the cavity length is set by the manual cleave, and therefore it cannot be controlled with precision by the operator. Due to the semi-stochastic nature of the SDI spectra, the fact that the user cannot set the cavity length is not affecting the operation of the sensor, since each section of the EBF is anyway regarded as a unique reflector due to its irregular scattering pattern.

2.2. Enhanced backscattering fibers

The sensing mechanism of the SDI is therefore entirely encoded in the EBF fiber. At the tip side, the Fresnel reflection occurring at the interface with the surrounding medium provides an RI-dependent mirror; at the distal side, the presence of a high Rayleigh scattering increment with respect to an SMF provides the reflectivity required to form a cavity; within its length, the continuous set of distributed reflections provides intermediate layers that alter the output spectra.

The method proposed in this work for achieving the scattering enhancement is the use of a fiber having the core doped with La-silicate nanoparticles. The fabrication process is the same as previously reported to obtain Mg-silicate nanoparticles [35]. The preform was prepared with the modified chemical vapor deposition (MCVD) process. The germanium-doped silica porous layer was immersed for three hours with a doping solution containing 0.7 mol/l LaCl_3 dissolved in ethanol. Lanthanum ions are added to initiate the phase separation and the formation of La-silicate nanoparticles. Then, the porous layer was dried and sintered to form a dense layer. Finally, the tube was collapsed to form

the preform. Several drawing conditions were used to obtain fibers to alter the characteristics of the nanoparticles [35–37]. Drawing temperature and speed were varied in the range 1800–2050 °C and 15–32 m/min, respectively. The usual drawing conditions are 1950 °C, 21 m/min.

In order to evaluate the optimal properties of the fiber, we fabricated 18 different sensors made with 6 different EBFs, drawn at different temperature and speed, as shown in Fig. 2(a). The first fiber was drawn at the highest temperature (2050 °C) and intermediate speed (21.3 m/min). The second and third fibers have been drawn at the same speed, but with lower temperatures (1950 °C and 1800 °C, respectively). Fibers 4 and 5 have been drawn at a higher speed (32 m/min), respectively at 1800 °C and 1950 °C; the sixth fiber instead has been drawn at the smallest speed (15 m/min) at the temperature 1950 °C.

As shown in [37] and reproduced in the artwork in Fig. 2(b), the different temperatures and speeds for the fiber drawing process result in different types of defects, which in turn affect the Rayleigh scattering. The first fiber provides small nanoparticles in the fiber core, which are similar to the fibers used for distributed physical sensing [38]. Lower temperature drawing conditions result in an elongation of the nanoparticles within the fiber, which progressively result in an increment of overall scattering centers; conversely, an increase of the drawing speed result in the formation of smaller particles in the EBF core, while lower speed values promote defects with higher size and lesser elongation.

The Rayleigh backscattering traces for the six EBF fibers are shown in Fig. 3. All the fibers have similar scattering gain, defined as the increment of the scattering level with respect to an SMF fiber; the gain varies between 54.1 dB (fiber 6) and 59.9 dB (fiber 3). This confirms that the SMF/EBF interface provides a reflectivity in the order of 10^{-5} , considering that the reflectivity of the SMF fiber is lower than 10^{-10} . The first fiber has a two-way attenuation estimated as 30.8 dB/m, which is similar to other fibers with Mg-silicate nanoparticles [32,38]. All the other fibers have a very high attenuation, ranging from 809 dB/m to 1278 dB/m (considering that the exact value cannot be easily estimated due to the spatial resolution of the OBR (optical backscatter reflectometer) compared to the steep attenuation slope). Such significant losses imply that the fiber can only be used in a short length, but also that the distributed reflections occurring in the fiber can be substantial.

2.3. Numerical analysis

The effect of the scattering enhancement is shown in Fig. 4, which displays the electromagnetic model of the SDI sensor. The mirrors forming the cavity can be modeled as deterministic terms. The tip mirror corresponds to the Fresnel reflection occurring between the fiber core (effective refractive index 1.454) and the outer medium, considered to

be a watery analyte and therefore with refractive index 1.333; the distal mirror occurs at the EBF/SMF interface and has reflectivity equal to 10^{-5} . The inner reflections are modeled as a set of distributed mirrors, having reflectivity that ranges between 0 and F times the distal reflectivity; small values of F can be observed in fibers with small defects, while large values of F correspond to large density of defects in the fiber core, which lead to a randomization of the optical structure.

Each mirror corresponding to the structure was modeled through its transmission matrix, as shown in [39,40]. Intermediate layers were also modeled as a set of 75 mirrors (such that the spacing between mirrors is on average larger than the wavelength), spread along the cavity at random position and with random reflectivity, varying the value of F in order to model different fiber types; the propagation layer between each mirror was also modeled using its corresponding transmission matrix. The reflection spectrum was computed through the product of all the chain of mirror/propagation layers.

As shown in Fig. 4, the factor F entirely governs the spectrum of the device. For a small value of F (25%), the spectrum appears as a standard spectrum for a low-reflectivity extrinsic Fabry-Perot interferometer [39]. The spectral envelope appears as a sine-wave shape, with the peaks/valleys of the spectrum spaced by a constant periodicity. The increment of refractive index (in the chart, corresponding to 0.006 RIU) causes a reduction of the Fresnel reflectivity at the tip, which in turn results in the drop of the spectral level for each peak or valley of the structure [41]; this effect can be measured in each of the spectral feature, and appears as a quasi-constant term in the structure.

Raising the factor F to 125% causes a distortion in the spectral term, and a reduction of the number of observed spectral features; even maintaining the same cavity length, the inner random reflection causes phase shifts that alter the spectral pattern. While the average reflectivity is similar to the previous case, the visibility of each spectral feature is altered and we observe clearly a randomization effect.

When setting for $F = 1000\%$, and in the last case $F = 5000\%$, we observe that the spectral fingerprint has substantial distortions from the initial case; spectral peaks and valleys have spectral depth even larger than 20–30 dB, and very sensitive spectral valleys appear in the optical spectrum. While each peak maintains an RI sensitivity, this result in a large variation of the sensitivity between each feature, and this is observed in a larger amount for the spectral valleys. Interestingly, while for the previous cases the sensitivity is always a negative term (which corresponds to the fact that RI increments cause a reduction of the reflectivity), some of the spectral feature observed for large F factors show the opposite trend; this can be for example shown with the deepest spectral valley at 1510 nm obtained for $F = 5000\%$, in which the reflectivity increases by about 15 dB for the 0.006 RIU increment.

