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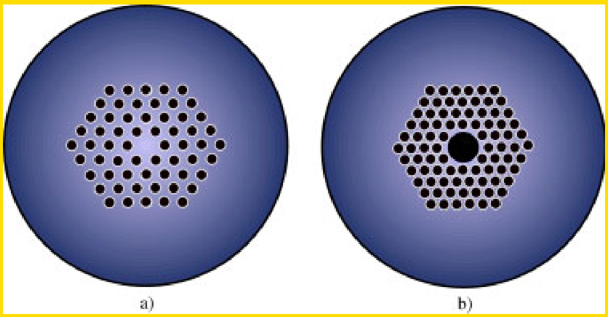
Abstract A review of optical fiber sensing demonstrations based on photonic crystal fibers is presented. The text is organized in five main sections: the first three deal with sensing approaches relying on fiber Bragg gratings, long-period gratings and interferometric structures; the fourth one reports applications of these fibers for gas and liquid sensing; finally, the last section focuses on the exploitation of nonlinear effects in photonic crystal fibers for sensing. A brief review about splicing with photonic crystal fibers is also included.



Two main classes of photonic crystal fibres (PCF): index-guiding PCF (a) and photonic bandgap PCF (b).

Optical sensing with photonic crystal fibers

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1. Introduction

Since the first publication by Knight et al. in 1996 on photonic crystal fibers (PCF) [1], the optical fiber community has been continuously engaged on R&D activity around these new fibers. Indeed, the fiber structure with lattice of air holes running along its length shows remarkable properties that support a large variety of novel optical fiber devices that can be used both in communications and sensing systems. The works published by Knight in *Nature* [2] and by Russell in *Science* [3] are two important reviews in this field. Other review papers were also published by Broeng et al. in *Optical Fiber Technology* [4] and by Russell in *Journal of Lightwave Technology* [5]. All of them summarize the historic landmarks, the fabrication issues, the modelling approaches and optical properties, as well as some more emblematic applications of these fibers.

A commonly accepted classification of PCF divides them into two main classes: index-guiding PCF and photonic bandgap PCF (Fig. 1). The index-guiding PCF basic structure is a solid core surrounded by a microstructured cladding (Fig. 1a). Due to the presence of air holes, the effective refractive index of the cladding is below that of the core and the light is guided along the core by the principle of total internal reflection. The application of this type of fibers for sensing has been extensively researched, as outlined by Monro et al. [6] and Eggleton et al. [7]. The next sections will present an overview of such developments framed by specific concepts and sensing platforms, but some examples can be highlighted here. For example, the work of Fini [8], who reports improved sensing designs for these fibers with detailed simulations of guidance properties; the work of Mägi et al. [9], which demonstrates that by adjusting the holey structure of the fiber cladding, it is possible to shift the optimum spectral operation region to shorter wavelengths; the development of Ortigosa-Blanch et al. [10] shows that these fibers offer a substantial freedom on the birefringence level, achievable by changing the geometric arrangement of the air holes, with further variants based on the asymmetry of the fiber core (Hansen

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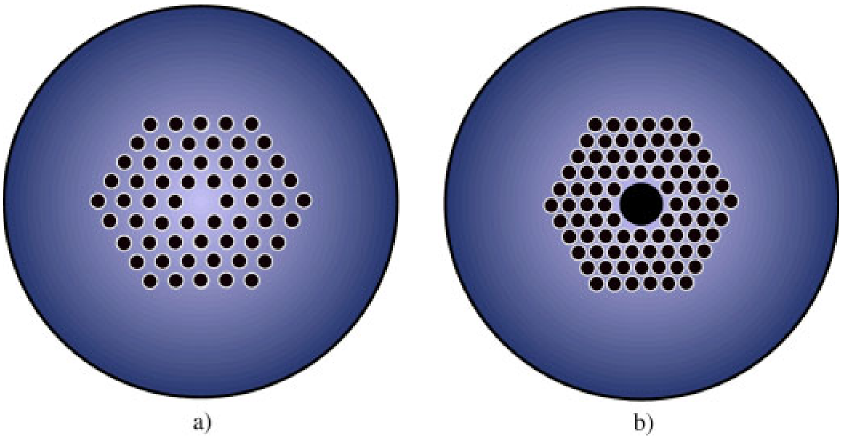

Figure 1 (online color at: www.lpr-journal.org) PCF structures: (a) index-guiding PCF; (b) photonic bandgap PCF.

et al. [11] and Sapulak et al. [12]), or on the asymmetry of the fiber cladding (Steel et al. [13, 14]).

