Hollow-core photonic crystal fibres for gas sensing applications

J. P. Carvalho, F. Magalhães, O. Frazão, J. L. Santos, F. M. Araújo, L. A. Ferreira

Abstract— **Gas sensing applications represent an enormous opportunity for hollow-core photonic crystal fibres, since large light-gas interaction lengths can be attained. Towards the implementation of practical sensing heads, we present a study on the coupling losses dependence on lateral and axial gap misalignment between single-mode fibre and a hollow-core photonic crystal fibre and also some results on the splicing of these fibres. Finally a possible practical sensing head configuration is briefly discussed.**

Index Terms—**Hollow core photonic crystal fibre, coupling loss, splicing, gas sensing**

I. INTRODUCTION

PHOTONIC Crystal Fibres (PCFs) [1,2] have generated a wave of excitement because they present properties that cannot be achieved with conventional optical fibres. The light guiding characteristics of conventional fibres are limited by the properties of the materials from which they are made. Internal microstructures add another degree of freedom in controlling light guidance in fibres.

Like conventional fibres, index-guiding PCFs (solid core microstrutured fibres) confine light inside a solid core by total internal reflection thanks to a cladding that has a slightly lower refraction index. By contrast, hollow core PCFs (bandgap-guiding microstrutured fibres) [3] 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 in the cladding that acts like an insulator for light. The HC-PCFs are made with hundreds of periodically spaced air holes in a silica matrix, typically arranged in a honey combed-like pattern. Because light guidance is no longer dependent on the core's effective index, it becomes possible to create fibres that guide light in an empty or gas-filled core.

To practically exploit this feature on the implementation of sensing heads with long light-gas interaction lengths, it is necessary to ensure proper diffusion of gas inside the fibre hollow-core. Several approaches can be envisaged to provide straight apertures through the cladding, creating multiple access points for the gas to reach the hollow-core. However, methods such as arc etching by fusion splicing, slit milling or laser drilling often lead to asymmetrical transverse disruption of the honey combed structure resulting in intolerable losses. Multi-coupling gaps overcomes this limitation, being one of the most promising methods for the implementation of practical devices. Nevertheless, the optimum design of multiple-coupling gaps still requires a careful assessment of excess loss dependence on lateral and axial gap misalignment, since optical power needs to be kept below safe levels imposed in most hazard gas sensing applications. Here, a study of the coupling losses performed for a type of HC-PCF, the 19-cell HC-PCF (see Figure 1), is presented.

Another important issue in the practical applications of PCF is its low loss connection with single mode fibres (SMF). Good splicing of PCF to standard SMF [4-7] is extremely vital in order to enhance its potential applications in gas sensing. A study of the splicing losses is also presented for the 19-cell HC-PCF.

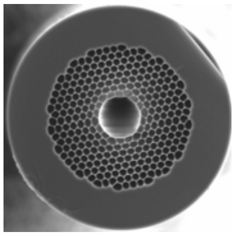
Figure 1 – 19-cell HC-PCF from Bath University

Finally a brief description of the design of a HC-PCF based sensing head is made.

II. EXPERIMENTAL PROCEDURE

For evaluating the gap coupling loss between a SMF and a HC-PCF, and also between two HC-PCFs, several measurements were made to determine the dependence on lateral and axial gap misalignment. A tuneable laser with 10 mW of maximum power was used as optical source. The alignment between different fibres was achieved through a system with an axial step resolution of 5 μm and an 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 shows the obtained results for axial displacement between SMF and the HC-PCF, and between two HC-PCFs of the same type. The excess loss values presented are referenced to minimal loss corresponding to direct fibre connection between the laser and the photodetector.

Our studies confirmed that 19-cell HC-PCF loss coupling has an acceptable dependence on axial and lateral displacement both with SMF and with another 19-cell HC-PCF. These results indicate that 19-cell HC-PCF presents an

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acceptable susceptibility to misalignments induced during multiple-coupling gaps implementation or during system operation due to environmental effects.

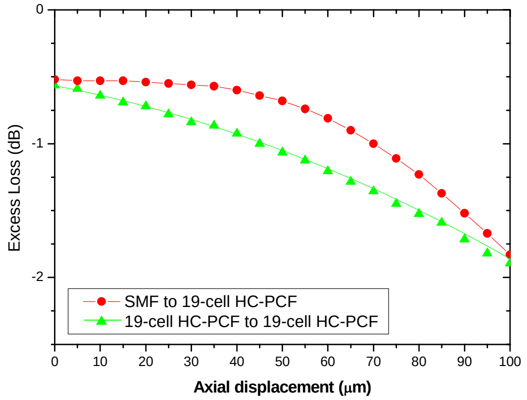

Figure 2 – Excess loss dependence on axial displacement between a SMF and HC-PCF, and between two HC-PCFs