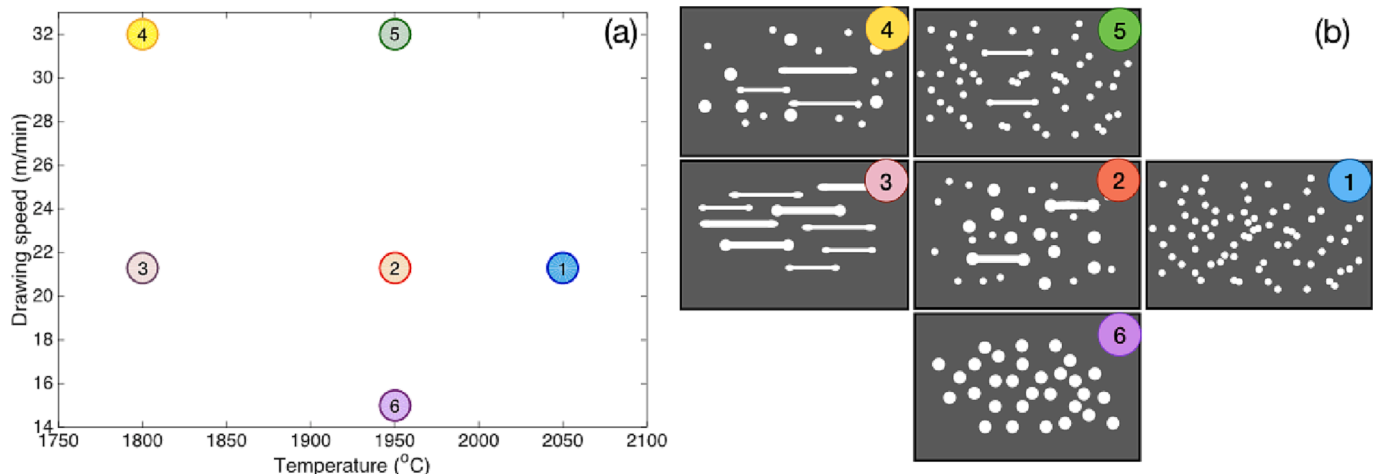


Fig. 2. Properties of the enhanced backscattering fibers considered for the fabrication of SDI sensors. (a) Drawing properties (temperature and speed) for the six fibers used for the SDI sensors. (b) Artwork reproducing the expected morphology of the scattering centers for each of the fiber type.

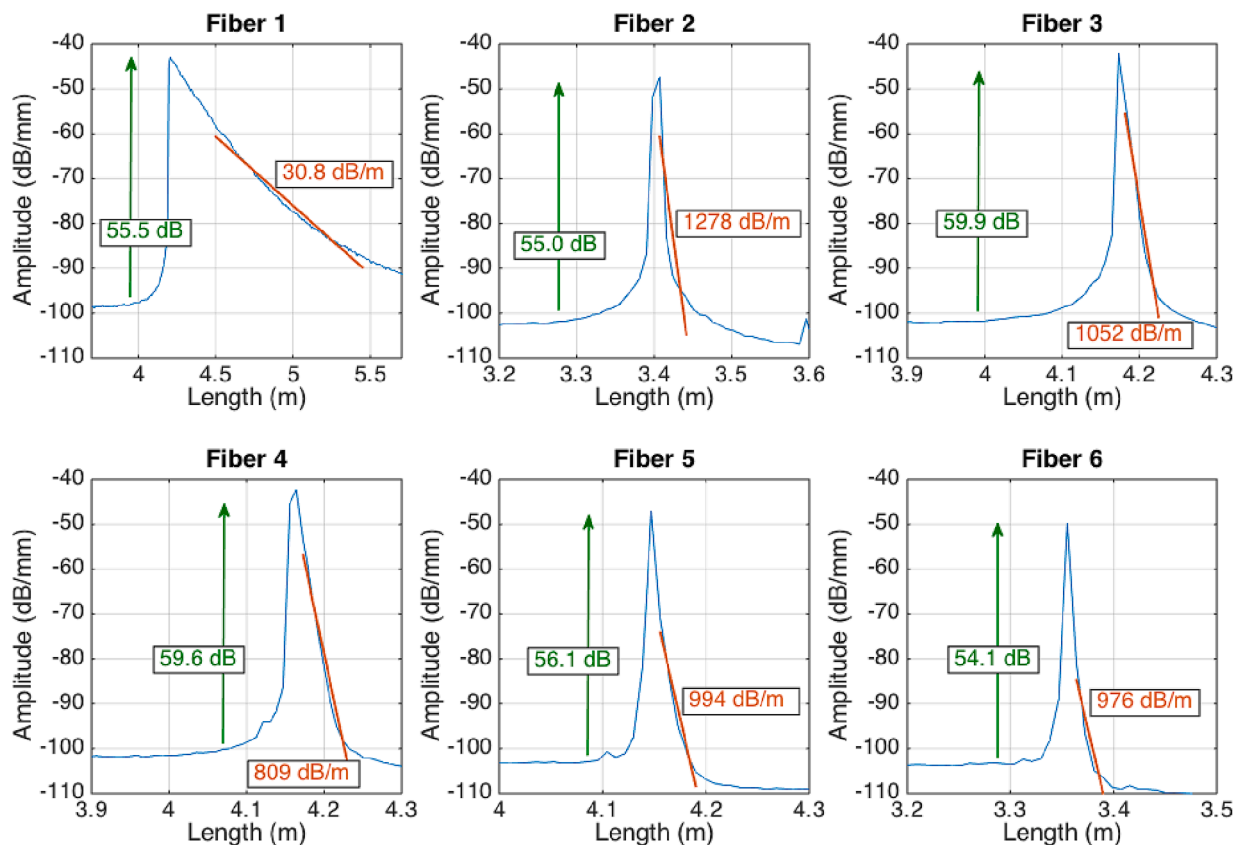


Fig. 3. Backscattering traces for the EBF fibers, displaying the amplitude of the reflected signal. Green markers show the scattering gain; red markers show the two-way attenuation measured as the slope of the trace. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The presence of such a large modulation of the intensity of the interferometer spectral valleys is due to the randomization effect of the fiber defects, which provide additional and random phase shifts to each order of reflection distributed within the SDI length.

We also observe that by increasing F the distance between adjacent peaks or valleys becomes shorter and more irregular, which confirms that when choosing EBF fibers with substantial defects the control of the cavity length is not an important factor in determining the spectral fingerprint.