The second type of PCF has a hollow core and the light guidance mechanism is the result of the presence of a photonic bandgap in the cladding region for a specific range of wavelengths (Fig. 1b). This can be understood if it is thought of as a multilayer mirror that, for certain angles and optical wavelengths, coherently adds up reflections from each layer, transforming the cladding into an almost perfect 2D mirror, keeping light confined in the lower index core of the fiber. This virtually loss-free mirror is called a photonic bandgap, and it is created by a periodic wavelength-scale lattice of microscopic holes in the cladding glass – a photonic crystal – that inherently has certain angles and wavelengths (*stop bands*) for which light is strongly reflected. The big attraction is that by varying the size and location of the cladding holes and/or the core diameter, the fiber transmission spectrum, mode shape, nonlinearity, dispersion and birefringence can be tuned to reach values that are not achievable with conventional fibers.

This fiber structure was first demonstrated in 1995 by Birks et al. [15], and later studies of Knight et al. [16] and Cregan et al. [17] established the guidance mechanisms and the main properties of these fibers. Due to the presence of a hollow core, the potential of these fibers for liquid and gas sensing, or even for photonic switching if the hollow core is filled with a liquid crystal with transmittance properties dependent upon an applied external voltage (Du et al. [18]) was clear from the beginning. The fabrication of these fibers using microstructured polymeric materials (MPOF) (Eijkelenborg et al. [19]) was also reported, thus enlarging the spectrum of application for photonic bandgap fibers.

The next sections review the progress in optical sensing based on PCF. From many possible review layouts, the option was to organize the presentation by selecting a restricted set of important sensing platforms (fiber Bragg gratings and long-period gratings), a modulation concept (interferometric sensing) and a highly promising application field (liquid and gas sensing). The last section deals with reported developments on the use of nonlinear effects in PCF fibers for sensing. Finally, several studies and methods for splicing between Microstructured fibers and standard single-mode fibers are also reviewed.

2. PCF sensing based on fiber Bragg gratings

Fiber Bragg gratings (FBG) have been extensively studied as sensing elements in conventional optical fibers (Kersey et al., [20]). Since the outcome of index-guided PCF, the fabrication and characteristics of FBG in these fibers have also been under continuous study and development. Microstructured index-guided fibers can contain germanium or other doping in the core, which allows an efficient fabrication of Bragg grating structures with low insertion loss (Eggleton et al., [21]). This, of course, is not the case in hollow-core PCF. Groothoff et al. [22] have reported the fabrication of Bragg gratings in air–silica microstructured optical fiber using two-photon absorption at 193 nm (see Fig. 2a)). The annealing of the FBGs in air–silica fiber is highly stable when compared with what occurs in germanosilicate fibers (one-photon process at 244 nm). The FBG reflectivity decreases only after ~ 500 °C, which means that this type of FBG is an interesting solution as a high-temperature sensor. An FBG written in erbium-doped PCF with two modes has also been tested and characterized. The effective indices of the two modes produced two distinct grating peaks, corresponding to the fundamental and the high-order modes (Martelli et al., [23]). The FBG was characterized for strain and temperature. Similar temperature responses and distinct strain coefficients were obtained for the two grating peaks. This behavior was attributed to the fact that the FBG associated with the higher-order mode has a more complex strain response due to compressive stress in the holes' interface.

Bragg gratings written in Hi-Bi PCF have been proposed as a temperature-insensitive strain sensor (Frazão et al., [24]). Fig. 2b) shows the cross-sectional layout of the PCF used in the experiment. For a range of 2000 $\mu\varepsilon$, a strain resolution of ± 7 $\mu\varepsilon$ was achieved. In this work, FBGs written in Hi-Bi PCF and in standard single-mode fibers were also combined to obtain different sensitivities to

