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[INVITED] New perspectives in photonic crystal fibre sensors

Joel Villatoro [a,b,*], Joseba Zubia [a]

[a] Department of Communications Engineering, Escuela Técnica Superior de Ingeniería (ETSI) de Bilbao, University of the Basque Country (UPV/EHU), Alda. Urquijo s/n, E-48013 Bilbao, Spain
[b] IKERBASQUE –Basque Foundation for Science, E-48011 Bilbao, Spain

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ABSTRACT

In this paper we analyse the recent advances on sensors based on photonic crystal fibres(PCFs) and discuss their advantages and disadvantages. Some innovative approaches to overcome the main limitations of PCF sensors are also analysed. In addition, we discuss some opportunities and challenges in PCF sensing for the coming years.

1. Introduction

Photonic crystal fibres (PCFs), also known as micro-structured or holey optical fibres, are considered a major breakthrough in optical fibre technology. PCFs are characterized by a pattern of microscopic voids in the transverse plane that runs all over the waveguide [1–3]. Due to their holey structure PCFs have unique guiding mechanisms and modal properties or optical properties that are not possible to achieve with conventional optical fibres. Some key features that define the unique properties of a PCF include: (i) the composition of the material the PCF is made of, (ii) the design of the array of voids that form the waveguide, and *iii*) the use of functional materials inside the PCF voids or of post-processing techniques. A PCF can be made of different materials, as for example, pure silica, chalcogenide, doped, and multi-component glasses, or polymers. The design of the PCF microstructure makes possible light guidance by photonic band gap effects or by the modified total internal reflection effect [3]. On the other hand, the infiltration of materials in the PCF or its post-processing can give additional functionalities to a photonic fibre [3]. Due to all these features, PCFs offer outstanding potential for the development of sensors and many other devices (polarisers, filters, etc.). That is why, the interest of the scientific community on PCFs has increased remarkably in the last years as the number of publications, patents, and conference proceedings suggest. Presently, the fabrication of PCFs is so advanced that fibres with complex patterns with voids with sub-micron precision can be fabricated [3]. Currently, different types of PCFs are commercially available and several research groups around the world can fabricate PCFs with *ad hoc* optical properties. Thus, we can say that the design and fabrication of PCFs is in a mature stage.

PCFs have attracted considerable attention by the sensor community as they represent new alternatives to devise optical fibre sensors. Fig. 1 summarises the different alternatives and techniques to develop sensors with PCFs. Like in a conventional optical fibre, the light guided by a PCF can be modulated by physical parameters such as strain, temperature, curvature, pressure, etc. Thus, sensors for such parameters can be devised with PCFs. In fact, the sensing of physical parameters with PCFs is the more developed area of application. A number of innovative sensing architectures have been reported so far; see for example the reviews [4–6]. From the number of possibilities to devise a sensors with PCF those that employ Bragg gratings have attracted considerable attention, largely due their potential application in the development of new sensors or sensors with better performance [7–9]. Bragg gratings can be inscribed in PCFs in different manners [7–9]. However, the inscription of the grating in PCFs is challenging due to the presence of the microscopic voids [8,9]. Therefore, considerable research effort will be required to make Bragg gratings in PCFs a real alternative to those inscribed in conventional fibres. Another type of grating that can be written in PCFs is the so-called long-period grating (LPG) [10–13]. The inscription of LPGs in PCFs is less complicated than that of Bragg gratings. In fact, the microscopic voids of the PCF can help to inscribe LPGs [14]. Unlike Bragg gratings, LPGs are sensitive to the medium that surrounds

* Corresponding autor at: Department of Communications Engineering, Escuela Técnica Superior de Ingeniería (ETSI) de Bilbao, University of the Basque Country (UPV/EHU), Alda. Urquijo s/n, E-48013 Bilbao, Spain.
E-mail address: agustinjoel.villatoro@ehu.eus (J. Villatoro).

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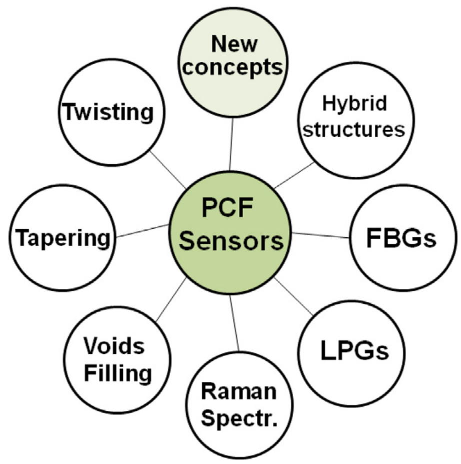

Fig. 1. Illustration of the different alternatives and techniques to develop sensors with photonic crystal fibres. FBGs means fibre Bragg gratings and LPGs long period gratings. New concepts and approaches to devise PCF sensors are expected in the years to come.

the PCFs, and therefore, they are good candidates to develop bio-chemical sensors [15]. The disadvantages of LPGs are the fact that they operate mostly in transmission mode and that the resonance peaks are broad. These factors limit the use of LPGs in practical applications. However, we believe that the aforementioned shortcomings of Bragg and long-period grating in PCFs will be overcome in the years to come.