2.4. Experimental setup and data analysis

The experimental setup, sketched in Fig. 5 schematic, includes an interrogator, a single-mode fiber cable to interconnect the SDI sensor, and a measurement chamber to evaluate the RI variations. The interrogator is an optical backscatter reflectometer (Luna OBR4600), operating over the 1527–1613 nm range with resolution 1.3 pm. SDI sensors were placed in a small chamber, varying the refractive index from 1.3476 to 1.3584, with an overall RI change of 10.8 mRIU in 6 incremental steps of 400 μ L; this small RI calibration mimics the operation of a typical biosensor, in which RI changes are in the order of 10^{-4} – 10^{-2} [33]. The RI change was obtained by different mixtures of water and sucrose with the method described in [21], and each RI solution was assessed using an Abbe refractometer (AbbeMat 300). All measurements were performed at room temperature.

SDI spectra have been processed with a digital finite-impulse response low-pass filter (Butterworth, 5th order, cut-off 0.006). On the reference spectrum, the wavelength location for each spectral feature (peaks and valleys) has been identified through a peak tracking algorithm with prominence ~ 1 dB. For each identified feature, the spectral intensity was obtained for each value of RI; then, the RI sensitivity has

been estimated through a linear regression. All the sensitivity figures estimated for each spectral feature presented in the following analysis has been obtained with coefficient of determination R^2 greater than 0.95; we also report the absolute value of the sensitivity, since its sign can be either positive or negative depending on the spectral feature. The peak detection process has been integrated in a MatLab (Mathworks, UK) function, that can be used for the RI detection.

In order to estimate the width of the spectral features, we define the fringe visibility (FV), defined as in [42]: $FV = (S_{\max} - S_{\min}) / (S_{\max} + S_{\min})$ where $S_{\max}$ and $S_{\min}$ are respectively the maximum and the minimum intensity recorded for each sensor over the spectral window, in dB units.

The same analysis was carried out for the 18 SDI sensors, 3 for each fiber; the dataset of all spectra acquired through the interrogator is enclosed as supplementary material.

3. Experimental results

3.1. SDI sensors working principle

In Fig. 6, we report the spectral and sensitivity analysis reported for a sensor drawn at the highest temperature (fiber 1), and therefore having smaller and more evenly distributed scattering centers in the fiber core. The first chart shows the reflection spectra for all the RI values. The spectral fingerprint appears similar to the numerical analysis in the case of lower F factor, as the spectrum appears as an almost regular interferometric fingerprint with maximum reflectivity equal to -30 dB; the RI increment results in a decrease of the intensity level across the full spectrum, which can be evaluated for each spectral feature. Fig. 6(b) shows the RI dependence for 4 different spectral features; we observe that the sensitivity appears to be larger for the valley rather than for the peaks. The third chart shows the envelope of all the detected peaks and

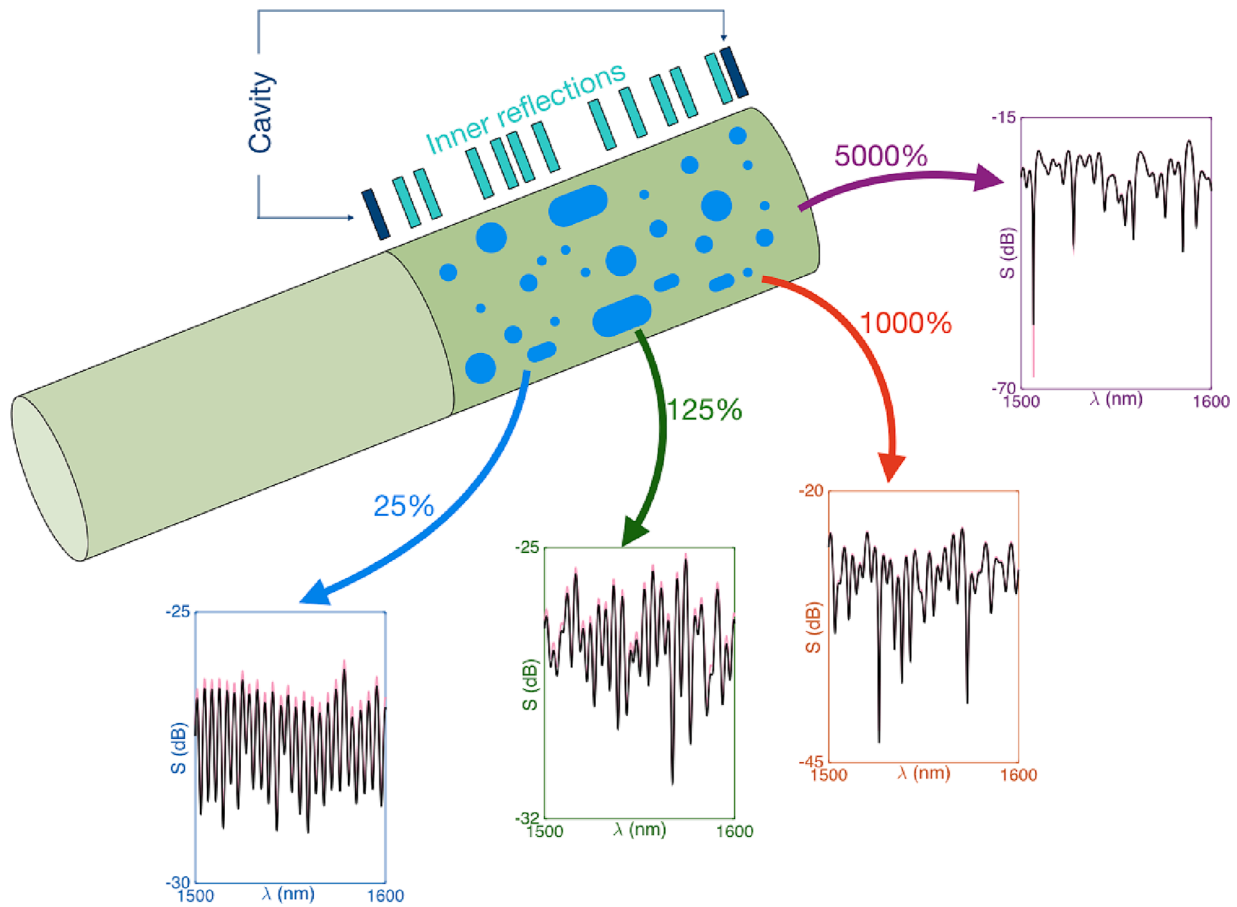


Fig. 4. Effect of the distributed reflections on the SDI sensor and its reflection spectra. The schematic shows the effect of the cavity and the inner reflections due to the Rayleigh scattering within the EBF fiber. The resulting structure can be modeled as two mirrors, with known reflectivity, interleaved by a series of inner mirrors with random reflectivity and location. The resulting reflection spectra $S(\lambda)$, λ = wavelength, are displayed for inner mirrors having maximum reflectivity equal to 25%, 125%, 1000%, and 5000% of the SMF/EBF interface. Pink curves show the spectra estimated for the reference RI value (1.333) while black curves show the spectra for an RI increase of 0.006. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

