Lateral access to the holes of photonic crystal fibers – selective filling and sensing applications

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Abstract: A new, simple, technique is demonstrated to laterally access the cladding holes of solid-core photonic crystal fibers (PCFs) or the central hole of hollow-core PCFs by blowing a hole through the fiber wall (using a fusion splicer and the application of pressure). For both fiber types material was subsequently and successfully inserted into the holes. The proposed method compares favorably with other reported selective filling techniques in terms of simplicity and reproducibility. Also, since the holes are laterally filled, simultaneous optical access to the PCFs is possible, which can prove useful for practical sensing applications. As a proof-of-concept experiment, Rhodamine fluorescence measurements are shown.

OCIS codes: (060.2310) Fiber optics; (060.2370) Fiber optics sensors; (230.1150) All-optical devices; (230.3990) Microstructure devices.

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1. Introduction

Due to their unique characteristics photonic crystal fibers (PCFs) have found a broad range of applications in optics and photonics [1-2], from nonlinear optics [3] to sensing [4-6], from high-intensity pulse delivery [7] to endlessly single mode guidance [8]. In particular, for sensing physical, chemical and biological characteristics of liquids and gases, PCFs may offer unprecedented sensitivity since the material being sensed can be inserted into the fiber holes and experience long range interaction with confined (guided) light. Prior to PCFs such interaction could only be obtained by tapering a conventional fiber to a few microns [9] or by using D-shaped fibers [10]. With PCFs a high light/matter overlap is achieved while maintaining the waveguide external diameter (and thus its robustness and mechanical strength) unaltered. In the case of hollow-core PCFs (HC-PCFs) the material under study can be selectively inserted into the core hole, thus forming a liquid rod, which is surrounded by a low refractive index cladding which guides by total internal reflection [5]. In this case, a virtually complete light/matter overlap is obtained.

Guided-wave nonlinear optics experiments in liquids can also be greatly simplified by using PCFs. Early experiments were limited to high-refractive-index liquids in capillary fibers [11] or the use of low-index (e.g. Teflon [12]) cladding materials. For optical experiments, hollow core PCFs can have their central hole selectively filled, increasing the efficiency of nonlinear effects. Stimulated Raman scattering has been observed in an ethanol-core PCF [13].

The use of HC-PCFs for the fabrication of liquid-core fibers, however, requires that the core be selectively filled, while the cladding holes remain unfilled. This requirement leads to the need for techniques that block all cladding holes while keeping the core open and free to be filled. Two different methods have recently been described to this end [14-16]. In one of them [14,15] a UV-curable polymer is inserted into the fiber and a multi-step injection-cure-cleave process results in the sealing of the cladding holes. The implementation of this technique is, however, complex and time consuming.

The second method uses an arc fusion splicer to close the cladding holes [15,16]. The tip of the PCF is exposed to the electrical arc, which heats the fiber and induces the collapse of all holes. Since the cladding holes are smaller than the core hole (typically by a factor 3), their complete closure occurs before that of the core, thus allowing for selective filling. Despite being significantly quicker than the first technique, this method contains two drawbacks. Firstly, as shown in [16], its success is critically dependent on parameters such as arc time, electric current and fiber position relative to the arc center. Clearly, these parameters vary from fiber to fiber, as they depend on PCF parameters such as air-filling fraction, pitch and hole diameter. The second drawback is that the arc inevitably reduces the core diameter at the fiber tip, creating a bottleneck. In [16], the best results indicate a reduction of 34% in the central hole diameter (from 10.9 to 7.2 μm). This partial collapse slows the fiber filling process, especially when viscous fluids are to be inserted.

The two selective filling methods described above have in common the fact that the liquid is inserted into the HC-PCF via its tip, which is also where the core is optically accessed. This characteristic forces the filling process to be carried out prior to the optical alignment process and requires that the fiber tips be cleaved between processes. The same

problem occurs when the cladding holes of a solid-core PCF (SC-PCF) are to be filled for sensing through the evanescent field.