The holey structure of PCFs offers an additional degree of freedom in the design of optical sensors as they can be infiltrated with liquids, gases or nanomaterials [16–23]. In most cases the PCF plays also the role of gas or liquid chamber. As the voids of a PCF have microscopic dimensions, the amount of liquid or gas needed to carry out the sensing task is minimal, on nanolitre levels. The guided light can interact directly with the liquid or gas present in the voids of the PCF in a long section of the fibre, even metres. This gives rise to a strong light–matter interaction, hence to high sensitivity. The complexity of the setups to infiltrate gases, liquids or nanoscale materials in the PCFs [16–23] is an issue that must be minimised otherwise it will be difficult to find practical applications of PCFs for gas or liquid sensing. On this regard, PCF sensors can benefit from the advances in micro- and opto-fluidics and nanotechnology.

The commercialisation of PCFs sensors is still in its infancy. However, the growing use and acceptance of optical fibre sensors in various sectors and fields suggests that there are significant business and R&D opportunities in fibre optic sensors and associated technologies. This also represents opportunities for PCF sensors and other devices. The global market for optical fibre sensors is forecasted to grow steadily in the coming years to reach US$4.33bn in 2018 [24,25]. In that year, the market share for point sensors is estimated to be around 30% or US$1.236bn [24]. Some sensors based on PCFs reported so far can rival the performance of those based on conventional optical fibres. PCF sensors may also open up new applications (and even markets) since they show considerable promise for monitoring gases, biological or chemical agents [26]. Thus, it seems possible that PCF sensors go from proof-of-principle concepts or laboratory prototypes to commercial devices.

For the present authors it is clear that to make PCF sensors a commercial reality they must exhibit at least the same advantages than those of sensors based on conventional optical fibres. PCF sensors must be sensitive only to the parameter of interest (the measurand), and ideally, immune to noises, environmental disturbances, and to any other parameter that is likely to be present during its use. Another possibility is to make PCFs sensors with multi-parameter sensing capability. Other important aspects of a PCF sensor include high performance and functionality, low cost, reproducibility, and simple operation. Thus, in the design of PCF sensor for a particular use, the mechanism with which light interacts with the measurand and the different properties that may affect the sensor performance must be carefully analysed.

Here, we analyse some innovative PCF sensors and discuss some possible trends and challenges for the next years.

2. Point sensors based on PCFs

Point sensors based on conventional optical fibres are in a mature stage. Such sensors are being used for detecting or monitoring (and even for controlling) a myriad of parameters such as temperature, strain, vibrations, pressure, refractive index, humidity, etc. [27,28]. Several point fibre optic sensors are commercially available. Point sensors based on PCFs have been proposed as an alternative to those based on standard fibres. Different physical parameters can modulate or perturb the guided light in a PCF by means of elasto- or thermo-optic effects, in a similar manner than they do in standard optical fibres. There are several alternatives to sense a physical parameter with PCFs. So far the most studied parameter is strain, largely due to the number of applications in which the monitoring of strain-induced changes is important. Two examples include the health monitoring of complex structures (aerospace, marine, or civil structures) and the curing process of composite materials. As many physical parameters can be converted to strain, thus PCF strain sensors can be easily adapted to sense other parameters such as load, pressure, vibrations, impact, curvature, bending, etc.

The most reliable and successful fibre optic strain sensors employ Bragg gratings [27,28]. Such gratings consist of a periodic modulation of the refractive index in the fibre core. The Bragg gratings typically reflect a narrow band of wavelengths centred around the so-called Bragg wavelength which is commonly denoted as λ_B. The Bragg wavelength is defined as $\lambda_B = 2n_{ef}\Lambda_G$, where Λ_G is the period of the grating and n_{ef} is the effective refractive index of the mode propagating in the optical fibre. The period of a Bragg grating can be modified if the optical fibre is subjected to axial strain. This will result in a change of the position of λ_B. Presently, there are several models of interrogators for fibre Bragg gratings which can determine the position of λ_B with picometre precision. Unfortunately, a change of temperature as small as 1 °C can also cause a detectable change in the position of λ_B because temperature changes n_{ef}. The concurrent sensitivity to strain and temperature can distort the strain (or temperature) readings. As a single Bragg grating cannot discriminate temperature and strain, a second grating is typically used as a reference. However, this solution is not always appropriate, particularly when the two gratings are in different locations.

Different alternatives to sense strain with Bragg gratings inscribed in PCFs have been proposed and demonstrated [29–33]. In most cases the concurrent sensitivity to strain and temperature is not avoided. However, it is possible to design PCFs with particular structures to inscribe Bragg gratings that do not exhibit the strain–temperature cross sensitivity or that can discriminate both parameters. For example, if the grating is inscribed in a high-birefringence (Hi-Bi) PCF, two Bragg wavelengths can be reflected which correspond to two polarisation modes [34,35], see Fig. 2. In a solid Hi-Bi fibre two Bragg wavelengths separated by less than 1 nm can be observed [36]. However, in a Hi-Bi PCF the separation between the two Bragg wavelengths is on the order of 2 nm. The large separation is due to the large value of the phase modal birefringence in a Hi-Bi PCF [34].