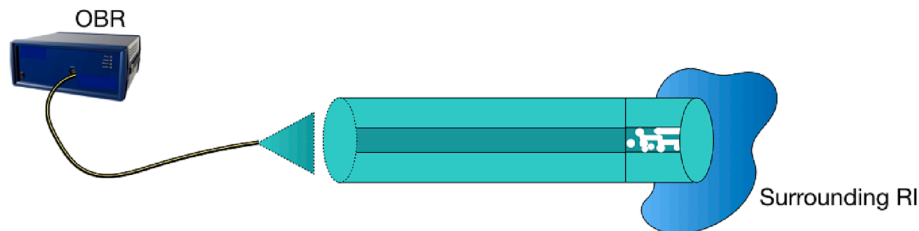


Fig. 5. Setup for the interrogation of the SDI probe using an optical backscatter reflectometer.

valleys in the optical spectrum; hereby we can display how the peak tracking routine correctly identifies 26 spectral peaks and 25 valleys, with a quite consistent wavelength difference between adjacent features. In Fig. 6(d) we report the sensitivity estimated for each feature, across the full spectrum. We can observe that, for this sensor, the spectral peaks have lower sensitivity, ranging from to 39.3 dB/RIU to 59.9 dB/RIU (average 51.2 dB/RIU), while the sensitivity is higher for spectral valleys, from 45.7 dB/RIU to 84.3 dB/RIU (average 62.4 dB/RIU).

A different pattern is observed for an SDI sensor fabricated with the fiber 4, as shown in Fig. 7. Consistently with the numerical analysis and with the lower drawing temperature that promotes the presence of elongated particles in the fiber, the inner reflection layers cause the spectrum to appear as an interferometer with a larger fringe visibility. The maximum reflectivity is higher (-24 dB), while the deepest spectral

valley has -57 dB reflectivity; spectral valleys in general appear as sharp lines, while the spectrum is flatter in proximity of the peaks. The RI sensitivity of the two most prominent spectral valleys is 405.2 dB/RIU and 240.7 dB/RIU. The analysis of all spectral feature shows that the sensitivity for the spectral valleys is more prominent (average: 117.4 dB/RIU; standard deviation: 75.3 dB/RIU), while the sensitivity for the spectral peaks is inferior to the previous sensor (average: 37.9 dB/RIU; standard deviation: 13.5 dB/RIU).

In Fig. 8, we report the SDI sensor having the highest sensitivity, and fabricated with the fiber 6. The spectrum of the sensor appears as a clearer interferometer, with a well-defined free spectral range between two adjacent reflection peaks. The most prominent feature is the peak at 1596 nm; in this case, we observe that the RI dependence has the opposite sign of the previous sensors, and the sensitivity is 787.0 dB/RIU, which is the highest value reported for the SDI sensors in this study.

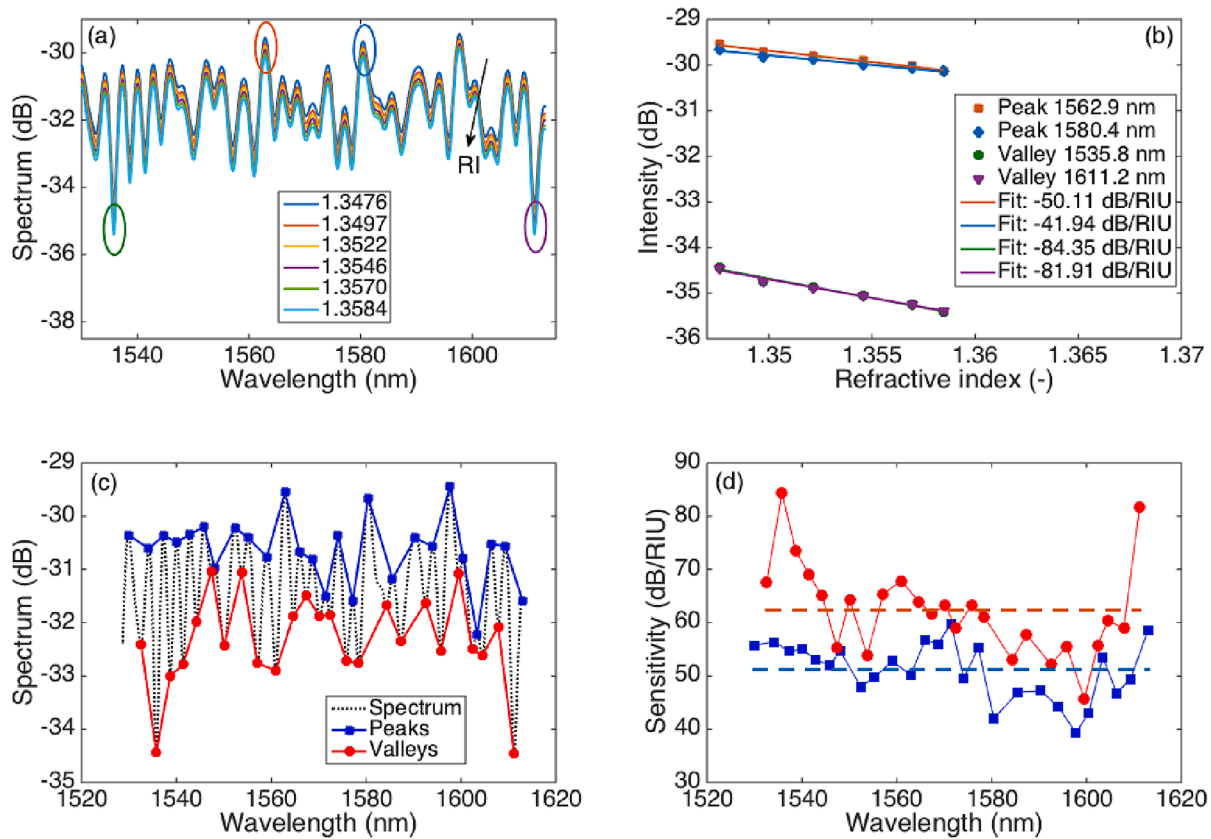


Fig. 6. Working principle and experimental analysis for a SDI sensor fabricated with the EBF fiber 1, drawn at the highest temperature. (a) Reflection spectra for the SDI sensors, for different RI values ranging from 1.3476 to 1.3584. The markers display four different spectral features, two peaks at 1562.9 nm and 1580.4 nm and two valleys at 1535.8 nm and 1611.2 nm. (b) For each of the previous peak/valley, the chart shows the spectral intensity for different RI values (markers), and the linear regression (solid lines) identifying the sensitivity. (c) Spectral feature identification: each peak (blue) and valley (red) within the SDI spectrum (black) is shown. (d) Sensitivity recorded for each peak (blue) and valley (red); horizontal dashed lines report the average values across all wavelengths. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Concerning the RI measurement stability, the root-mean square error for a 100-minute measurement with 10-minute sampling is 0.02 dB, compatible with the analysis in [5]; the resulting RI variation for the feature with the highest sensitivity corresponds to 2.5×10^{-5} RIU. The RI detection stability is mainly influenced by the power fluctuations of the OBR laser source over a measurement interval.