A way to simplify the whole procedure would be to insert the material from the side of the fiber, by locally and laterally accessing the fiber holes. However, most techniques available to this end, such as mechanically polishing, laser drilling [17] or chemically etching the fiber, are rather complex and would contaminate the fiber. More importantly, in the case of hollow-core PCFs these techniques would not provide access solely to the central hole, as desired.

In this work we propose and demonstrate a method to laterally access either some of the cladding holes of a solid-core PCF or the core of a hollow-core PCF, in which an arc fusion splicer is used to heat and melt the side of the fiber while a positive internal pressure expands the desired holes. The technique compares favorably with the above-mentioned selective-filling methods in terms of simplicity and reproducibility, solving the partial core collapse issue of the previously-reported splicer method. In addition, and importantly, the lateral exposure of PCF holes opens new possibilities toward practical liquid or gas sensing applications with the material being laterally inserted while the fiber tips are aligned in an optical system. As a proof-of-principle experiment, we show fluorescence sensing of laterally-inserted Rhodamine.

2. Lateral hole fabrication

We tested the proposed method using one sample of HC-PCF and one sample of SC-PCF. Scanning electron microscope images of these samples are shown in Fig. 1(a) and 1(b) respectively. The hollow-core fiber has a 10.7-μm core diameter, an average pitch of 2.2 μm and an average cladding hole diameter of 1.9 μm. Its external diameter is 125 μm while its microstructured region is 37 μm wide. The solid-core PCF has a 102-μm external diameter, a microstructured region that is 58 μm wide, a core diameter of 2.5 μm, a pitch of ~5.1 μm and a cladding hole diameter of ~4.3 μm.

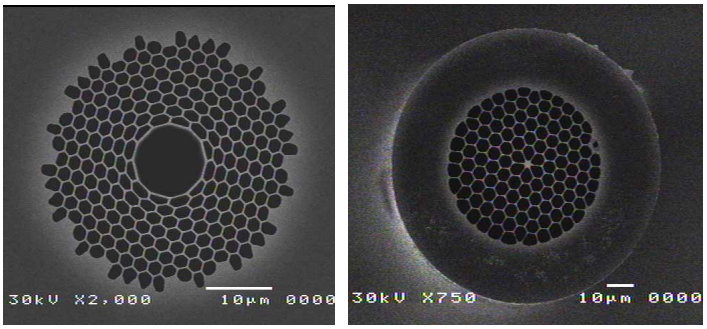

Fig. 1. Scanning electron microscope images of the hollow- (a) and solid-core (b) PCFs used.

The process to create a side hole in the SC-PCF using a standard fusion splicer is rather simple. Firstly, all holes are collapsed in one fiber end with a long (~1 second) arc. Subsequently, pressure (around 4-5 bar) is applied from the opposite fiber end while an arc is generated between the two extremities, at the position where the side hole is desired. This second arc softens the glass, which in turn tends to expand due to the applied pressure. Note that this technique is similar to that long used by glass blowers to fabricate glass items. If the pressure is sufficiently high and the arc sufficiently long, the solid silica outer cladding is forced to open, creating the side hole. The process is quite insensitive to arc parameters, which can easily be optimized after a few trials. Figure 2 shows side views of the fiber with the lateral hole, which is ~64 μm wide.

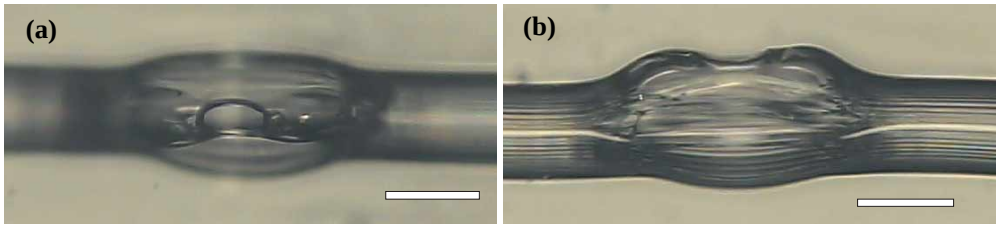

Fig. 2. Optical microscope longitudinal images of a solid-core PCF showing front (a) and side (b) views of the fabricated lateral hole. The white bar is 100 µm wide.