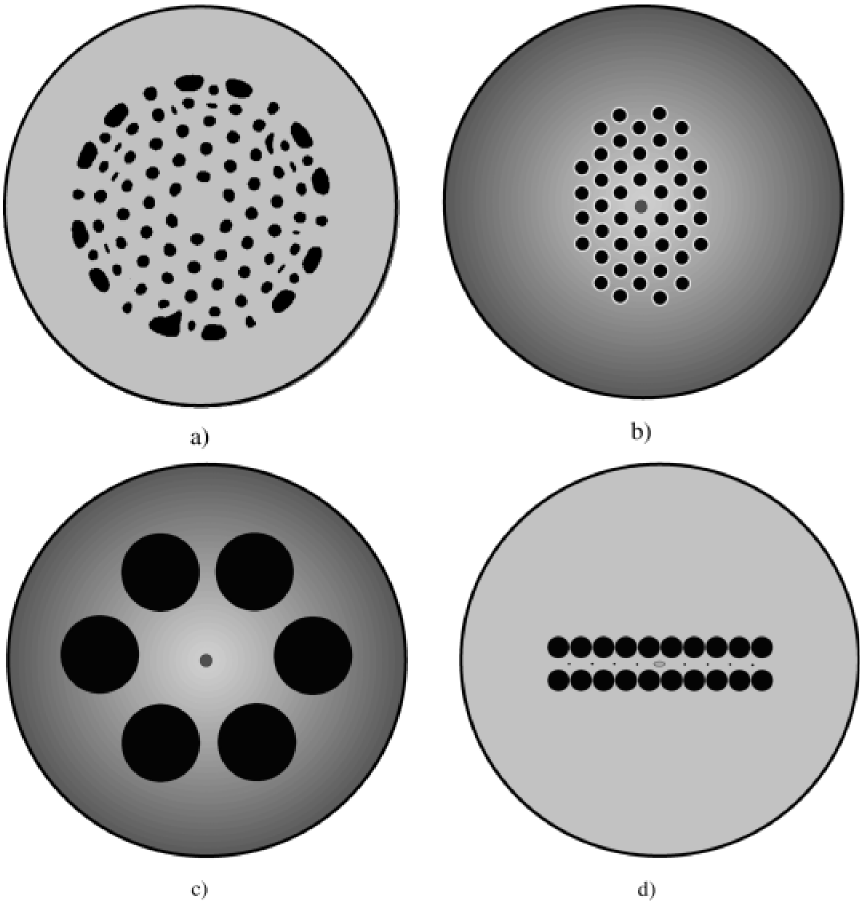

Figure 2 Some PCF structures where FBGs have been written and explored for sensing purposes: (a) pure silica fiber [22]; (b) Hi-Bi fiber [24]; (c) fiber with six holes cladding [25]; (d) special Hi-Bi fiber [30].

those physical parameters. The temperature sensitivity in an FBG written in PCF depends on the core size and presents a lower value when compared with the one obtained with a standard FBG. For simultaneous measurement of strain and temperature, the obtained resolutions were ± 1.5 °C and ± 10 $\mu\varepsilon$ over a measurement range of 100 °C and 2000 $\mu\varepsilon$, respectively. Recently, Bragg gratings written in PCFs with different air-hole sizes were also studied (Fig. 2c); Han et al., [25]). The work reports a dependence of the strain sensitivity on the air-hole size – the values for the strain sensitivity are enhanced ($\sim 28.4\%$) when the air-hole size is increased because the area with silica in the fiber cross section decreases. However, due to the same material composition in PCFs, similar temperature sensitivities were obtained. The measurement of other parameters with Bragg gratings written in PCF, such as refractive index, has also been studied. Phan et al. [26] used two fiber structures to measure the refractive index of liquids in the range 1.29–1.45; one fiber has a cross section with six holes, while the other has a two-ring triangular structure. The liquids were inserted in the holes, originating a shift in the FBG resonant wavelengths. For refractive index near that of water, a measurement resolution of 7×10^{-4} was obtained for the PCF with two-ring triangular geometry; a similar value was obtained for the six-hole fiber (4×10^{-4}). However, when the refractive index approached the effective refractive index of the guided mode (1.45), the measurement resolutions became 2×10^{-5} for the two-ring triangular geometry and 7×10^{-6} for the six-hole PCF. Recently, an FBG sensor photowritten in a suspended Ge-doped silica core was proposed as an optical refractometer (Huy et al., [27]). This refractometer exhibited a sensitivity approximately two orders of magnitude greater when compared with the results obtained with the six-hole PCF. The measurement of refractive index with a tilted FBG photowritten in PCF has also been demonstrated (Huy et al. [28]).

As will be detailed in one of the next sections, FBGs written in PCF have been explored for gas sensing. An interesting ground result came from the work of Florous et al. [29], who claimed that the temperature sensitivity of a 70-mm FBG operating at 1550 nm is enhanced when more dense gases are considered. Indeed, the authors reported a temperature sensitivity enhancement by a factor of four when there is carbon dioxide in the holes instead of dry air.

