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[INVITED] New perspectives in photonic crystal fibre sensors

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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

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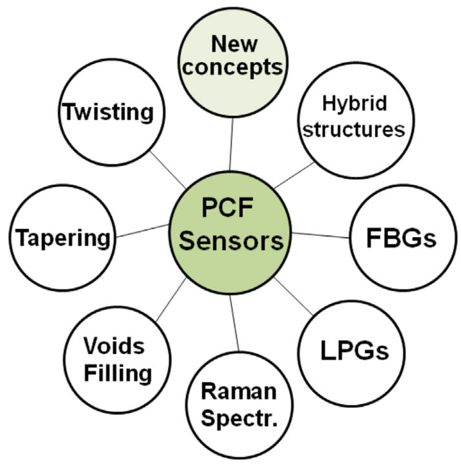

Fig. 1. Illustration of the different alternatives and techniques to develop sensors with photonic crystal fibres. FBGs means fibre Bragg gratings and LPGs long period gratings. New concepts and approaches to devise PCF sensors are expected in the years to come.

the PCFs, and therefore, they are good candidates to develop biochemical 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].