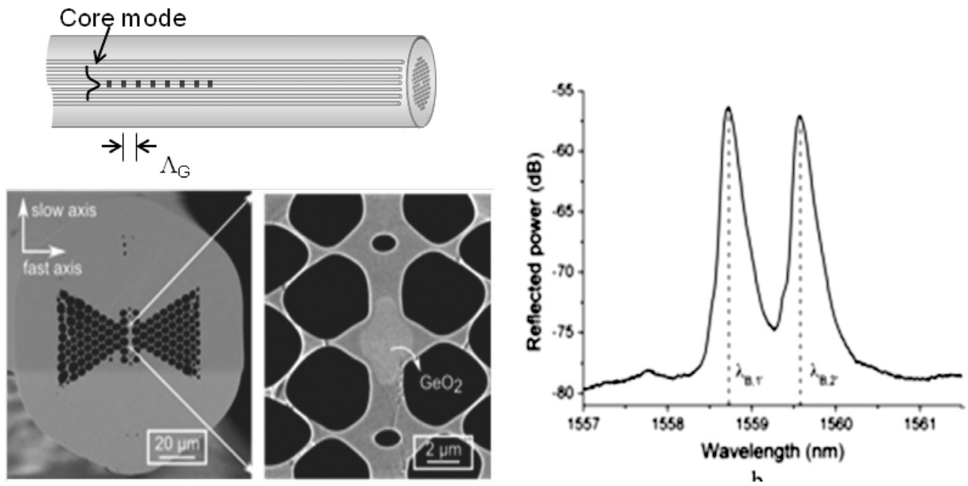

Fig. 2. Schematic representation of a PCF with a Bragg grating inscribed in the core. The micrographs show the cross section of a Hi-Bi PCF and a close up of the core which was designed to inscribe Bragg gratings. The graph shows the two Bragg wavelengths that a grating inscribed in HiBi PCF exhibits. The images and graph were taken from [9].

A single grating with two Bragg wavelengths can be used to sense or monitor two parameters such as temperature and pressure [36] or a single parameter such as transverse load or force [37]. The position of the two Bragg wavelengths or the separation between them can be monitored. The separation between the two Bragg wavelengths is not affected by temperature; however, it does change with external force or load [37]. An important advantage of Bragg gratings inscribed in HiBi fibres (standard or PCFs) is the fact that several gratings can be placed in series. Thus, multipoint (temperature-independent) sensing with grating in HiBi fibres is possible.

Another possibility to sense physical parameters is by means of mode PCF interferometers [38–46]. Such devices have centimetre lengths, are highly-stable over time, operate in a broad wavelength range or at extreme temperatures, and exhibit higher strain sensitivities than Bragg gratings. In Fig. 3 we show a compellingly simple PCF mode interferometer that can be used to sense physical parameters [38]. Basically, the device consists of a short segment of PCF inserted in a conventional single mode optical fibre (Corning SMF-28). To do so, the standard fibre and the PCF are joined with a conventional fusion splicing machine. The splicing is carried out with *ad hoc* programmes in such a way that the voids of the PCF get collapsed in a microscopic region. The splicing process induces a permanent transformation of the PCF geometry over a microscopic region which is the key to achieve a mode interferometer. The collapsed zones in the PCF cause a broadening of the propagating beam when it travels from the SMF to the PCF and also introduce a mode field mismatch between the optical fibres. The mode field mismatch along with the axial symmetry of the device is what allows the efficient excitation and recombination of two core modes. As the modes travel at different speeds, thus they accumulate a phase difference as they propagate along the length of PCF.

When only two modes participate in the interference the transfer function of the PCF interferometer can be expressed as:

$$I = (I_1 + I_2)\left[1 + V\,\mathrm{Cos}(\Delta\phi)\right]. \tag{1}$$

In Eq. (1), I_1 and I_2 are the intensity of the two interfering modes. V is called visibility and it is defined as $V=(I_1-I_2)/(I_1+I_2)$. $\Delta\phi=2\pi\Delta nL/\lambda$ is the phase difference, $\Delta n=n_1-n_2$, with n_1 and n_2 are the effective indices of the two interfering modes, L is the length of the PCF and λ is the wavelength of the optical source. It is clear from Eq. (1) that the reflection spectrum of a PCF mode interferometer is sinusoidal. The maxima of the reflection spectrum appear at periodic wavelengths given by

$$\lambda_m = \Delta nL/m, \tag{2}$$

where $m = 1, 2, 3, \ldots$

It is not difficult to demonstrate that if L changes by δL, then the position of λ_m will change by $\delta\lambda_m$, i.e., the interference pattern will shift. On the other hand, if the effective index of the interfering modes change (e.g. with temperature) then the interference pattern will also shift. This means, the device is sensitive to strain