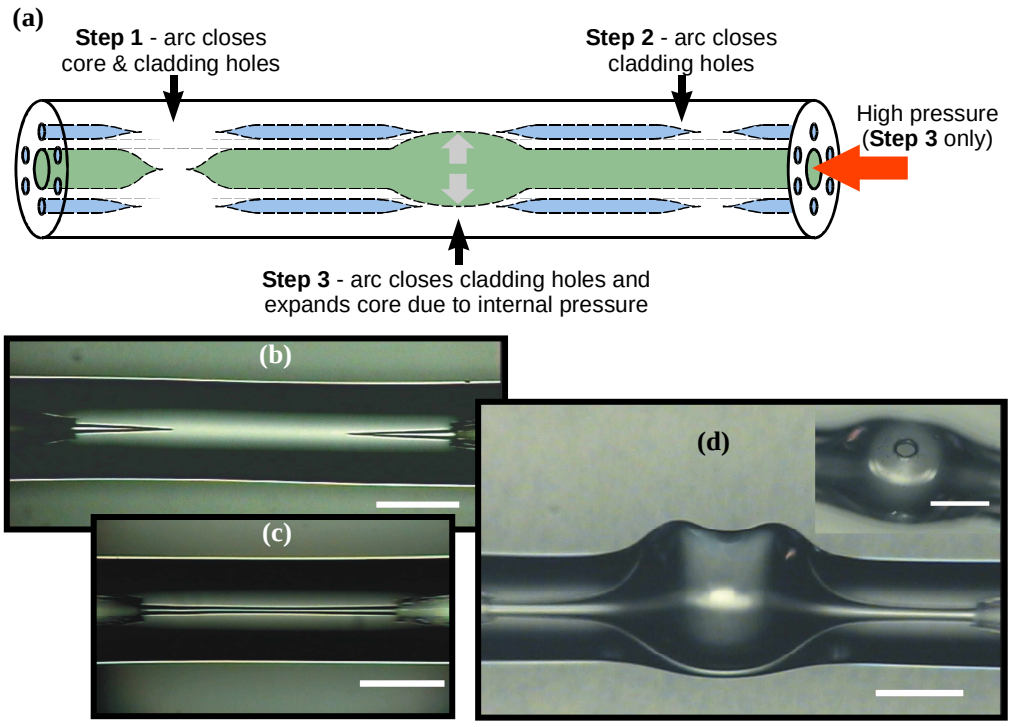

Fig. 3. (a) Schematic diagram showing the three steps to opening the side hole in a hollow-core PCF. Optical microscope images of the steps 1, 2, and 3 are shown in (b), (c), and (d) respectively. White bars are 100 µm wide.

The procedure to create a side access to the central hole of HC-PCFs requires one extra step compared to that described above. The complete procedure is schematically shown in Fig. 3(a) while side-view microscope images of each step are depicted in Figs. 3(b), 3(c) and 3(d). First, as for a solid-core PCF, all holes are closed near one fiber end (Fig. 3(b)). Next, in order to increase the pressure in the core hole only, the cladding holes are collapsed near the other end (Fig. 3(c)) while keeping the central hole open (although partially collapsed). The last step consists of simultaneously applying pressure (around 4-5 bar) in the core and producing an arc at the position where the side hole is to be created. Figure 3(d) shows the lateral hole formed. In the inset of this figure the hole is 31-µm wide; this width can be adjusted by adjusting the applied pressure. Note that the arc in step 3 should be produced at a fiber position that is between the positions of the arcs of steps 1 and 2. It has been observed through inspection of the microscope images that the arc of step 3 locally collapses the cladding holes, thus exposing solely the core hole. This feature is a crucial requirement for

selective filling and demonstrates the suitability of the proposed method. As in the case of the solid-core fiber, the arc parameters can easily be found for each fiber with very few trials.