3.2. Refractive index sensitivity analysis

Fig. 9 reports the sensitivity obtained for each sensor by analyzing the spectral valleys, reported in boxplot format that shows the statistical analysis for all the spectral features.

The first fiber has the lowest RI sensitivity (71.0–100.2 dB/RIU), and the spectral features have nearly all the same sensitivity, as given by the short range of the sensitivity variation. The median sensitivity ranges from 54.8 dB/RIU to 71.8 dB/RIU.

For the other fibers, the sensitivity exhibits a similar pattern: the range of sensitivity values is much wider, but the width of the boxplot and the median sensitivity values is much higher (median values from 76.1 dB/RIU to 155.1 dB/RIU). Since the peak sensitivity occurs in proximity of the sharpest spectral dips, the top sensitivity ratings for each sensor appears as an outlier in the chart. Since the interrogation can be targeted only for the most sensitive feature, the maximum sensitivity is the most important performance metric: for the second fiber the sensitivity ranges from 100.2 dB/RIU to 388.8 dB/RIU; for the third fiber 198.9–453.7 dB/RIU; for the fourth fiber, 405.2–517.4 dB/RIU; for the fifth fiber, 130.8–273.7 dB/RIU; for the sixth fiber, 209.6–787.0 dB/RIU. The fourth fiber shows the most consistent trend,

with average maximum sensitivity value of 457.9 dB/RIU, while the average sensitivity for all the 18 sensors is 299.5 dB/RIU. The OBR analyzer can resolve the power detection with accuracy of 0.02 dB; considering the average sensitivity value, the SDI can resolve refractive index changes of 6.7×10^{-5} RIU, which is well compatible with the most performing biosensors [33].

The sensitivity value obtained for SDI sensors is higher than the figures obtained for other reflection-based RI sensors; specifically, it is about 5–8 times higher than ball resonators [21] and 6–10 times higher than arc-discharge Fabry-Perot interferometers [30], considering the 5 most sensitive SDI sensors compared to single-mode fiber sensors with an interferometric structure. The effect of the random defects of the EBF is beneficial for an increment of sensitivity, as the fiber drawn at the highest temperature has the lowest sensitivity.

A similar analysis has been carried out for the sensitivity of each spectral peak; as suggested from the numerical analysis, and displayed in Fig. 4, the sensitivity on the fiber peaks is inferior to the valleys; in addition, we notice a reverse trend as the sensors fabricated with the fiber 1 have a larger median sensitivity, while for all the other sensors the median sensitivity is < 40 dB/RIU. The largest maximum sensitivity value that is observed is 108.0 dB/RIU, while the lowest value is 37.2 dB/RIU. The sensitivity analysis is reported in Fig. 10.

For all the sensors, the sensitivity observed in correspondence of the spectral peaks is substantially inferior to the one observed along the spectral valleys; in addition, the sensitivity measured along the peaks has a much more regular pattern with fewer outliers producing a highly sensitive response, and the results are more comparable with other interferometers and ball resonators based on Fresnel reflection [21,30].

