Microstructured Optical Fibers for Gas Sensing: Design, Fabrication and Post-fab Processing

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ABSTRACT

Air/silica Microstructured Optical Fibers (MOFs) offer new prospects for fiber based sensor devices. In this paper, two topics of particular significance for gas sensing using air guiding Photonic Bandgap Fibers (PBGFs) are discussed. First, we address the issue of controlling the modal properties of PBGFs and demonstrate a single mode, polarization maintaining air guiding PBGF. Secondly, we present recent improvements of a femtosecond laser machining technique for fabricating fluidic channels in PBGFs, which allowed us to achieve cells with multiple side access channels and low additional loss.

Keywords: Microstructured Fibers, Photonic Bandgap Fibers, Single Mode Fibers, Femtosecond Laser Micromachining, All-fiber Gas Sensor.

1. INTRODUCTION

The advent of Microstructured Optical Fibers (MOFs) is widely recognized as one of the most significant breakthroughs in optical fiber technology of the last decade. In their commonest type (air/silica MOFs), these fibers comprise arrays of wavelength-scale air holes running along their length, which define their waveguiding properties by the hole size, shape and arrangement. The greater variety and control of optical properties that can be attained in MOFs provides a definite advantage for these fibers over conventional fibers for sensing applications. A variety of schemes based on different types of MOFs have been investigated, including absorption sensing [1], interferometric [2] and grating-based sensing [3], and schemes exploiting surface enhanced Raman scattering and plasmonic resonance [4].

An application area attracting considerable interest is gas sensing, which can either accomplished in hollow core Photonic Bandgap Fibers (PBGFs) [5] or solid core MOFs specially engineered to provide a large evanescent field [1]. Such fibers offer an unparalleled platform for accessing the optical field propagating through the holes and, due to their low transmission loss, allow for very long interaction lengths. This opens up the possibility for compact, high sensitivity optical sensors, where only tiny amounts of sample are required (≈μL per meter length) – a key advantage when monitoring hazardous formulations. All this goes in addition to the advantages of "traditional" optical fiber sensors, i.e. immunity from electromagnetic interference, robustness and durability, small size and possibility for remote interrogation through interfacing with fiber networks.

As well as advantages, some significant drawbacks have also been identified, which have impaired the performance of gas sensors based on MOFs to date. A well-known obstacle is the slow gas diffusion in the holes, which severely limits the response time of a MOF based sensor [1]. Furthermore, it is not straightforward to provide both the gas access and a stable input/output optical coupling, while retaining a compact arrangement. A crucial but perhaps less recognized drawback, relating specifically to air guiding PBGFs, originates from the multimode nature of the most commonly used fiber types [6]; the presence of "higher order" optical modes in addition to the fundamental air guided mode often leads to interference effects, which severely limit the ability to discern gas lines, in particular at low concentration levels.

In this paper we focus on two key issues concerning air guiding Photonic Bandgap Fibers (PBGFs) and aim to identify suitable solutions. First, we address the control of the modal properties of such fibers and demonstrate a single mode PBGF. Next, we present recent developments of a technique based on femtosecond laser micromachining, which allows fabrication of compact multi-port gas sensing cells with reduced response times.

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2. FABRICATION OF SINGLE MODE AIR GUIDING PBGFS

Hollow core PBGFs typically comprise of a triangular lattice of air holes, which define the fiber's operational wavelength range, and a core, which is obtained by removing 7 (7c) or 19 cells (19c) from its centre, and determines the fiber's modal properties. Although interest in other fiber designs is growing, the overwhelming majority of the studies in the literature refers to 7c and 19c PBGF, due to these fiber types being commercially available. It is well established, however, that these fibers are multi-moded: 7c PBGFs support a few (≥6) optical modes, while 19c PBGFs are heavily multi-moded. Similar to conventional fibers, the number of core modes roughly scales as the square of the core diameter of a PBGF. In addition to air guided modes, PBGFs also support interface modes located at the core boundary, which are termed Surface Modes (SMs), although these can be managed through careful fiber design [7].