Recently, the feasibility of writing FBGs with a conventional inscription setup in a highly asymmetric microstructured fiber was reported (Geernaert et al., [30]). The cross section of this fiber is shown in Fig. 2d). These FBGs have substantial fast and slow peak wavelengths splitting due to the high fiber birefringence (2×10^{-3}) associated with the geometric asymmetry.

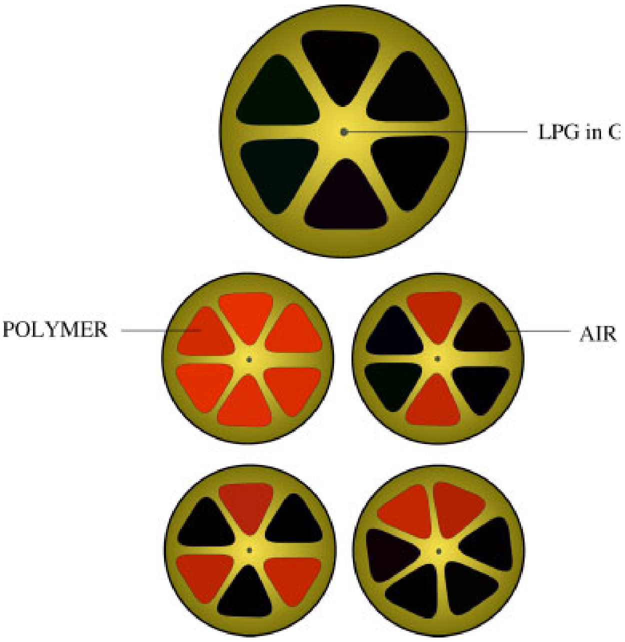

Figure 3 (online color at: www.lpr-journal.org) (a) Cross section of a PCF with inner and outer cladding where an LPG has been impressed in the core [31]; (b) PCF with total or partial hole filling with polymer [31].

3. PCF sensing based on long-period fiber gratings

A long-period grating is another structure that can be written in PCF. This has been done in different ways in the past and the devices have been used in diversified applications. For example, a tuneable long-period grating (LPG) filter based on cladding-mode resonance in a hybrid polymer–silica structure was reported (Kerbage et al., [31]). As shown in Fig. 3, the polymer is infused into the holes and it is possible to change the LPG resonance wavelength in a range of 200 nm, with a temperature variation of 10 °C. Focusing on sensing applications, several configurations have been suggested in order to measure different parameters. Dobb et al. [32] demonstrated a temperature-insensitive LPG sensor to measure strain or curvature. The LPG structure with a period of 500 μm was written by electric arc discharge. The LPG was characterized for temperature, strain and curvature, the results being sensitivities of 0 ± 10 pm/°C, -2.04 ± 0.12 pm/με, and 3.7 nm m, respectively. Along similar lines, Petrovic et al. [33] have recently theoretically studied the sensitivity of LPGs in PCF fabricated by electric arc to different physical parameters, such as temperature, strain and external refractive index. In a different approach, LPGs written in large mode area PCF using CO_2 laser were also demonstrated (Zhu et al., [34]). These LPGs present a strong resonance after a reduced number of laser shots, which turns out to be highly sensitive to refractive index variations of the external medium. Indeed, for an aqueous medium with a refractive index around 1.33, a minimum detectable refractive-index variation of 2×10^{-5} was reported (Rindorf and Bong [35]). These structures written with CO_2 laser were proposed as strain-insensitive high-temperature PCF sensors (Zhu et al., [36]). For high-temperature applications, LPGs written in PCF with the electric arc technique have also shown an adequate performance, as was reported by Humbert et al. [37].

Han et al. [38] demonstrated simultaneous measurement of strain and temperature using LPGs written in PCFs with different air-hole sizes. The same functionality was reported by Sun et al. [39] with processing based on an artificial neural network.

Pressure sensing using an LPG fabricated in a PCF was presented by Lim et al. [40]. Later, a hydrostatic pressure sensor using a tapered LPG written in PCF by the electric arc technique was also reported (Bock et al., [41]). The pressure sensitivity was found to be 11.2 pm/bar, a factor of two higher than the value found in standard single-mode fibers.