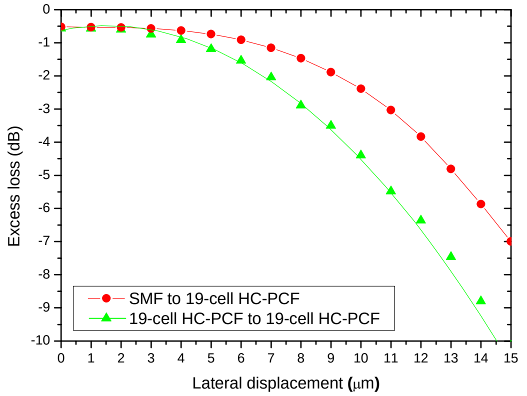

Figure 3 – Excess loss dependence on lateral displacement between a SMF and HC-PCF, and between two HC-PCFs.

Furthermore, spectral measurements were performed for evaluating splicing losses at different conditions between SMF and 19-cell HC-PCF. Obtained results are presented in Fig. 4. From our experiments we concluded that for an arc current around 13.5 mA the ideal electric discharge time is on the interval 300-400 ms, using a splicing technique previously reported by the authors [8].

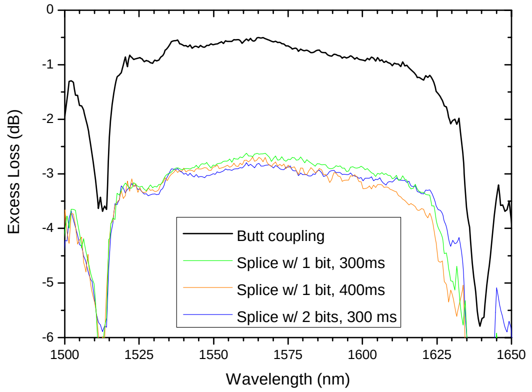

Figure 4 - Experimental results obtained for estimation of losses in light coupling between SMF and 19-cell HC-PCF in different cases.

The use of these splicing parameters allows reproducible splice losses to be attained. Nevertheless, even using optimum splice parameters the coupling efficiency is always significantly lower when compared with straight butt-coupling.

III. SENSING HEAD

The principle of operation of the envisaged sensing interrogation system is based on wavelength modulation spectroscopy (WMS). An optimized optoelectronic system is currently being developed to be integrated as a portable processing unit, which will be able of interrogating different remote sensing heads by implementation of a proper multiplexing approach.

For the sensing head, a possible configuration is depicted in Figure 5. Since interaction of light with the gas traces will take place in the core of the HC-PCF, the sensing head must be optimized for ensuring proper diffusion of the gas inside the hollow core. Accordingly to the obtained results, this can be done by using small lengths of fiber comprised in coupling gaps that act as multiple gas inlets. The interrogation unit is then connected to the sensing head by means of a lead fibre spliced to the HC-PCF, which guides the light to and from the sensor.

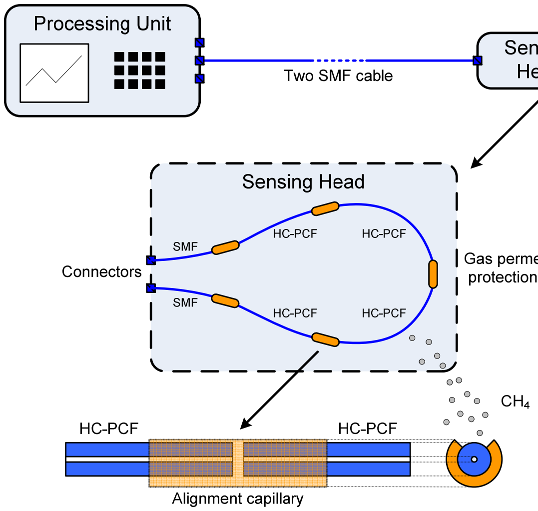

Figure 5 – Possible outline of the sensing head in a transmission scheme (top) and the possible solution for a capillary-reinforced opening that serves as a gas inlet to the HC-PCF core (bottom).

IV. CONCLUSION

In this work an analysis of the coupling losses dependence on axial and lateral displacement between SMF and HC-PCF fibres and between two HC-PCFs of the same type was performed. The obtained results are very encouraging towards the implementation of practical multiple-coupling gap based gas sensing systems based in HC-PCFs. A simple analysis on splice losses between 19-cell HC-PCF and SMF was also done, being the lowest insertion loss attainable ~2 dB. A possible outline of the sensing head scheme for gas methane detection was also presented.

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