An effective way to reduce the number of modes in a PBGF consists in reducing its core size to just three missing elements (3c-PBGF) [6]. We have fabricated this novel type of PBGF by a two-step stack and draw technique. Fibers with operating wavelength ranging from 1000 to 1800nm were obtained by suitably varying the scale factor of the structure during the fiber draw. Fig 1a shows a detail of the intermediate drawing stage (the ≈mm sized "cane"), while Fig. 1b and Fig.1c show images of a 3c PBGF optimized for transmission at about 1500nm. The core diameter (≈9μm) is approx 25% smaller than that of a 7c PBGF designed for the same wavelength.

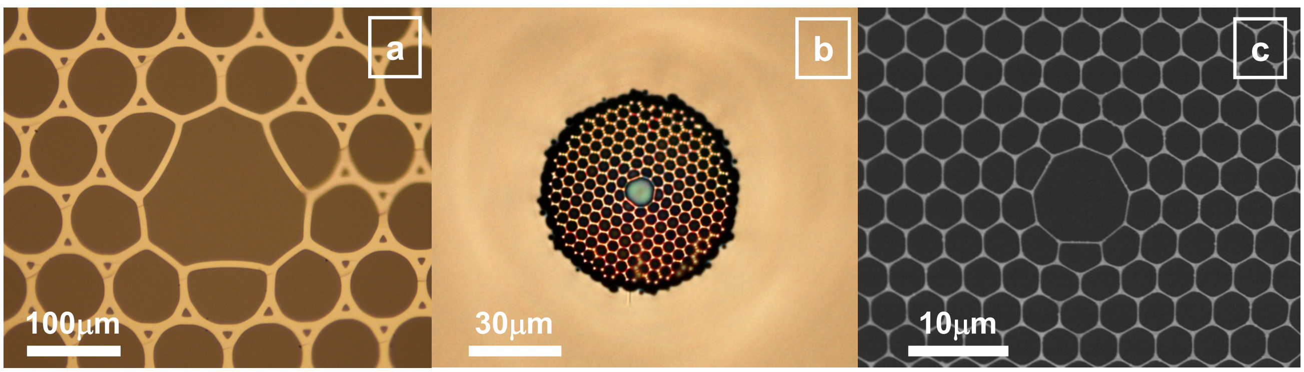

Fig. 1. Fabrication of a 3c PBGF: (1a) optical microscope cross-sectional image of the cane and (1b) of a fiber optimized for transmission at 1500nm; (1c) Scanning Electron Microscope (SEM) image of the same fiber showing detail of the core.

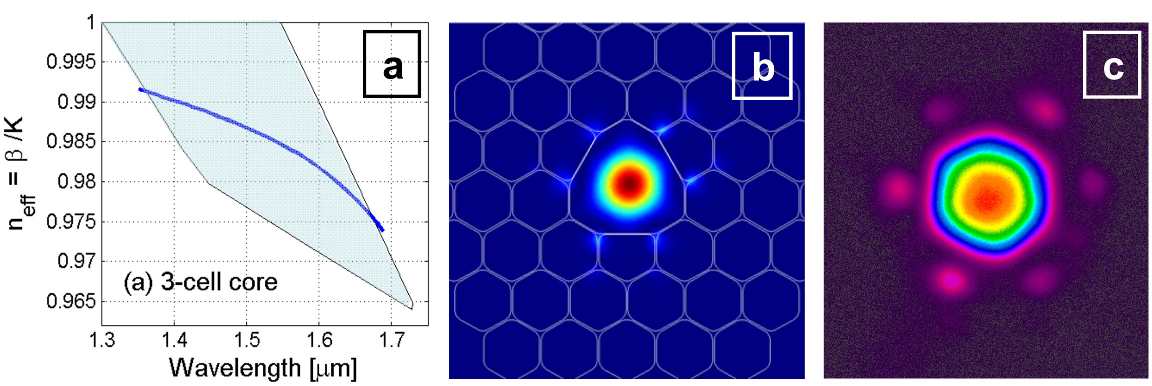

Fig. 2. Modal Properties of a 3c PBGF designed for operation at 1500nm: (2a) Calculated modal map: the shaded area is the bandgap, the curve represents the optical mode; (2b) Calculated mode profile; (2c) Measured near-field mode profile.