The procedure of Fig. 3(a) can also be used to expand the central hole without opening it to the external environment. In this case, a lower pressure has to be applied and the arc duration has to be reduced. Figure 4(a) shows a side picture of a hollow-core fiber with the core expanded by a factor 18 and collapsed cladding holes. The PCF can subsequently be cleaved at the expanded core region if liquid is to be inserted from the fiber tip. This procedure solves the bottleneck issue resulting from partial core collapse. The cross-sectional profile of a HC-PCF that was cleaved at the expanded core region is shown in Fig. 4(b). The core diameter has increased by 68% to 18 μm. Obtaining a good cleave with larger core expansion factors has proved difficult.

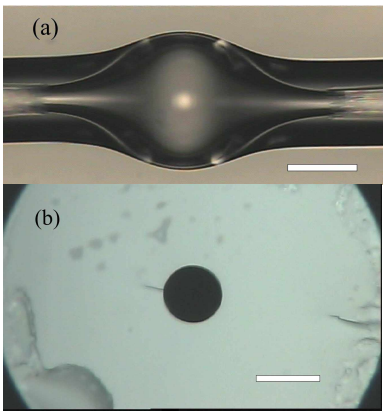

Fig. 4. Longitudinal (a) and cross-sectional (b) optical microscope images of hollow-core PCFs with expanded, but not laterally opened, cores. White bars are 100 μm (a) and 20 μm (b) wide.

3. Lateral filling of PCF holes

As mentioned in the previous section, and observed in Fig. 3(d), the procedure followed to open the side hole in hollow-core PCFs naturally closes the cladding holes around the side hole area. In order to further confirm this observation and to demonstrate selective core filling through the side of a PCF, a UV-curable polymer (NOA 73) was dropped over the side hole and subsequently sucked into the fiber via the application of a negative pressure at one fiber end. After curing the polymer the fiber was cleaved and the cross section image is shown in Fig. 5(a). As can be seen, just the central hole is filled, which demonstrates selectively core filling, as desired. In comparison to the other available methods, the authors found the present method to be the simplest and most robust. In addition, the method yields reproducible results, allowing for the trivial preparation of liquid-core PCFs without requiring much skill.

Unlike the HC-PCF case, with SC-PCFs it is not clear from the microscope images (Fig. 2) whether the side opening gives access to all, part or none of the cladding holes. The UV-curable polymer was then inserted in five SC-PCF samples (with the procedure described above for HC-PCFs) and their cross-sections analyzed. It was found that on average 30-50% of the holes are filled. The cross-section microscope image for one of the samples can be seen in Fig. 5(b). As at least one of the holes next to the core is generally filled, sensing via evanescent-field light-matter interaction is likely to be possible. The statistical nature of the number and position of holes that can be filled from the side is currently a limitation of the described technique in the case of SC-PCFs. Nevertheless, it may be possible to increase and/or control the number of such holes by adjusting SC-PCF parameters such as pitch, hole diameter and thickness of the solid silica cladding region.

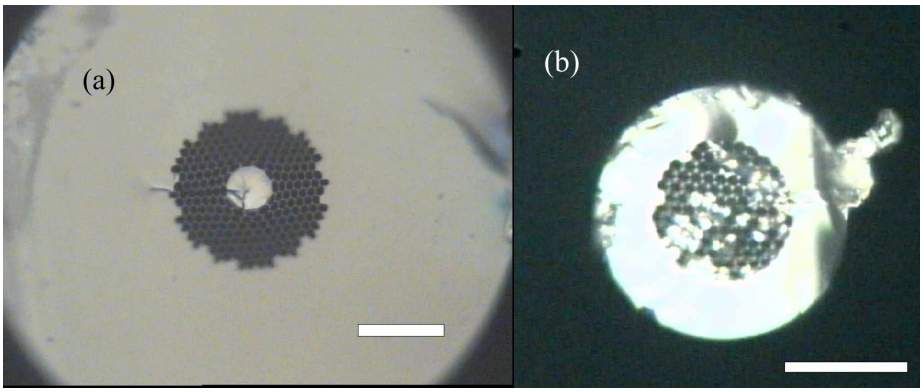

Fig. 5. Cross-sectional optical microscope images of a hollow-core PCF (a) and of a solid-core PCF (b) with holes laterally filled with polymer. White bars are 20 µm (a) and 50 µm (b) wide.