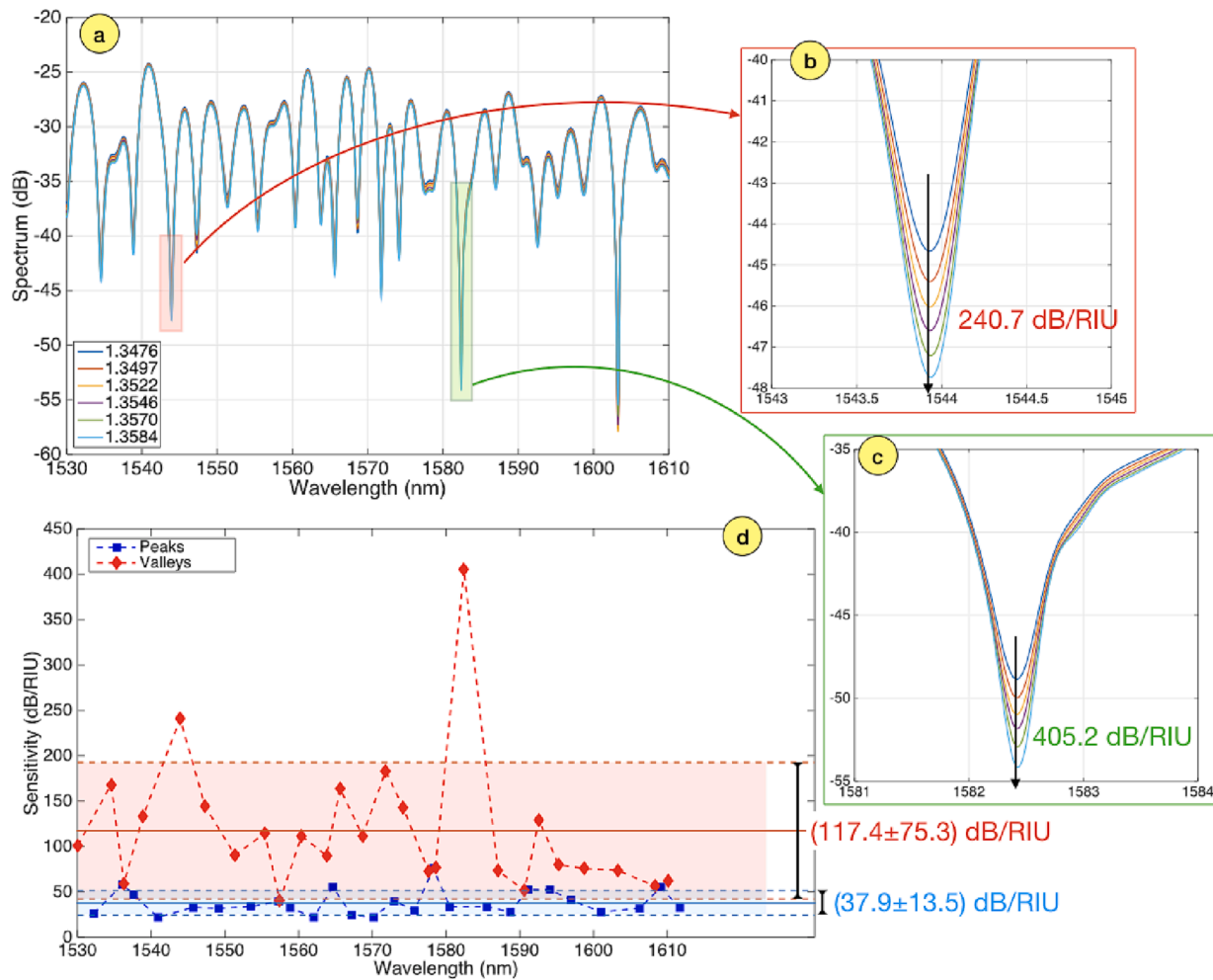


Fig. 7. SDI sensor fabricated with fiber 4. (a) Reflection spectrum of the SDI sensor; two spectral valleys have been highlighted, having the highest sensitivity for the sensor. (b-c) Inset reporting the two spectral valleys for different RI values, and the obtained RI sensitivity. (d) Sensitivity for each peak (blue) and valley (red) of the SDI spectrum; the blue/red strips show the average value (solid) and the standard deviation (dashed). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Therefore, the optimal interrogation of the SDI sensors should target the detection of spectral valleys; in this work this is implemented on an OBR instrument, but other analyzers such as Fiber Bragg Grating interrogators based on a swept-laser, or optical spectrum analyzers, or optical vector analyzers can obtain the same performance ratings. The sensitivity on the spectral peaks is however important when employing an analyzer with inferior performances, lower cost, and better portability, such as fiber-coupled infrared spectrometers or interrogators based on a broadband light source; in this case the higher reflectivity at the SDI spectral peaks, together with the broader spectra observed in proximity of the spectral peaks, is beneficial for the interrogation, as the analyzers might not correctly identify the highly sensitive spectral valleys due to the low reflectivity. This is confirmed by the fact that the spectral dips with the highest sensitivity have also a low reflectivity (e.g. -67 dB in Fig. 8) which might not be correctly evaluated by detectors with lower dynamic range such as infrared fiber-coupled spectrometers.

We remark that the results obtained from the experimental analysis have a significant match with the transmission-matrix theoretical model of the SDI, tailoring the statistical variations of reflectivity in each fiber cross-section; on the other side, due to the random distribution and density of each high-scattering fiber section, the optimization of the fiber design can be achieved only in a statistical sense, as confirmed with Figs. 9-10.

Finally, in Fig. 11 we display the relationship between the sensitivity values in the spectral valleys (maximum and average between all

features) and the fringe visibility. In both cases, we can observe the significant difference between the leftmost cluster corresponding to fiber 1 in which the fringe visibility is inferior to 0.1, and the rightmost cluster corresponding to all the other fibers 2-6, in which the fringe visibility is within 0.27 and 0.48. From this chart, we notice that the scattering properties of each type of EBF fiber does not provide a clear variation, as the sensitivity data are substantially scattered. We do however notice a marginal trend that links the average sensitivity, and the maximum sensitivity in a less clean pattern, to the fringe visibility; higher levels of sensitivity are achieved for sensors having a higher fringe visibility, which means that the EBF design should target towards lower drawing temperatures and promoting a larger amount and randomization of scattering centers.

On the other side, the influence of the cavity length on the sensitivity is marginal, as the free spectral range (FSR, defined as the wavelength difference between adjacent peaks/valleys) does not seem to play a significant role in determining the sensitivity. By estimating the cavity length through the FSR, we obtain a marginal slope of -0.46 dB/RIU $\times \mu\text{m}^{-1}$ ($R^2 = 0.15$) in terms of maximum sensitivity per units of cavity length.

The whole set of experimental data is summarized in Table 1, reporting the fiber properties and the achieved performances for each SDI sensor.

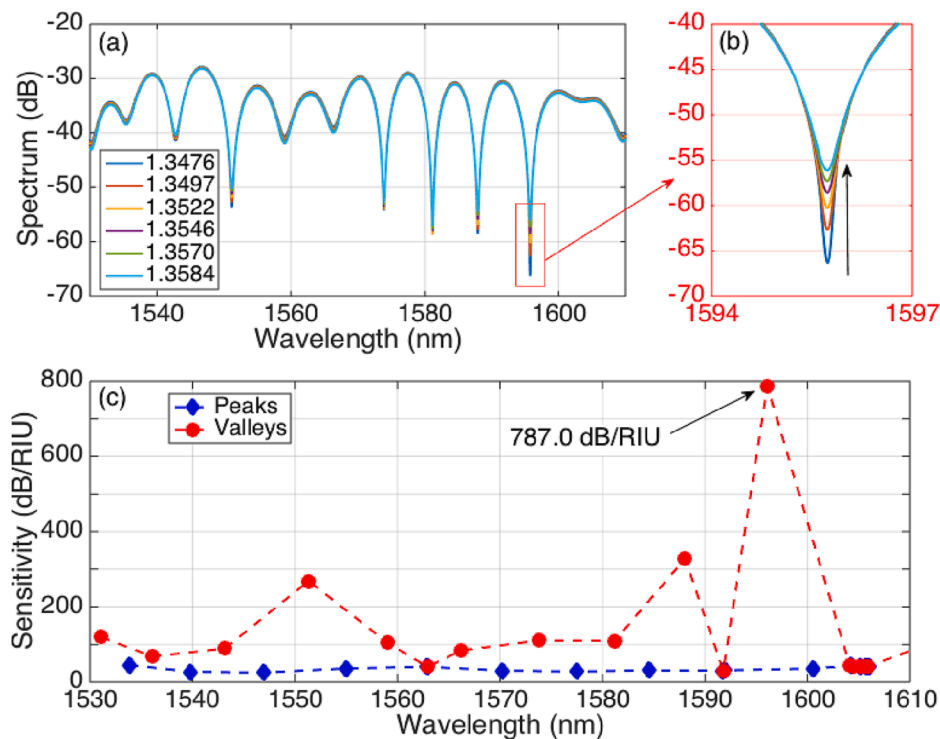


Fig. 8. SDI sensor fabricated with fiber 6, and reporting the highest sensitivity. (a) Spectrum of the sensor for different RI values; (b) inset on the most sensitive feature at 1596 nm, with the arrow showing the RI trend. (c) Sensitivity for each peak/valley within the spectrum, highlighting the top sensitivity value of 787.0 dB/RIU.