The modal and transmission properties of the 3c PBGF were studied both experimentally and through modeling, using an in-house developed code based on a full vector finite element method. Fig. 2a shows the bandgap and modal map calculated for the 3c PBGF at 1500nm; only a single pair of degenerate air guided modes was found to be supported. The calculated and the experimental intensity profiles of this mode are shown in Fig. 2b and 2c, respectively.

The transmission loss of the 3c PBGF was measured by the cutback method, finding a minimum value of approximately 0.2dB/m at 1540nm (Fig. 3a). We also investigated the effect of bending by measuring the transmission of a 2m long, straight sample and that of the same sample after imposing five tight coils (≤10mm radius). Since no noticeable difference was observed (Fig. 3b), we concluded that bend loss is negligible for 3c PBGF. The ability to coil the fiber with no loss penalty is clearly of great practical importance for obtaining compact sensors.

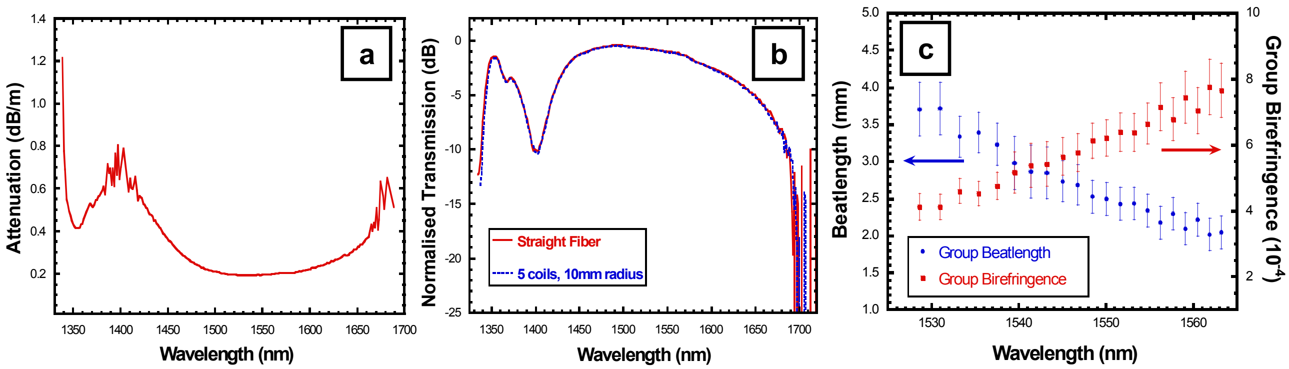

Fig. 3. Transmission properties of a 3c PBGF designed for operation at 1500nm: (3a) White light loss measurement over 40m cutback; (3b) Bending Loss; (3c) Group Birefringence measured by the beat length method.

The modal properties of the 3c PBGF were investigated by recording the near-field mode profiles (we used a tunable laser source and a beam profiler based on a phosphor coated Si camera). Fig. 2c shows a typical mode profile collected at the centre of the bandgap (1540nm). A remarkably robust single mode behavior was observed for the 3c PBGF, even when very short samples were analyzed, and under extremely un-optimized input coupling conditions (i.e. large spot size mismatch and offset launch). By contrast, similar launch conditions resulted in higher order modes being readily excited in samples of 7c PBGF and 19c PBGF. The birefringence of the 3c PBGF was measured by a wavelength scanning method. The output of an Er-ASE source was passed through a polarizer and a half-wave plate and launched into a 2.4m long fiber sample; the output from the 3c PBGF was then passed through a second polarizer and recorded by an optical spectrum analyzer. The modulation observed in the transmitted spectrum was used to calculate the beatlength and the group birefringence according to the method explained in ref. [8]. As shown in Fig 3c, we obtained a value of $4\text{-}8\cdot 10^{-4}$ in the wavelength range covered by our setup (1525-1565nm). Differently from the fiber reported in ref. [8], our fiber was observed to hold the polarisation. We believe that the measured birefringence originates from some form factor or minor structural asymmetry in the fiber. While no specific effort was made to obtain a birefringent fiber in this instance, the combination of an air guiding, single mode, and polarization maintaining fiber promises to be extremely enabling for sensing applications requiring a short device length.