LPGs in PCF have also been used as auxiliary devices for other types of fiber sensors. That is the case when LPGs are used to interrogate FBG-based sensors (Zhao et al., [42]). Also, a PCF modal interferometer has been recently demonstrated. In the proposed structure, an LPG induces strong mode coupling from the fundamental core mode to the cladding modes of the PCF, while recoupling to the core mode is performed by collapsing the air holes in a particular point of the fiber. Therefore, by simply cascading these two coupling elements, the LPG and the collapsing region, a very sensitive Mach–Zehnder interferometer can be implemented (Choi et al., [43]). This is an example of interferometric sensing configurations with PCF that will be detailed in the next section.

4. PCF sensing based on interferometric configurations

Fiber modal interferometers are attractive due to their compactness and substantial intrinsic temperature compensation in view of their differential operation. Therefore, this type of interferometer has also been researched in the context of PCF. One configuration that has been widely explored consists of a structure where a length of Hi-Bi PCF (with a cross section such as the one shown in Fig. 4a) is inserted in a fiber loop mirror (FLM). The works of Zhao et al. [44] and Kim et al. [45] follow this line and, as expected, a low temperature sensitivity (0.29 pm/°C) was reported, not only because of the mentioned differential operation, but also considering the fact that it is not necessary to dope the core in this type of fiber. Therefore, based on this configuration, the development of a temperature-insensitive strain sensor was natural (Dong et al. [46], Frazão et al. [47]). However, it is important to mention that the temperature insensitive property can only be observed when the Hi-Bi PCF used in the FLM is uncoated. With the same type of fiber, a pressure sensor was demonstrated (Fu et al. [48]), with the measurement of a large wavelength–pressure coefficient of

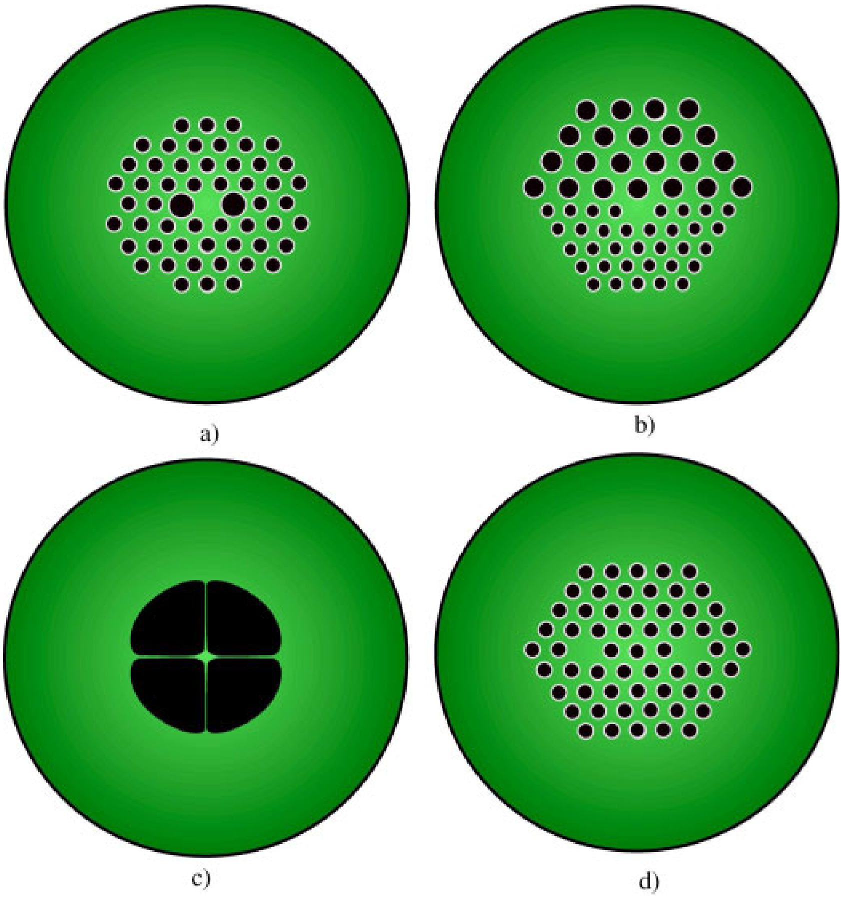

Figure 4 (online color at: www.lpr-journal.org) (a) and (b) Cross sections of Hi-Bi PCFs integrated in fiber loop mirror interferometric configurations [46–48]; (c) two-core PCF for curvature sensing [56], Four-hole suspended core [52].

