Recent Advances on Optical Sensing Using Photonic Crystal Fibers

M. B. Marques[a, b], F. Magalhães[a], J. P. Carvalho[a,b], O. Frazão[a,b], F. M. Araújo[a], J. L. Santos[a,b], L. A. Ferreira[a]

[a]*INESC Porto, Rua do Campo Alegre, 687PT-4169-007 PORTO, Portugal*
[b]*Physics Dep. FC, Univ. Porto, Rua do Campo Alegre, 687PT-4169-007 PORTO, Portugal*

Abstract. The application of hollow-core photonic crystal fibers for gas sensing is reviewed and discussed. Some problems with splicing to standard fibers and gas diffusion into the core are addressed. Current work at INESC Porto in the development of sensing heads and interrogation units is also reported.

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INTRODUCTION

Since the first publication in 1996 on photonic crystal fiber (PCF) [1], the optical fiber community has studied the optical properties and fabrication of these new classes of fibers. The fiber structure with lattice of air holes running along the length provides a large variety of novel optical PCF. A commonly accepted classification of PCF divides the fibers into two main classes: index-guiding PCF and photonic bandgap PCF [2, 3].

With index guiding PCF and in optical sensing, Monro *et al* [4] presented a review that includes a range of applications in which PCF offer new alternatives for sensing applications. On the other hand, Fini [5] presented an interesting work in optical sensing for gases and liquids using PCF, reporting improvement designs for sensing applications, including detailed simulations of guidance properties.

Photonic bandgap fibers rely on an entirely new mechanism for transmitting light. Light is trapped in the core not by total internal reflection, but by a photonic bandgap (PBG) in the cladding that acts like an insulator for light. This new kind of optical fiber propagation was demonstrated in 1995 by Birks *et al* [6]. The PBG cladding is made with hundreds of periodically spaced air holes in a silica matrix, typically arranged in a honey combed-like pattern. Because the light guidance is no longer dependent on the core's effective index, it becomes possible to create fibers that guide light in an empty or gas-filled core that can be used in optical sensing. Two papers published in Science presented the first bandgap guiding fiber in which light is trapped in a ring of glass around a central hole [7] and the first hollow-core photonic bandgap fiber consisting in a triangular lattice of holes from which were removed seven capillaries to form an hollow-core [8].

With the possibility of filling the air holes of PCF with gas, with large interaction lengths, new ways to monitor or detect gas are possible. Evanescent field gas sensing in the holes of PCF [9] or a random hole [10] has been reported. Hoo *et al* [11] demonstrated an experimental evanescent wave gas detection using PCF. Using 75 cm of PCF, the authors obtained 6 % of the sensitivity through absorption spectroscopy of the acetylene. Other work of the same group proposed a design and modeling of PCF for gas sensor and also the use of a single section of PCF or sensing PCF with periodic openings [12].

Ritari *et al* [13] studied characteristics of gas by the use of photonic bandgap within hollow-core PCF. Methane detection at 1670 nm band using hollow-core PCF has been reported [14]. It is estimated a detection limit of 10 ppm/v with the system configuration used in the experience. Other authors studied the characteristics of gas sensing for evanescent-wave absorption in solid-core by filling the cladding air holes [15, 16]. Side access to the holes of PCF was demonstrated by Cordeiro *et al* [17]. The method consists in inserting the liquid or gas to be sensed laterally to the fiber while the tips are optically monitored.

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BASIC CONCEPTS

Within hollow-core photonic crystal fibers, light is not guided by total internal reflection but by confinement in a waveguide, similar in principle to microwave propagation. We can imagine a multi-layer mirror that, for certain angles and optical wavelengths, coherently adds up reflections from each layer, transforming the cladding into an almost perfect 2-D mirror keeping light confined in the lower index core of the fiber. This virtually loss-free mirror is called a photonic band gap (PBG), and is created by a periodic wavelength-scale lattice of microscopic holes in the cladding glass – a photonic crystal – that inherently have certain angles and wavelenghts ("stop bands") where 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 fibers transmission spectrum, mode shape, nonlinearity, dispersion and birefringence can be tuned and reach values that are not achievable with conventional fibers. For this work two types of hollow-core PCF have been provided by the University of Bath, the 7-cell and the 19- cell PCF as can be seen in Fig. 1.