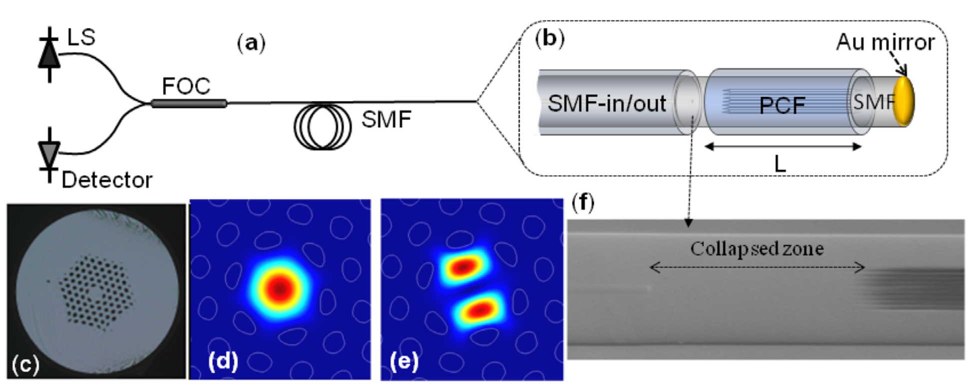

Fig. 3. Schematic representation of a PCF interferometer and the main parts. (a) The interrogation of the device comprises a light source (LS) a fibre optic coupler or circulator (FOS) and a light detector or an optical spectrum analyser. (b) Shows a drawing of the interferometer, L is the length of PCF. (c) Cross sections of the PCF used to build the interferometer, (d) and (e) are the core modes that participate in the interference. (f) shows a micrograph of the SMF–PCF junction. SMF is single mode optical fibre. (d) and (e) were taken from Ref. [48].

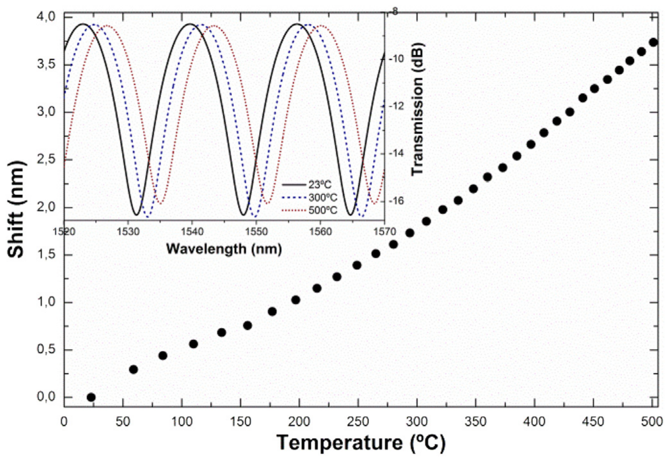

Fig. 4. Interference patterns (inset) of a 15 mm-long PCF interferometer at different temperatures and shift of the interference pattern as a function of temperature. The PCF used to build the interferometer is shown in Fig. 3(c).

and/or temperature.

In Fig. 4 we show the interference patterns and the temperature dependence of an interferometer fabricated with index guiding PCF whose cross section is shown in Fig. 3(c). We have demonstrated that for such a PCF the modes that participate in the interference are two core modes [38]. Note from the figure that the interference patterns are sinusoidal which suggests that the interference takes place predominantly between two modes. The temperature sensitivity of the device described in Fig. 4 is ~7.5 pm/°C which is comparable to that of Bragg gratings (~10 pm/°C). The temperature sensitivity does not have a strong dependence on the length of PCF as it depends mainly on the thermo-optic coefficient of pure silica which is low, on the order of 8.6×10^{-6}/°C. The temperature sensitivity can be enhanced by an order of magnitude if the PCF core is doped, for example, with Germanium [47]. In Ref. [47] a miniature temperature PCF sensor with sensitivity of 78 pm/°C was demonstrated.

Since the collapsed zones in the PCF do not degrade with temperature, a PCF interferometer can operate at high temperatures, up to 1000 °C [48]. This makes PCF mode interferometers suitable for applications in harsh environments.

The sensitivity of a PCF temperature sensor can be increased by two orders of magnitude by means of infiltration of liquids or polymers in the PCF voids. The enhancement in the temperature sensitivity is due the large thermo-optic coefficients of most polymers or certain liquids. For example, a short segment (6 cm) of alcohol-filled HiBi PCF inserted in loop mirror was demonstrated for ultrahigh sensitivity temperature sensing [49]. Due to the high dependence of the birefringence of an alcohol-filled HiBi PCF the device reported in [49] exhibited a temperature sensitivity of 6600 pm/°C. PCF interferometers filled with Cargille oils have been also demonstrated for high sensitivity temperature sensing [50]. Temperature sensitivity as high as 1830 pm/°C was observed in an interferometer built with 7.5 mm of PCF. Other PCF interferometers infiltrated with UV curable polymer material with a high thermo-optic coefficient were also demonstrated as highly sensitive (up to 1595 nm/°C) temperature sensors [51]. A luminescent temperature sensor based on quantum dots aqueous solution encapsulated in a PCF was also demonstrated [52]. Temperature modifies the peak, intensity, and full-width at half-maximum of the luminescent emission band. Temperature sensitivity on the order of 130.9 pm/°C was demonstrated [52].

The filling of a PCF with liquids or polymers is usually carried out by capillary effects. To do so, precise position and visualisation systems are needed. The filling process can be tedious and time consuming. In addition, the splicing of liquid- or polymer-filled PCF by means of the arc-discharge method is complicated as the melting point of polymers or liquids is substantially lower than that of pure silica. Other issues are related with evaporation or leakage of liquids and the aging or degradation of polymers. Such issues must be taken into account in the design of a temperature PCF sensor.