3.42 nm/MPa using a fiber length of 58 cm. Recently, with the Hi-Bi PCF structure shown in Fig. 4b), it was possible to demonstrate an FLM-based curvature sensor with residual temperature and strain sensitivity (Frazão et al. [49]). Using a standard differential interferometric configuration, Ju et al. [50] also researched the temperature sensitivity of a two-mode PCF sensing head.

A fiber loop mirror layout with Hi-Bi PCF was also proposed by Yang et al. [51] as an FBG interrogation device with high immunity to temperature variations. Frazão et al. [52] characterized a Sagnac interferometer in strain and temperature that includes a length of four-hole suspended-core PCF. The coefficients were 1.94 pm/$\mu\varepsilon$ and 0.29 pm/°C, respectively, which indicates that this sensing structure has potential for a temperature-insensitive strain sensor.

Franco et al. [53] proposed a new design of Hi-Bi PCF for temperature measurement consisting of a side-polished PCF with the flat side coated with a material that has a large thermo-optic coefficient. Monzón-Hernández et al. [54] and Villatoro et al. [55] demonstrated the application of a compact PCF modal interferometer for strain and high-temperature measurements. The sensing head consisted of a tapered PCF with collapsed air holes over a localized region. By collapsing the air holes, a PCF zone is transformed into a multimode fiber. As a consequence, the fundamental mode is coupled with the other modes of the optical fiber, thus originating a cross-coupling phenomenon with the associated spectral oscillatory pattern. The wavelength shift showed a linear dependence on temperature, with a slope of 12 pm/°Cin the range between 200 °C and 1000 °C.

MZ modal interferometric configurations in PCF have been reported (Choi et al. [56]). Two types of MZ structures were fabricated based on the splicing and collapsing methods. The first method relies on splicing a piece of PCF between two lengths of PCF fiber with a lateral mismatch. The other method consists of collapsing the air-holes of a single PCF in two regions using an electric arc, thus obtaining the two MZ coupling regions. These interferometers were used as temperature-insensitive strain sensors, achieving a sensitivity of 2.2 pm/$\mu\varepsilon$. A variant to the first MZ structure was proposed by Villatoro et al. [57], where the PCF length is now spliced between two conventional single-mode fibers, obtaining a strain sensitivity of 2.8 pm/$\mu\varepsilon$. Using the same interferometric concept, a curvature sensor based on two-core PCF was presented. Here, each core acts as an arm of the Mach–Zehnder (MacPherson et al. [58]; Fig. 4c). A linear response was observed and a phase sensitivity to bend of ~ 127 rad/rad was obtained. The use of multicore PCF for two-dimensional bend sensing was also demonstrated (Blanchard et al. [59]). Using the same fiber, a Doppler differential velocimeter was also reported