4. Optical tests and application to sensing of liquids

Before an optical characterization of the fibers with side holes is given, it is worth analyzing the modal properties of the filled fibers in the absence of a side hole. This was done by numerically simulating the waveguides with the use of a commercial software that is based upon the finite difference method. The optical wavelength used was 633 nm. Note, however, that such simulations depend on the exact material to be inserted while the technique described here is general. To be consistent with the results of the previous section, for the SC-PCF simulation a single hole next to the core was assumed to be filled, while for the HC-PCF just the core was filled. Simulations were performed using both water and ethylene glycol as the inserted materials and the respective refractive indices were assumed to be 1.3316 (measured) and 1.4311 [18]. Figure 6 shows the fundamental modes found in each fiber with ethylene glycol as the inserted material. The mode of the HC-PCF (Fig. 6(a)) presented an effective index of 1.4306 and a negligible confinement loss that was within the error provided by the simulation (~10^{-11} dB/m). Similar losses were found for other low-order modes. The virtually complete light/liquid overlapping is evident from the figure. The confinement loss for the fundamental mode of the fiber filled with water was ~0.9 dB/m. Note that the material loss has to be added to these values to obtain the total loss. Note also that with the filled core, guidance is obtained through total internal reflection rather than through a cladding bandgap.

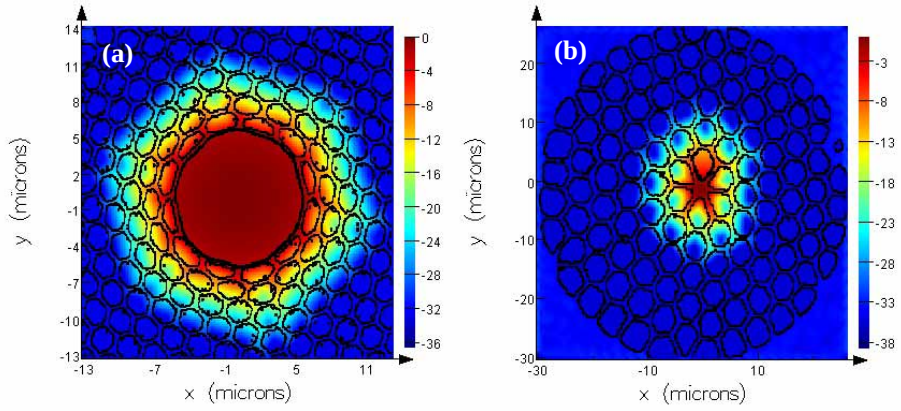

Fig. 6. Simulated normalized intensity profiles (in decibels) of the fundamental modes for the ethylene glycol filled HC-PCF (a) and SC-PCF (b). In (b) solely the top-most hole next to the core is filled.

The fundamental mode for the SC-PCF filled with ethylene glycol (Fig. 6(b)) presented an effective index of 1.4507 and a negligible confinement loss (within the simulation error of ~10^{-11} dB/m) with other low-order modes presenting similar losses. Figure 6(b) shows that the light is still well confined to the core but that a good light-liquid overlapping is obtained through the evanescent field (the power traveling through the hole corresponds to 1.7% of the total power). With water in the hole, the confinement loss is also negligible and, as expected, the evanescent field extends less into the hole (0.4% of the power travels through the hole).