The multiplexing of most PCF interferometric strain or temperature sensors is not simple, largely due to the output signal of the PCF sensors themselves (spectra with multiple peaks or dips), the lack of passive PCF devices (circulators, couplers, etc.) and the high insertion loss that PCF sensors typically exhibit. However, important advances on the multiplexing of PCF sensors had been reported [53,54]. In a recent work it was demonstrated that with a commercial fibre Bragg interrogator combined with a fast Fourier transform measurement technique, the simultaneous real-time monitoring of several PCF sensors can be achieved [55]. Therefore, with instrumentation already available it is possible to implement PCF sensor networks.

In addition to grating- and interferometer-based architectures, PCFs offer more possibilities for sensing applications. For example, a short length of large mode area PCF fusion spliced between conventional single mode fibres with two collapsed zones of different lengths allows the selective excitation and overlapping of specific modes in the PCF [56]. The transmission spectrum of such a structure exhibits a single and narrow notch whose position changes with strain or temperature [56]. Another example is a twisted PCF [57,58]. The twisting of the PCF is carried out while it is being heated. In this way the twisting of the PCF is permanent. The transmission spectrum of a twisted PCF exhibits also a dip whose position changes with axial strain or temperature [57,58]. More recently, it was demonstrated that a photonic band gap PCF with an optically-trapped particle inside the hollow core can be used as a reconfigurable sensor [59]. Electric field and temperature sensing with high spatial resolution were demonstrated with such a configuration [59]. The aforementioned examples demonstrate the potential of PCFs to devise completely new optical fibre sensors.

Sensors based on polymer microstructured fibres (MOFs) have also been demonstrated. In the last decade MOFs made of polymers have attracted considerable attention, largely due to their numerous advantages over their glass counterparts [60]. For example, it is possible to fabricate polymer MOFs with holes of different shapes and sizes in literally any arrangement since the processing temperatures of polymers is much lower and the polymerisation process is more controllable. For instance, the drawing temperature of PMMA- Poly(methyl methacrylate)- MOFs can be varied from 150 °C to 200 °C without significant change to the fibre structure. Polymers have lower Young modulus and higher tensile strength than glass. Thus, a polymer MOF can be bent and strained to values in which glass optical fibre would normally break. The lower Young modulus of polymer gives optical fibres made of such material high mechanical flexibility. An additional advantage of polymer MOFs is their biological compatibility which is important for biomedical applications. Also, it is easy to make single mode polymer MOFs for the visible or near infrared wavelength range where cost-effective light sources, detectors and spectrum analysers are commercially available. Some drawbacks of polymer MOFs are the high transmission loss at the telecommunications wavelength region (1550 nm) or their concurrent humidity–temperature sensitivity, although with appropriate polymers the humidity sensitivity can be eliminated [61].

Point sensors based on polymer MOFs have been demonstrated [62–64]. Most of them use Bragg gratings. In fact, polymer MOFs with gratings inscribed in them had been commercialised (by Kiriama Pty Ltd., an Australian start-up) which reflects, to some extent, the maturity of polymer MOF technology. Thus, it seems possible that in the years to come polymer MOF sensors find applications outside the laboratory. However, to make it possible, predictable and high quality gratings must be achieved regardless of the geometry of the MOFs or the polymer they are made of.

3. Trends in PCF sensing

As discussed in the previous section, PCFs are being used to develop sensors, but mostly for monitoring a single parameter, typically a physical parameter. For strain (and strain-related) sensing, PCFs do not offer a significant advantage over strain sensors based on standard optical fibres; except lower temperature sensitivity or the possibility to operate at high temperatures. In case of temperature sensing, PCFs offer the possibility to enhance the temperature sensitivity, up to two orders of magnitude, by infiltrating materials with high thermo-optic coefficients in the PCF voids. Thus, to go far beyond existing PCF sensors it is desirable to investigate schemes with multi-parameter sensing capability or to develop single-parameter PCF sensors that outperform the performance of the existing ones. Next, we discuss some examples.

Sensors based on PCF interferometers can be designed to be immune to temperature, attenuation losses, or power fluctuations of the optical source. To do so only a proper packaging is necessary. Fig. 5 shows a schematic representation of a lateral force sensor based on the PCF interferometer described in Fig. 3. The device is sandwiched with two plates, one has a V groove to partially embed the interferometer and the other plate is serrated. When a force acts on the plates, the PCF interferometer experiences localised pressure [65]. The latter induces losses to the interfering modes, and consequently, changes in the visibility of the interference pattern. The graph in Fig. 5 shows the changes in the interference pattern when the external force changed from 0 to 3.92 N. It can be noted that as the force augments the changes in visibility are more prominent.

The visibility of the interference pattern does not depend on temperature as the intensities of the two interfering modes (I_1 and I_2) are not affected by temperature. Power fluctuations of the optical source do not alter the visibility of the interference pattern either. Therefore, a PCF interferometer with a proper package allows the accurate measurement of lateral force and any other parameter that can be converted to lateral force (impact, load, pressure, etc.).