3. FABRICATION OF PBGF CELLS WITH MULTIPLE FLUIDIC MICROCHANNELS

Arguably, the key limitation of MOFs used as gas sensors is the very slow diffusion of the gas in the holes. When the fiber is filled from its ends, gas filling of ≈meter scale samples typically requires several minutes, even if a vacuum assisted method is used, and much longer (≈hours) in the case of free diffusion. An obvious solution is to provide additional points of access for the gas along the fiber; however, this must be accomplished by introducing minimal loss, or perturbation (ideally, none at all), and without recurring to bulky arrangements. Different techniques have been proposed, including: using short, butt-coupled lengths of fiber with small gaps [9] and focused ion beam (FIB) processing [10]. We have investigated a fs-laser machining technique to manufacture side-access fluidic microchannels in MOFs. In a previous publication [11], we have demonstrated that this technique affords a high degree of precision and control by fabricating such channels in PBGFs with minimal structural damage (see insert in Fig. 4b) and thus very low additional loss. Very compact, ≈meter long PBGF cells comprising one or two microchannels were obtained by splicing the PBGF ends to standard single mode fiber (SMF) pigtails, which were subsequently employed in practical gas sensing configurations such as correlation spectroscopy [12] and cavity ring-down spectroscopy [13].

Here we report further improvements of this technique which have allowed us to achieve cells with multiple channels. In this case, we used a 7c PBGF with bandgap at about 1500nm. Several cells with up to five microchannels were fabricated, which enabled faster in- and out-diffusion of gas as compared to backfilling from the fiber ends (Fig. 4a). In addition, the gas pressure could readily be reduced to obtain gas absorption lines with narrower linewidth. We have been able to consistently fabricate channels with additional loss of 0.1 to 0.2dB per channel (Fig 4b). The maximum number of microchannels is currently limited to approximately five per meter length due to the increased fragility at the machined point, which makes it difficult to coil the fiber tightly without significant risk of mechanical failure. However, we anticipate the feasibility of PBGF cells with up to ≈20 holes per meter simply by mounting the PBGF on a suitable fiber holder prior to fs laser processing. The microchannels were observed to have surprisingly good lifetime (≈years) when the fiber was places in a container under clean, dry atmosphere. If water condensation at the microchannels occurred, it could be removed by placing the cells under a flow of dry gas a few minutes prior to use.

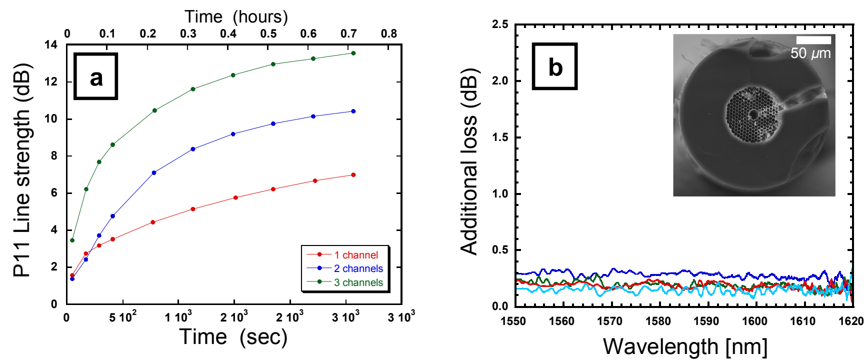

Fig. 4. Acetylene in-diffusion curves obtained by plotting the increasing linestrength of acetylene P11 line in 1m long PBGF cells with 1, 2 and 3 microchannels (4a). Additional loss due to each channel in a cell with four microchannels (4b).

4. CONCLUSIONS

In this work two key limitations concerning the use of PBGFs in gas sensors were addressed. Control of modal properties is paramount and a single mode, polarization maintaining PBGF at 1500nm was demonstrated. Furthermore, a fs laser machining technique can be employed to obtain compact, multiport gas measurement cells with reduced response time.

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