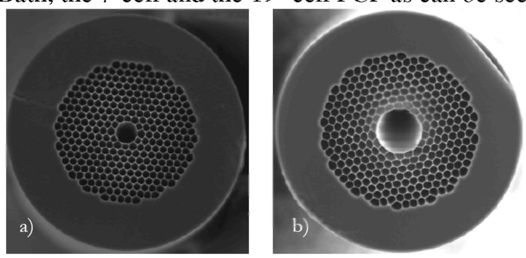

FIGURE 1. Hollow-core photonic bandgap fibers provided by the University of Bath. a) 7-cell PCF b) 19-cell PCF

To develop a practical remote detection system, light must be transmitted over large distances. Moreover, to be practically useful in remote gas detection systems, a PCF must also be connected to standard single mode fiber (SMF), which is still a rather delicate process. The splice losses between PCF and SMF have been studied in the last years by several groups [18-22]. A study of the splicing and coupling losses was performed for the two different types of HC-PCF previously mentioned. The coupling coefficient between two fibers separated by a distance d, can be determined from the superposition of their mode profiles at the input face of the second fiber [23].

In order to develop a HC-PCF-based gas sensor, allowing direct interaction of light with gases within its structure, it is important to study the diffusion of gas inside of the fibers. For this purpose, we assume a HC-PCF fiber with both open butt-ends immersed in a methane atmosphere. Methane gradually penetrates the fiber by diffusion. We characterize this diffusion by the relative concentration of gas inside the fiber, averaged over the fiber length found by integrating the local concentrations that are obtained by solving the diffusion equation with corresponding boundary conditions. For the average relative concentration as a function of time (t), fiber length (l) and diffusion constant (D) we use the following expression, represented in a form of an infinite sum [12],

$$C(t) = 1 - \frac{8}{\pi^2} \sum_{j=1,3,5}^{\infty} \frac{1}{j^2} \exp\left[-\left(\frac{j\pi}{l} \right)^2 D \cdot t \right]. \tag{1}$$

The diffusion coefficient for methane in nitrogen is 2.2×10^{-5} $m^2 s^{-1}$ [24]. Using this value, the dependence of the average relative concentration on time for four fiber lengths (0.02, 0.06, 0.18, and 0.54 m) was plotted. The result is shown in Fig. 2a.

EXPERIMENTAL RESULTS

In order to practically evaluate the theoretical analysis presented before, some experiments were conducted. A 13.7 cm segment of HC-PCF was aligned with a SMF, effectively transmitting light through the segment and then gas was inject into the chamber and the decay of the transmitted light with time was registered. The obtained data is presented in Fig. 2b. The time taken to achieve 95% of the steady-state was about 248 s. In comparison to the theoretical value (241 s), obtained with equation 1, we have a relative error of less than 3%, thus validating the adopted model. For evaluating gap coupling loss between a SMF and a HC-PCF, and also between two HC-PCF, several measurements were made to evaluate the dependence on lateral and axial gap misalignment. A tunable laser with 10 mW of maximum power was used as optical power source. The alignment between different fibers was achieved through a system with an axial step resolution of 5 μm and a horizontal/vertical step resolution of 0.1 μm. The light detection was made through a large area detector for the 1.55 μm wavelength region.

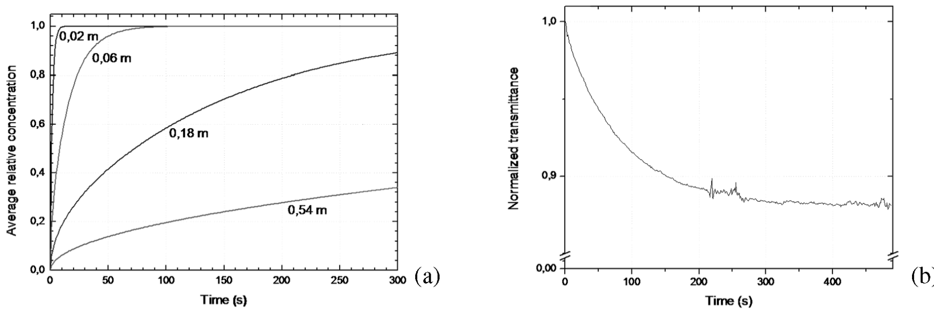

FIGURE 2. (a) Theoretical time-dependence of the average relative methane concentration inside different lengths of HC-PCF, with both ends open. (b) Transmittance as a function of time, for a 13.7 cm HC-PCF, having both ends open, in methane (5%).

Fig. 3a shows the obtained results for axial displacement between SMF and HC-PCF, and between two HC-PCF of the same type. The excess loss values presented are referenced to minimal loss corresponding to direct fiber connection between the laser and the photodetector. The obtained results show that for similar axial displacements, the 19-cell HC-PCF has much lower loss dependence than the 7-cell HC-PCF. Fig. 3b shows the obtained results for lateral displacement between SMF and HC-PCF, and between two 19-cell HC-PCF. During these measurements, the fibers were kept in close proximity.