In Fig. 6 we show a simple PCF interferometric bending sensor. The peculiarity of the device is that it is able to distinguish the bending orientation [66]. To induce bending to the device it was immobilized in the collapsed region of the PCF and the free extremity had a cleaved end that acted as low-reflectivity mirror. Bending was introduced with precise micropositioners. The figure shows the observed interference patterns when the interferometer was bent in the $-y$ direction (a blue shift was observed) and $+y$ direction (a red shift was observed). It can be noted that the interference pattern shifts but the visibility also changes. This means that our PCF interferometer subjected to bending exhibits a dual signal which is important for accurate measurements. The origin of the dual change of the interference pattern when the PCF is bent is the gradual change in the refractive index of the PCF core which modifies the effective index of the interfering modes and their intensities [66].

The above examples demonstrate the versatility of PCF interferometers to sense a single physical parameter. We believe that by combining PCFs with complementary technologies such as thin film, nano-, or micro-fluidics technologies, it will be possible to develop PCF sensors capable of sensing multiple parameters. The combination of complementary sensing modalities in a single platform may allow the development of highly sensitive and comprehensive hybrid optical fibre sensors. Such sensors may have multi-parameter (multimodal) sensing capability as this is typical of hybrid structures.

One of the architectures we propose is sketched in Fig. 7. It is a hybrid fibre optic sensor which combines mode interferometry and nano-scale materials. The device is compellingly simple as its fabrication consists of fusion splicing a millimetre-long segment of commercially-available PCF (e.g. LMA8 or LMA10, NKT Photonics) with conventional optical fibres [67,68]. The structure allows also to fabricate a mode interferometer if the PCF voids are collapsed over a microscopic length. The collapsed zones in the PCF cause a broadening of the propagating beam when it travels from the SMF to the PCF, or vice versa, and also introduce a mode field mismatch. The latter along with the geometry of the PCF is what allows the efficient excitation and recombination of core and cladding modes, and thereby devising interferometers [67,68]. The PCF mode interferometer depicted in Fig. 7 has several distinctive features which are important for optical sensing. First, the collapsing of the PCF voids causes a permanent transformation of the PCF geometry. The collapsed zone of the PCF does not degrade with temperature or over time. As a result, the interferometers are highly-stable over time. Secondly, the modal properties of the PCF along with the configuration of the interferometer contribute to achieve compact devices (length of 10 mm or less) with well-

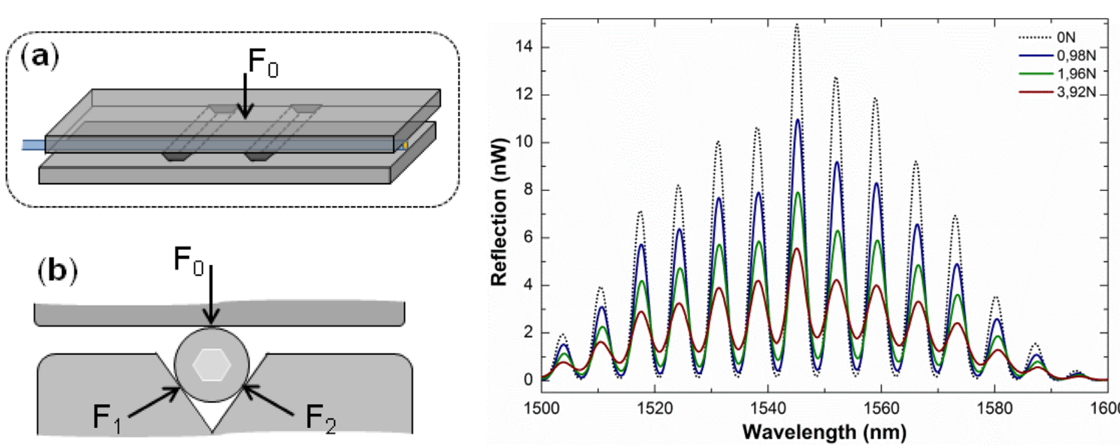

Fig. 5. (a) Schematic representation of a PCF interferometer pressed with a plate with grooves. (b) Detail of the PCF interferometer embedded in a V groove and the forces that act on the interferometer. F_0 is the external force and F_1 and F_2 are reaction forces. The graph shows the change observed in the interference pattern. The PCF used in the experiments is described in Fig. 3(c). The interrogation of the device is shown in Fig. 3(a). The length of the interferometer was 37 mm.