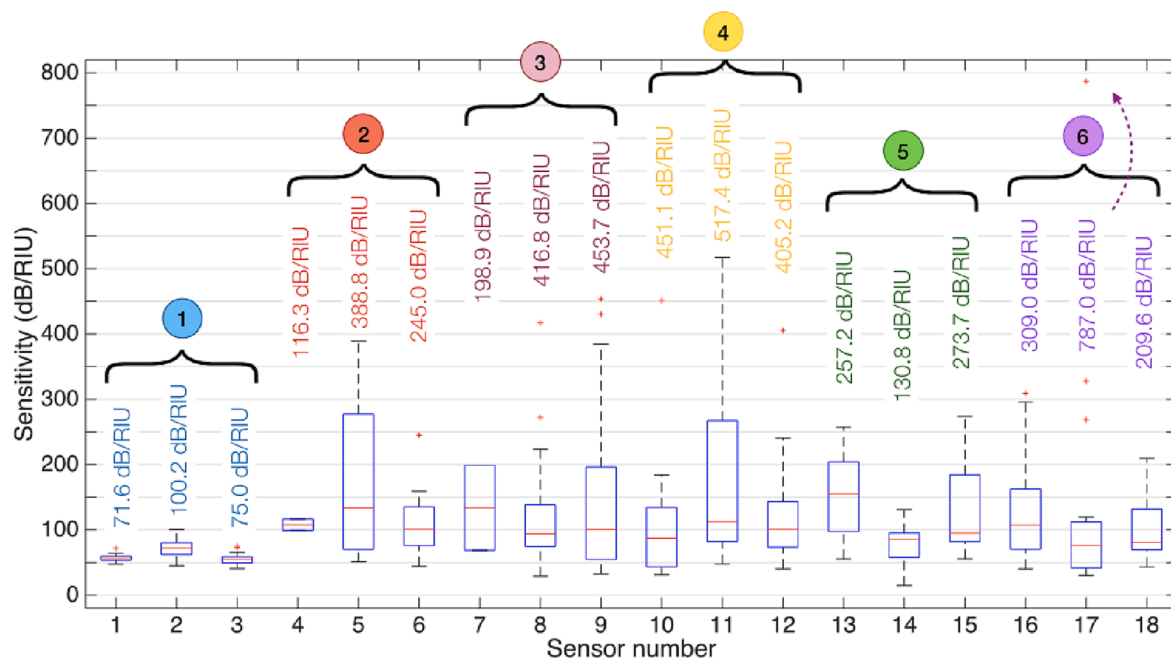


Fig. 9. Sensitivity of the SDI sensors, recorded for all the spectral valleys; the data for all 18 sensors, for each of the 6 EBF fibers, is displayed. The vertical labels report the highest sensitivity for each sensor. Data are reported by the analysis of all the valleys; the boxplot displays the median value (horizontal red marker), the 25th-75th percentile (blue box), the minimum/maximum values without outliers (black dashed lines), and the outliers (red markers) that provide the highest sensitivity. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Conclusions

In conclusion, we reported and experimentally analyzed a semi-distributed interferometer for fiber-optic refractive index sensing. The SDI structure is formed at the interface between a SMF and an EBF fiber,

and then manually cleaving the fiber tip; the splice-and-cleave fabrication process is rapid (~1 min), reliable, and can all be implemented on telecom-grade equipment.

The highest performances are obtained for EBF fibers drawn at lower temperatures, that promote a larger size of defects such as larger La-

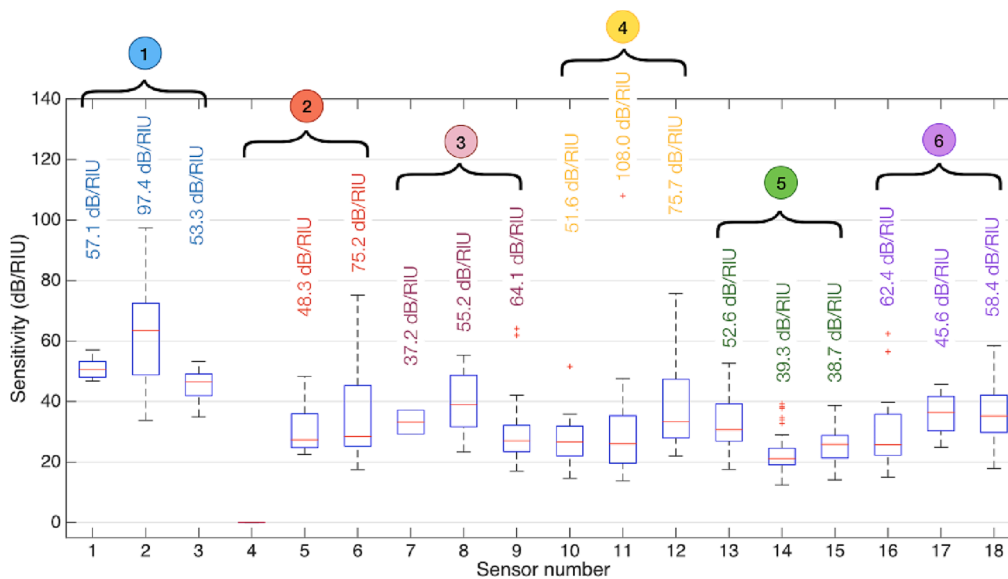


Fig. 10. Sensitivity of the SDI sensors, recorded for all the spectral peaks; the data for all 18 sensors, for each of the 6 EBF fibers, is displayed. The vertical labels report the highest sensitivity for each sensor. Data are reported by the analysis of all the valleys; the boxplot displays the median value (horizontal red marker), the 25th-75th percentile (blue box), the minimum/maximum values without outliers (black dashed lines), and the outliers (red markers) that provide the highest sensitivity. For sensor 4, no spectral peak with sufficient prominence was identified. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