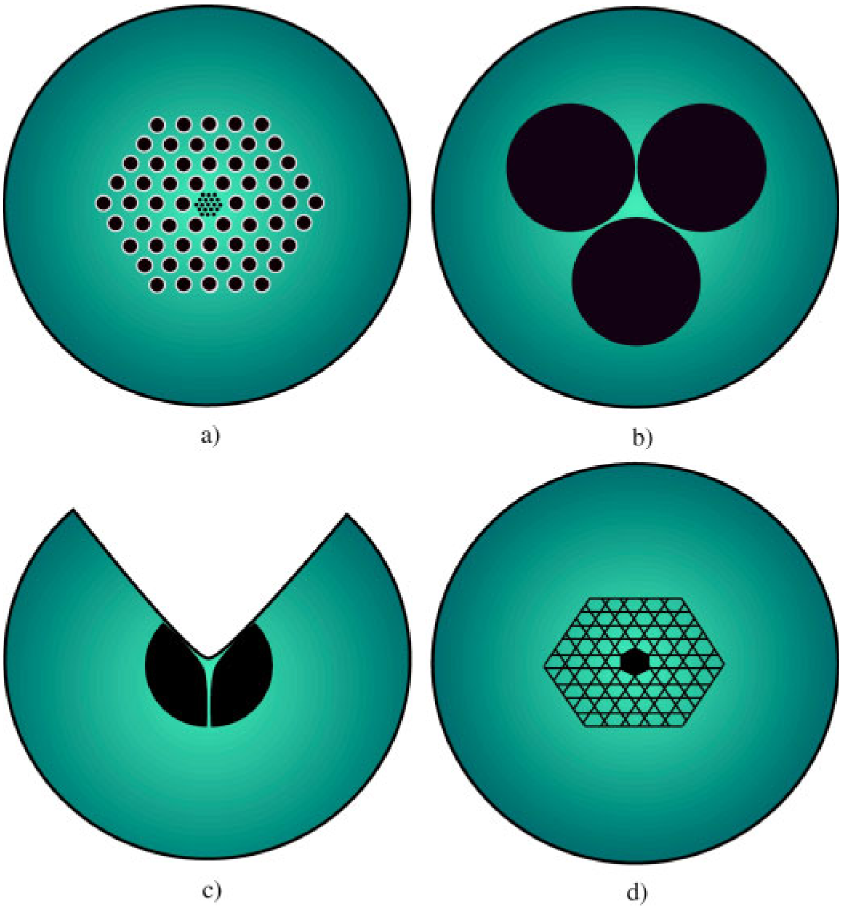

Figure 5 (online color at: www.lpr-journal.org) (a) PCF with microstructured core [70]; (b) PCF with suspended core [71], (c) exposed suspended core [79] and Kagome structure hollow core [81].

(MacPherson et al. [60]). At another level, the intrinsic sensitivity of standard PCF fiber to hydrostatic pressure was studied using interferometric techniques by Bock et al. [61], and PCF-based polarimetric sensing structures were studied for pressure and temperature measurements (Statkiewicz et al. [62] and Nasilowski et al. [63]).

5. PCF for gas and liquid sensing

It is nowadays recognized that the emergence of photonic crystal fibers was a breakthrough in fiber technology, not properly in the domain of optical transmission, where the standard single-mode fiber shows a remarkable performance, but particularly in the realm of optical processing. Therefore, PCF are highly valuable for the design of advanced optical fiber components with specific and often unique characteristics. As examples, it is possible to point out the use of the nonlinear properties of these fibers to readily achieve dispersion compensation in optical fiber communication systems, or the possibility of obtaining efficient supercontinuum optical fiber sources. In the optical fiber sensing domain, as is already clear from what was presented in previous sections, PCF essentially enables a substantial increase in design flexibility, allowing the possibility for new or improved sensing solutions relative to the situation where the choice of components and devices was limited to the standard optical fiber technology. This is particularly true in certain sensing domains, such as gas and liquid sensing, where the possibility of the fluid to occupy the fiber holes, and most notably the core hole in the case of photonic bandgap PCF, brings qualitatively better performances when compared with sensing solutions implemented with the standard fiber. Therefore, the high interest of the optical fiber sensing community in applying PCF in order to tackle the challenge of remote, multipoint and high-sensitivity detection of gas and liquids is quite natural.

The development of PCF fibers with enhanced characteristics for gas detection based on evanescent interaction and absorption has been reported by Monro et al. [64] and Pickrell et al. [65]. Relying on this phenomenon, Hoo et al. [66] demonstrated a sensitive detection of acetylene using a PCF with a length of 75 cm. The same group later proposed and modelled a PCF design for gas sensing with the fiber structured with periodic openings, an approach that aims to minimize the gas diffusion time into these fibers, which is normally a major operational constraint (Hoo et al., [67]).

The study of gas characteristics using a hollow-core photonic bandgap PCF was presented by Ritari et al. [68]. Due to its importance in safety, high-sensitivity methane detection is always seen as a target. With this type of fiber, Cubillas et al. [69, 70] reported a methane-sensing scheme using the 1666-nm and 1331-nm gas absorption bands, achieving a detection limit of 10 ppmv. Using the 1666 nm methane absorption band, a complete PCF-based sensing system was recently reported (Magalhães et al. [71]). Gas sensing was also demonstrated with solid-core index-guiding PCF fibers with the cladding holes filled with air (Li et al. [72]). Two approaches were reported in order to improve sensitivity. In one of them, in addition to the cladding holes, the core was also fabricated with holes in order to increase the evanescent interaction of the optical field with the gas (Fig. 5a); Cordeiro et al. [73]); the other one was based on the concept of suspended-core fiber, where a small diameter core is surrounded by a small number (typically three) of large holes (Fig. 5b); Webb et al. [74]). Side access to the PCF holes was demonstrated by Cordeiro et al. [75]. The method consists of inserting the liquid or gas laterally into the fiber so that it will be sensed while the tips are optically monitored. This configuration was used for fluorescence sensing of rhodamine. Antibody detection has also been reported using hollow-core PCF (Duval et al., [76]). Following the same path, Jensen et al. [77] detected biomolecules in an aqueous solution using the interaction between the evanescent field and the fluids in the PCF holes.