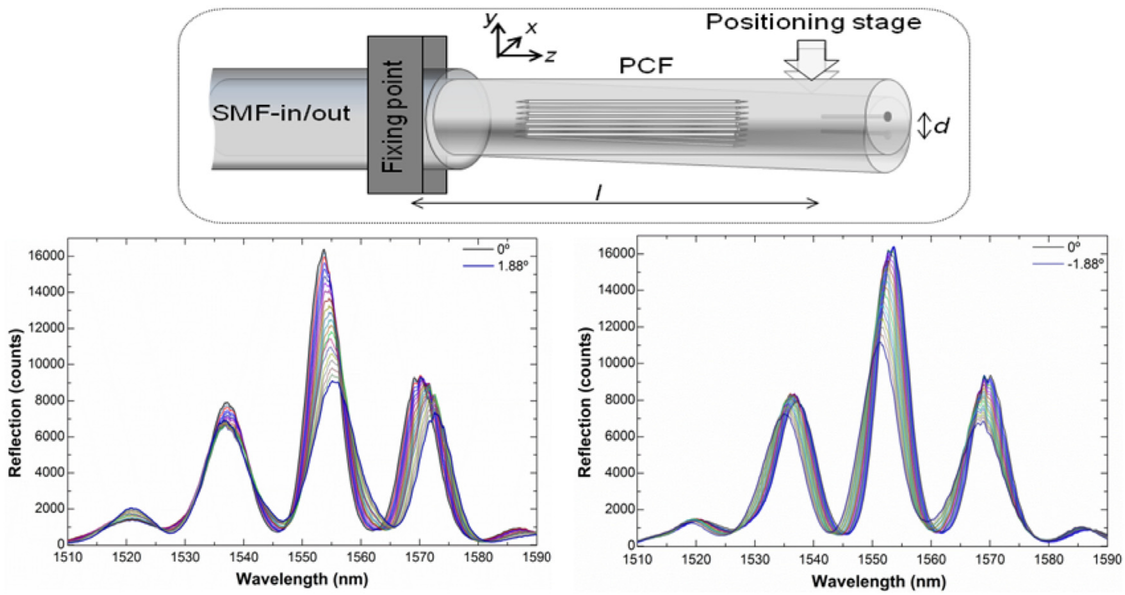

Fig. 6. Schematic representation of a PCF interferometer used to sense bending (top drawing). Interference patterns observed at different bending angles when the bending was in the $+y$ direction (left-hand side plot). Corresponding interference patterns observed at different bending angles when the bending was in the $-y$ direction (right-hand side plot). In all cases the interrogation of the device was carried out with the set up shown in Fig. 3(a). The length of the interferometer was 17.3 mm. The PCF used in the experiments is shown in Fig. 3(c).

defined and high visibility (exceeding 40 dB) interference patterns [68]. Thirdly, the PCF mode interferometer can operate in reflection or transmission modes and over a wide wavelength range, from 400 to 1700 nm, approximately. Fourthly, the period, visibility and shift of the interference pattern can independently or simultaneously be monitored, and thereby giving much more information about the medium that envelops the PCF, see Fig. 7. The high stability and visibility are important since they allow more accurate measurements [68]. The broad operating wavelength range is also important since one can choose the wavelength of operation of the sensor.

The structure shown in the figure has the potential to monitor multiple parameters as it is sensitive to temperature, strain, and surrounding refractive index because light propagates in the core as well as on the cladding of the PCF [68]. Tailored nano-scale materials can be deposited on the PCF to provide the structure ultrahigh sensitivity to surface refractive index changes and also selectivity to target bio/chemical molecules. The deposition of nanometric-scale layers or particles can be carried out with well-established deposition techniques such as dip coating; electrostatic self-assembly (ESA), Langmuir-Blodgett (LB), or layer by layer [69]. Prior works published in the open literature have demonstrated that PCF mode interferometers coated with dielectric layers or nanomaterials allow the development of highly sensitive refractive index or biosensors [70,71]. PCFs coated or infiltrated with gold layers or nanowires have been demonstrated for chemical and multianalyte biosensing [72,73]. In these cases the phenomenon of surface plasmon resonance is exploited.

There are different mechanisms to maximise the performance of a hybrid sensor. For example, the geometry of the PCF (shape, size and separation between holes) can be optimised to have controlled over the interfering modes. The properties of the nanoscale layers or particles deposited on the interferometer can also be optimised with the shape and size of the particles or the thickness and index of the nanolayers.

The transmission or reflection spectra of a hybrid fibre optic sensor will not exhibit the typical peaks and/or dips but something more complex because they have coded information of several parameters that surround the device. Thus, it is necessary to develop advanced algorithms to decode such information. An

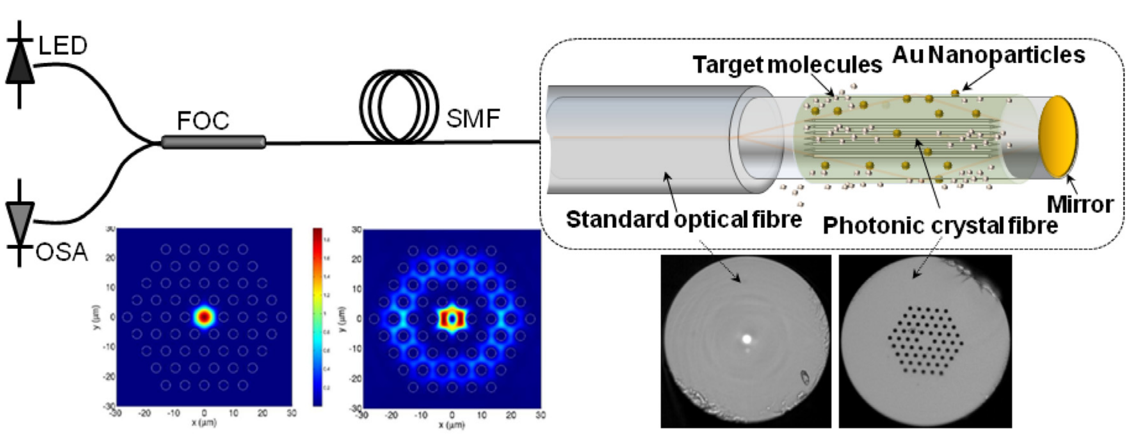

Fig. 7. Schematic representation of a hybrid structure that combines PCF, conventional optical fibre and nanoscale materials. The PCF for such an application can be LMA10 whose cross section is shown. The modes excited in the PCF are core and cladding modes. The latter can interact with the nanomaterial deposited on the PCF. The interrogation of the hybrid structure comprises a broad band source such as a LED and an optical spectrum analyser. The images were taken from [56].

advantage of hybrid PCF sensors is that for their interrogation similar light sources, spectrum analyzers, and conventional fibre components (circulators, couplers, switches, connectors, etc.) used in commercial fibre optic sensors can be used.