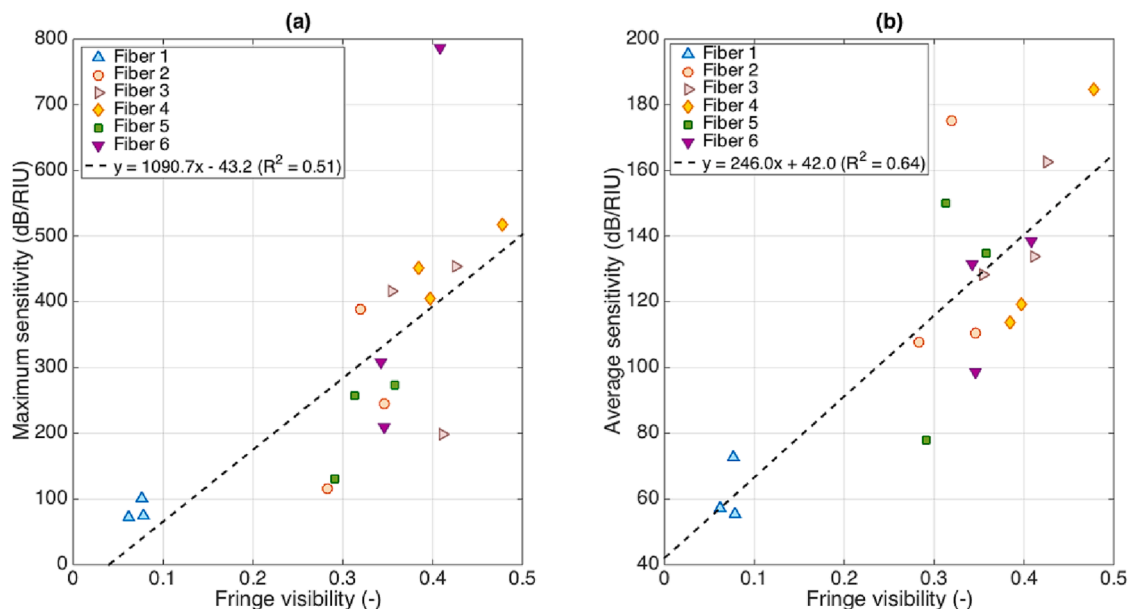


Fig. 11. Relationship between the RI sensitivity of the SDI sensors, recorded on the spectral valleys, and the fringe visibility of the reflection spectra. The data are reported for each fiber type, displaying (a) the maximum sensitivity, and (b) the average sensitivity for all peaks. Dashed lines show the regression for all data points.

silicate particles and elongated defects. In these fibers, we observe a larger amount of inner reflections, forming a distributed cavity with stochastic properties within the two mirrors (fiber-tip and distal position) having a deterministic reflective pattern.

An experimental analysis of a set of 18 SDI sensors, fabricated on multiple fibers, shows that the maximum sensitivity is 787.0 dB/RIU, while the optimal fiber allows achieving an average sensitivity of 457.9 dB/RIU. The maximum sensitivity can be observed by interrogating the sharpest spectral valleys. The SDI sensitivity values allows interrogating the refractive index changes with average accuracy of 6.7×10^{-5} RIU. The RI dependency is also encoded in spectral peaks, but obtaining a lower sensitivity.

The main advantage of the SDI applied for RI sensing relies on the combination between ease of fabrication and performances, compared to other intensity-modulated fiber optic sensors. Plasmonic tilted gratings, such as [8], can achieve a larger sensitivity (over 5,000 dB/RIU) but only for RI ~ 1 , while the typical sensitivity in watery media is few

hundreds dB/RIU [10]; the fabrication of the device is much slower and less scalable, as it involves the inscription of a grating and a subsequent sputtering of a metallic layer of optimal thickness. On the other side, a simple ball resonator reported in [5 21] has also a simple fabrication process, and comparable performances (usually up to 200 dB/RIU); a ball resonator however has a much lower reflectivity, and since its spectrum is almost flat the interrogation of the RI changes requires a specific feature extraction method.

Future work will address a further optimization of the fiber defects (position and size), controlling the scattering properties in order to tune the SDI spectra and performances, and developing a model that links the scattering properties to the fiber drawing parameters. From an application standpoint, further efforts will be deployed to functionalize SDI sensors for the targeted detection of biomolecules.

Data statement

The data related to this study is available as supplementary materials; these include the spectra for all the 18 sensors hereby reported, for

Table 1

Recap of the parameters of the EBF fibers, and the SDI sensors generated for each fiber. Data in bold show the best rating for each parameter.

Sensor #	Fiber properties					Sensor properties				
	Fiber #	Drawing speed (mm/min)	Drawing temp. (°C)	Fiber losses (dB/m)	Scattering gain (dB)	Max. RI sensitivity (dB/RIU) ¹	Median RI sensitivity (dB/RIU) ¹	Fringe visibility	Average FSR (nm) ²	Average max. sensitivity (dB/RIU) ³
1	1	21.3	2050	30.8	55.5	71.6	56.9	0.0618	4.76	82.3
2						100.2	71.8	0.0762	2.88	
3						75.0	54.7	0.0785	3.32	
4	2	21.3	1950	1278	55.0	116.3	107.7	0.2830	1.50	250.0
5						388.8	133.1	0.3191	9.96	
6						245.0	101.2	0.3456	5.66	
7	3	21.3	1800	1052	59.9	198.9	133.7	0.4105	11.56	356.5
8						416.8	94.0	0.3542	4.40	
9						453.7	100.9	0.4253	4.33	
10	4	32	1800	809	59.6	451.1	87.4	0.3848	4.06	457.9
11						517.4	112.5	0.4774	5.24	
12						405.2	101.1	0.3968	3.18	
13	5	32	1950	994	56.1	257.2	155.1	0.3133	3.96	220.6
14						130.8	85.6	0.2907	1.55	
15						273.7	94.9	0.3581	4.61	
16	6	15	1950	976	54.1	309.0	107.4	0.3424	2.15	435.2
17						787.0	76.1	0.4082	4.51	
18						209.6	80.8	0.3457	2.59	

¹ The data are referred to the spectral valleys.² The FSR (free spectral range) is the average difference between two adjacent spectral peaks.³ The data correspond to the average between the maximum sensitivity of the 3 SDI sensors on the same fiber.

various values of refractive index (also included).

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CRediT authorship contribution statement

Sakengali Kazhiyev: Methodology, Software, Formal analysis, Investigation, Writing – review & editing. **Albina Abdosova:** Methodology, Investigation, Writing – review & editing. **Damir Moldabay:** Methodology, Investigation, Writing – review & editing. **Aida Rakhimbekova:** Methodology, Investigation, Writing – review & editing. **Wilfried Blanc:** Investigation, Resources, Writing – review & editing. **Daniele Tosi:** Conceptualization, Software, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data is available to all readers via Dropbox; a link is sent in Supplementary Material, and access will be given by the corresponding authors.

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