In addition to the simulation with a filled hole next to the core, simulations were also performed with liquid inserted in a single hole away from the core. These simulations aimed at analyzing the possibility of launching, by mistake, the light at one of these holes and obtaining a completely different propagation condition. It was found that in this case a much less tight confinement was obtained with a considerable amount of light spreading across a large fraction of the glass microstructure (including the core). Consistently, the confinement loss for ethylene glycol and water was respectively determined to be 7 and 14 orders of magnitude higher than those found for a filled hole next to the core. Experimentally, such a propagation condition was avoided by always launching the light at the center of the fiber cross-section. However, perfectly inserting light into the core was found to be difficult since, as discussed below, a substantial amount of the light after the side-hole invariably propagates through the cladding, thus providing very little indication of the launching conditions.

In order to optically test PCFs with lateral holes, a He-Ne laser and an Argon ion laser set to 496 nm were launched both into an unfilled SC-PCF and into a HC-PCF with the core filled with water. In both fiber cases, imaging the output tip of the fiber with an objective lens revealed that only a small portion of the light actually leaves the fibers via the cores, irrespective of the input alignment. A subsequent cut-back process revealed that in both cases core guidance was achieved up to the side hole, which then scattered a considerable amount of the light into the cladding. Note, nevertheless, that a reasonable fraction of the launched light was found to reach the fibers output, via either the core or cladding, and can easily be detected. Systematic cut-back power measurements were then undertaken revealing that ~10% and 20-25% of the power remains in the SC-PCF and in the HC-PCF, respectively, after the side-hole. The losses associated to the post-side-hole propagation via the cladding were found to be ~1 dB/cm, which allows for the use of fibers up to ~10 cm long, which are typical for the aimed sensing applications. This output light can then be used to sense the inserted material. Note that coupling into the cladding occurs only at the side hole. For increasing the interaction between the core light and the material, this hole can, therefore, be placed near the output fiber end.

One of the most important advantages of the present filling technique is that, since selected filling occurs laterally, the fiber tips can be optically prepared and inserted into an optical sensing system even before the insertion of the liquid (or gas) to be measured. Once the lateral hole is created and the PCF is placed in the optical system, the presence of a fiber optics expert may be dispensable, meaning that both inserting the material of interest and sensing can be performed in chemistry or biology laboratories.

Figure 7(a) shows a possible setup to laterally insert liquids without contact to the fiber tips, in which the PCF passes through a pressure cell. The lateral hole is kept inside the cell, which can subsequently be filled with the material under study. Note that the liquid will flow to both fiber ends and fill the entire PCF length. This complete fill is essential for HC-PCFs, as guiding relies on the index contrast generated by the inserted material. In the case of SC-PCFs, and when leaving the fiber tips untouched is not required, the setup of Fig. 7(b) can also be employed for PCF filling. In this case the liquid is dropped at the lateral-hole region and remains at atmospheric pressure, while a lower pressure is applied to one fiber end. Although such a scheme is considerably simpler, waiving the need of the pressure cell, it only fills the region between one fiber tip and the side hole.