Another possibility to develop single- and multi-parameter sensors with PCFs is by means of Raman spectroscopy. The latter is a powerful analytical tool. PCFs offer important advantages for Raman spectroscopy as for example, large interaction area between the PCF and the sample, robustness, remote sensing capability, etc. These advantages are important for chemical sensing in micro-scale environments. To carried out Raman spectroscopy with PCFs, they voids of the fibre are decorated with metal nanoparticles [74–76]. The deposition of nanoscale materials in the PCF voids can be carried out by chemical vapour deposition at high pressure or by using colloidal solutions [74–79]. Target molecules absorbed on the nanoparticles within the PCF couple to the surface plasmon modes, thus releasing Raman-scattered photons which are collected by the PCF.

So far, Raman spectroscopy with isolated nanoparticles in the PCF voids has been demonstrated. Such an approach allows the detection of trace amounts of molecules in liquids. The incorporation of metal dimers and trimers (clusters of 2 or 3 nanoparticles) inside the voids of PCFs may further increase the detection sensitivity, probably, down to the single-molecule level. Dimers and trimers lead to the creation of hot spots of a strong electric field in the gap between the nanoparticles which can be used to enhance the Raman scattering [80].

The possibility of sensing multiple parameters with multi-core or photonic band gap (PBG) PCFs was demonstrated in recent years [81–83]. PBG fibres have a hollow core and guide light with low attenuation within a narrow spectral range which is sufficient to guide the pump laser light and the Raman-scattered photons [82,83]. The hollow core PCF is also the gas chamber. Due to the microscopic dimensions of the PCF voids, nanolitre sample volumes per centimetre fibre length are needed. This combined with long interaction lengths, up to a few metres, gives rise to highly efficient interaction of light and gas molecules, hence to high sensitivity. The quantification of several environmental-relevant gases with just a single measurement was demonstrated in [82]. More recently, the selective and sensitive detection of molecular hydrogen and methane in exhaled breath were demonstrated [83].

As a few metres of PCFs (which can be coiled) are needed for Raman spectroscopy and the components necessary to excite and collect light to and from the fibre are small, thus, there is great potential in the miniaturisation of PCF-based Raman spectroscopy. Therefore, we foresee applications of Raman PCF sensors in fundamental studies of chemical or biological interactions, chemical and biological sensing, early-stage diagnosis of metabolic diseases etc. The high cost of photonic band gap PCFs can be compensated with such applications.

4. Conclusions

It is recognised by the sensor community that photonic crystal fibres offer outstanding potential for the development of sensors. The optical properties or the geometry of PCFs can be tailored for a particular sensing application. For example, PCFs can be designed to be single mode in an ultrabroad wavelength range (1000 nm or more) which can be useful for spectroscopy. PCF with large voids can also be designed to facilitate the infiltration of liquids or materials in the fibre. PCF sensors can also benefit from decades of developments and innovations by the telecommunications industry. Presently, high quality light sources (LEDs and lasers), detectors or spectrum analysers, and different types of passive optical fibre devices are commercially available which can be used to interrogate PCF sensors. The advances in microfluidics, thin films and nanotechnologies can also be exploited to fabricate completely new PCF sensors or sensors with added functionalities.

There are different platforms that can be implemented with PCFs to develop point sensors. Bragg gratings can be inscribed in different types of PCFs by means of UV and infrared femtosecond light exposure. Long period gratings can also be inscribed in different types of PCFs by different methods. There are some issues in the inscription of gratings but more likely they will be overcome in the years to come. PCF interferometers are also attractive to sense physical parameters as they are compact, robust, and easy to fabricate. In addition, PCF interferometers can be multiplexed as demonstrated by some research groups.

The cross sensitivity to temperature and the parameter to be sensed of some PCF sensors can be avoided with a proper design of the PCF or with an adequate packaging. For example, it has been demonstrated that with a HiBi PCF it is possible to fabricate gratings that exhibit two Bragg wavelengths whose separation does not change with temperature but does change with a load. PCF interferometers have also been demonstrated for temperature-independent force sensing or for sensing bending along with the bending orientation.

The possibility of sensing multiple parameters with a single PCF sensor has also be discussed. Raman spectroscopy has been demonstrated for multigas sensing and hybrid structures involving PCF interferometers with nanoscale materials have the potential to sense several parameters.

The testing of PCF sensors by certified procedures, their validation in a real-world environment and their benchmarking against standard sensors will provide important feedback to improve the performance of PCF sensors. Such testing is a necessary step if one wants to commercialise PCF sensors.

We believe that in the years to come we will see some PCF sensors or devices that used PCFs in real-world applications or commercially available. The performance exhibited by some PCF sensors is good enough to compete with well-established optical fibre sensors.

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