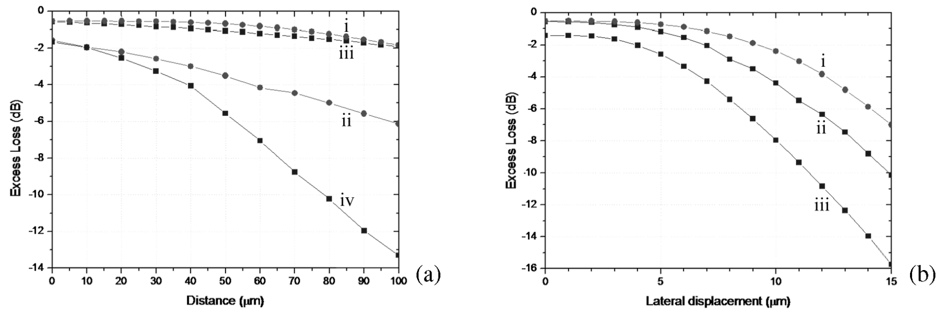

FIGURE 3. (a) Excess loss dependence on axial displacement between: (i) SMF and 19-cell HC-PCF, (ii) SMF and 7-cell HC-PCF, (iii) two identical HC-PCF 19-cell, (iv) 7-cell to 7-cell HC-PCF. (b) Excess loss dependence on lateral displacement between: (i) SMF and 19-cell HC-PCF, (ii) two 19-cell HC-PCF, (iii) SMF and 7-cell HC-PCF.

The presented results confirm that the 19-cell HC-PCF loss coupling has much lower dependence on lateral displacement both with SMF and with another 19-cell HC-PCF. The coupling losses in the 7-cell HC-PCF have always a larger dependence either on lateral or axial gap misalignment. This behavior was expected due to the higher mode field diameter of the 19-cell PCF when compared to both the SMF fiber and the 7-cell PCF which are quite similar. These results indicate that 19-cell HC-PCF is less susceptible to misalignments induced during multiple-coupling gaps implementation or during system operation due to environmental effects.

Furthermore, measurements were performed for evaluating splicing losses at different conditions between SMF and 19-cell HC-PCF. From our experiments, using a splicing technique previously reported [21], we concluded that for an arc current of 13.5 mA, the ideal electric discharge time is around 300-400 ms. These splicing parameters allow reproducible splice losses to be attained. In spite of having different shapes, the losses between SMF and HC-PCF aren't significantly affected, being the lowest insertion loss attainable ~2 dB. Nevertheless, even using optimum splice parameters the coupling efficiency is always lower than with straight butt-coupling.

Having in mind the previous assumptions and practical results, we devised a HC-PCF-based sensing head incorporating multi-segments with gaps between them in order to increase the system sensitivity without compromising the sensor response time. This splitting is necessary since the length of contiguous fiber directly affects the gas diffusion inside of it. Zirconia ferrules and sleeves were elected to the assembly of our sensing heads as these are cheap, common, standard and easy to find components.

The opto-electrical setup that was implemented and tested for the interrogation unit in is presented in Fig. 4 and it is based on the well known Wavelength Modulation Spectroscopy technique [25]. In this setup, the normalization of the sensing head response at 2ω by its DC level gives us an output independent of power fluctuations, being therefore only dependent of gas concentrations. The reference cell is used to keep the laser wavelength locked to the gas absorption line.

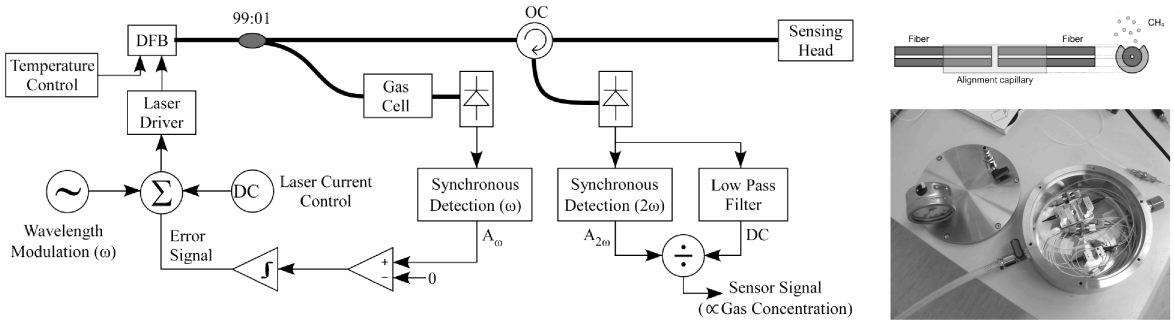

FIGURE 4. a) Experimental setup developed for the interrogation unit, sensing head and gas chamber.

CONCLUDING REMARKS

Hollow-core photonic crystal fibers appear as an exceptionally interesting player in the field of gas sensing since they promote the creation of short and direct interaction paths between light and gas and can be tuned to address any specific gas. Two practical issues, essentials for the implementation of viable gas sensor, were addressed; coupling losses, and gas diffusion time. Experimental results for these issues were presented. We also presented an overview of the current work being carried out at INESC Porto in this area.

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