Recently, a simple and new technique to simultaneously insert a liquid into the core of a hollow-core PCF and different liquids into the microstructured cladding was demonstrated (de Matos et al., [78]). The final result was a liquid-core, liquid-cladding waveguide in which the two liquids can be selected to yield specific guidance characteristics. For instance, they can be optimized for the measurement of the refractive index in a certain interval.

The concept of suspended-core fiber was also applied to optimize fluorescence sensing in fluids and, with this, to measure particular entities, such as biomolecules, in an approach with high potential for biochemical sensing (Afshar et al., [79]). Following this line, the absorption and fluorescence sensing properties of liquid immersed in exposed suspended-core fibers were recently studied (Warren-Smith et al., [80]). The Kagome structure hollow-core fiber was proposed by Benabid et al. [81] for stimulated Raman scattering.

6. Nonlinear effects in PCF for sensing

The presence of air holes in the cladding provides a large index step between the interface of the core and the cladding. This characteristic produces a strong confinement of the guided mode causing an impact on the nonlinearity level present in these fibers, which is typically much larger when compared to what happens in standard single-mode fibers, and even when short fiber lengths are considered (Sharping et al., [82]; Omenetto et al. [83]; Lee et al., [84]). Equally important, by adjusting size, location and number of holes, this nonlinearity level can be adjusted to a substantial extent. This flexibility has been explored in the communication field in order to achieve new functionalities and performances. In the context of sensing, this characteristic is still largely unexplored, a situation that surely will change in the future.

Meanwhile, work on strain and temperature-distributed sensing based on nonlinear effects in PCFs has been reported. Zou et al. [85] studied the dependence of the Brillouin frequency shift on strain and temperature in a PCF with the core partially doped with germanium. The presence of two distinct Brillouin shifts with identical sensitivity to strain but different sensitivities to temperature was identified. This fact opened up the possibility of simultaneous measurement of strain and temperature, a possibility later explored with results being 15 $\mu\varepsilon$ and 1.3 °C for strain and temperature, respectively, for a centimeter spatial discrimination (Zou et al., [86]).

7. Splices in PCF/SMF

An important issue in optical-fiber sensors is the connection of the microstructured fibers with single-mode fibers (SMF) with low loss. Good splicing of microstructured fibers to standard SMF is vital in order to enhance their potential use in communication systems. In 1999, Bennett et al. [87] reported a splice loss of 1.5 dB using a conventional fusion splicer between a holey fiber and a SMF-28 (Corning). Lizier and Town [88] reported numerical calculations of splice loss between standard step-index fibers and holey fibers. An alternative method was proposed in 2003 by Chong and Rao [89] that included the use of a CO_2 laser. Also, in 2003, Bourliaguet [90] described a simple method to splice microstructured optical fibers by relying only on commercial electric-arc splices machine. Yablon et al. [91] proposed the PCF fusion splices using GRIN fiber lenses. Frazão et al. [92] presented a simple technique for splicing between PCF/SMF that consists of applying the electric arc in the standard single-mode fiber region. The use of the same technique, but repeating arc discharges in SMF, was also studied by Xiao et al. [93]. Leon-Saval et al. [94] demonstrated a spliceless ferrule interface between an SMF and a PCF adapted from the fabrication of PCF preforms from stacked tubes and rods. Splices between hollow-core fibers and SMF were also studied through the use of electric arc discharges in the region of the SMF (Thapa et al. [95], Xiao et al. [96]). In order to reduce the Fresnel back-reflection in the splice between hollow core and SMF, Couny et al. [97] proposed the use of the SMF with a small cleaved angle.

8. Conclusions

In this paper, the most important sensing developments based on PCF over recent years were reported. General issues have first been addressed and then PCF sensing approaches relying on specific fiber structures, such as Bragg and long-period fiber gratings have been presented. Also, due to its relevance, a section was dedicated to the review of PCF interferometric sensing approaches. The exploitation of nonlinear effects in PCF for sensing purposes was also discussed. Finally, a specific yet important application field for sensing with PCF was outlined, namely the issue of liquid and gas sensing, which is of high relevance for biochemical and environmental monitoring.

The level of the reported work and the corresponding results demonstrate that PCFs are no longer a promise for the fiber optic sensing field, but a technology with a potential that is now fully demonstrated. It will therefore be no surprise if some of the ideas presented in this paper begin to follow the path from the optical tables in laboratories to production lines in start-up companies, and thus become the base of innovative commercial products in the near future.

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