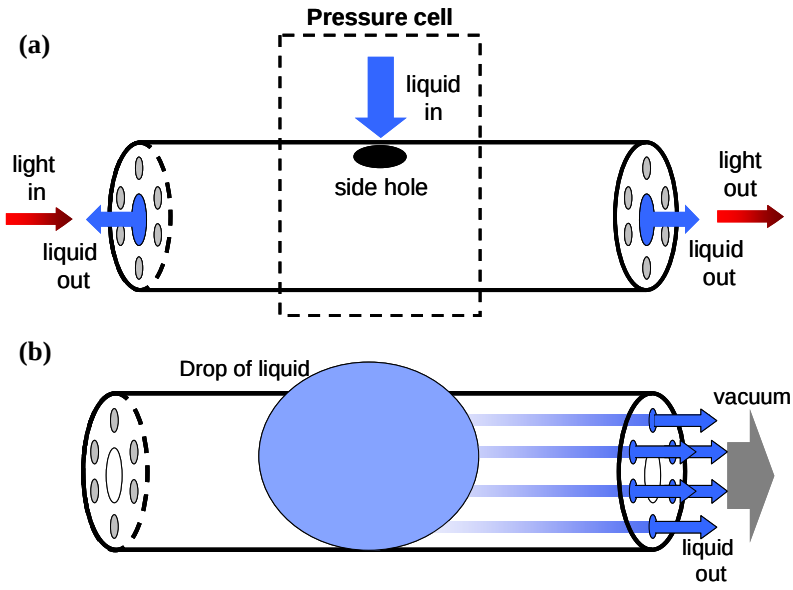

Fig. 7. (a) A possible setup to insert liquids into the core of a HC-PCF and to optically access it simultaneously – this setup is also suitable for SC-PCFs; (b) alternative method to insert liquids into SC-PCFs.

As a proof-of-concept experiment for the proposed sensing procedure, Rhodamine diluted in ethylene glycol was inserted into a HC-PCF and into a SC-PCF and the fluorescence (at ~600 nm), generated by excitation at 496 nm, was detected at the output of the fibers. The pump radiation was produced by an Argon ion laser and had a power of up to 6 mW. The schemes to selectively fill the core of the HC-PCF and to fill the holes of the SC-PCF were those of Figs. 7(a) and 7(b), respectively. Light at the fibers output was collected with the use of a multimode fiber and directed into an optical spectrum analyzer. The HC-PCF sample had a total length of 39 mm with the side hole being placed at 6 mm from the output end. In the case of the SC-PCF, a length of 41 mm, between the fiber input and the side hole, was filled with Rhodamine. The length of the unfilled fiber section, located after the side hole was 24 mm. To infer the impact of the side-hole-induced loss on the results, control experiments were also undertaken, in which a HC-PCF and a SC-PCF without the lateral hole, but with the same Rhodamine-filled lengths, were employed. Note that for the comparison to be fair, especially in the case of the SC-PCF in which only a few holes are filled, the control experiment fibers were filled through a side-hole generated as described above, which was subsequently removed before the measurements were carried out.

Figure 8(a) shows the fluorescence spectra obtained with the HC-PCF with a lateral hole, for a pump power of 4.6 mW. It is clear that even for moderately low pump powers the spectrum is well above the measurement noise floor (27 dB). As a comparison, Fig. 8(b) depicts the fluorescence spectra obtained with the HC-PCF without the side hole and same pump power. Note that the fluorescence powers are about the same to within the estimated experimental errors of ~2dB.

The output fluorescence obtained in the SC-PCF with the side hole is seen in Figure 8(c) for a pump power of ~6 mW. Again, the fluorescence signal is high enough to be easily detected. Similar results were obtained when this fiber had its input and output ends swapped and the unfilled length cut to ~ 3 mm. It is worth mentioning the differences in the fluorescence generation process in these two cases. When the filled region is closer to the fiber input, the pump light is expected to interact with the Rhodamine mainly via its evanescent field. Upon reaching the side hole both the pump and the fluorescence are

irradiated to the cladding and reach the output end as explained above. In contrast, when the unfilled region is closer to the input end, the pump propagates through the core up to the side hole, where it is launched into the microstructured cladding and interacts with the Rhodamine. It is, thus, surprising that the two cases yield about the same fluorescence efficiency. The fluorescence generated in the control-experiment SC-PCF is shown in Fig. 8(d). The spectral signal in this case is ~13.5 dB higher than when the side hole is present, meaning that the impact of such a structure is higher in SC-PCFs than it is in HC-PCFs. This feature may be expected because while in a HC-PCF the core simply expands (and the microstructured cladding locally collapses), in SC-PCFs the application of pressure and the generation of the side hole severely displace the core and may cause its rupture.

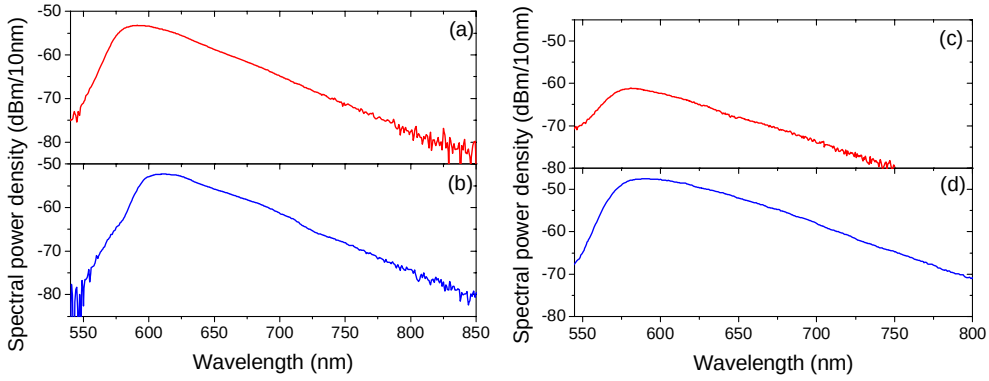

Fig.8. Rhodamine fluorescence spectra obtained with a HC-PCF with (a) and without (b) the side hole and obtained with a SC-PCF with (c) and without (d) the side hole.

Note that the fluorescence experiment described above is just an example of sensing application. In practice, other sample properties, such as the attenuation spectrum and nonlinear optical properties, can be sensed. Nevertheless, it is worth estimating the benefit of undertaking the fluorescence measurement above using the filled PCFs in comparison with using a bulk tank of the same length filled with Rhodamine. It can be shown [19] that for continuous-wave pumping, assuming that a reasonable population inversion is achieved, and neglecting saturation effects, the dye gain coefficient is proportional to the pump intensity that is absorbed across the filled length. As the absorbed intensity is the absorbed power divided by the modal area (in the case of waveguide propagation) or the beam cross-sectional area (in the case of bulk propagation) and the absorbed power, in the absence of saturation, is independent of these areas, it can be clearly seen that the gain coefficient is expected to be considerably larger when a PCF is employed. In particular, for a HC-PCF modal area of $\sim 80\times10^{-12}$ m^2 and a beam cross-sectional area of 78×10^{-8} m^2 (beam diameter of 1 mm) the fiber gain coefficient is expected to be 9750 times larger than the bulk gain coefficient. In the case of the SC-PCF and assuming that a single hole next to the core is filled with Rhodamine, the fiber gain coefficient is expected to be 910 times larger than the bulk gain coefficient (taking into account the cladding hole area and the fraction of power that overlaps with Rhodamine). If some saturation and/or limited population inversion are considered, these numbers are expected to decrease but to remain well above 1. Note that the beam can be focused in the bulk tank but that the beam area will only be comparable to fiber modal area over a length of less than a millimeter.

5. Conclusion

A technique to laterally access the holes of photonic crystal fibers was proposed and successfully implemented. It is based upon the increase in the gas pressure inside the holes

while local heat is locally provided to a section of the fiber so that it melts, expands and laterally tears, creating a side hole. In hollow-core PCFs it was shown that the side hole is connected solely to the central fiber hole and the technique can, thus, be used to selectively fill the core. The present method compares favorably with other selective filling techniques reported in terms of simplicity, robustness and reproducibility. In solid-core PCFs the side hole was shown to be connected with about 30-50% of the cladding holes. In both types of PCF, the technique allows one to laterally fill the fibers with liquids or gases, which can be used for optical sensing applications. Since no contact with the fiber tips is needed, the filling procedure is completely independent from and compatible with the optical alignment procedure. In order to demonstrate liquid sensing, Rhodamine diluted in ethylene-glycol was inserted through the side holes of a solid- and a hollow-core PCFs, and the associated fluorescence spectrum was measured. Although the lateral hole, was found to radiate light out of the core, a reasonable fraction of the light reaches the fiber output via the cladding and can be detected and used for sensing the inserted material.

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