Novel Sealing Technique for Practical Liquid-Core Photonic Crystal Fibers

Rodrigo M. Gerosa, *Student Member, IEEE*, Alexandre Bozolan, Christiano J. S. de Matos, Murilo A. Romero, *Member, IEEE*, and Cristiano M. B. Cordeiro

***Abstract*— In this letter, we describe a simple and effective technique to prevent evaporation in liquid-core photonic crystal fibers (PCFs). The technique consists of using a micropipette to deploy a micro-droplet of an ultraviolet curable polymer adhesive in both core inputs. After it is cured, the adhesive creates sealing polymer plugs with quite satisfactory insertion loss (overall optical transmission of about 15%). Processed fibers remained liquid-filled for at least six weeks. From a practical point of view, we conducted a supercontinuum generation experiment in a water-core PCF to demonstrate a 120-minute spectral width stability and the ability to withstand at least 3-mW average power at the sealed fiber input. Similar experiments carried out with nonsealed fibers produced supercontinuum spectra lasting no longer than 10 minutes, with average powers kept below 0.5 mW to avoid thermally induced evaporation.**

***Index Terms*— Optofluidics, photonic crystal fiber (PCF), supercontinuum generation.**

I. Introduction

ALONG the last decade the development of optical fiber devices has gained impulse thanks to the maturing of the photonic crystal fiber (PCF) technology [1]. Typical PCFs are characterized by a microstructured cross section consisting of a regular array of air holes running across its length, thereby allowing the selective insertion of liquids [2]–[8] and colloids [9]–[10] into the fiber. These materials can then overlap with the guided optical field, offering a high degree of flexibility from the device design point of view. The light-material interaction is particularly strong if a hollow-core PCF is filled with a suitable liquid. Such liquid-core PCFs have been proposed and demonstrated in a large variety of applications, including supercontinuum generation [6]–[7], optical sensing [2], [8], [10] and dye laser engineering, with both conventional [11] and random [9] lasers being demonstrated. The main limitation for widespread use of liquid-core PCFs is the fast liquid evaporation, which often precludes practical use, beyond the research lab.

In this regard, Ong *et al*. [12] studied the evaporation of liquids in micro-capillaries. It was reported that, at room temperature, water inserted in a capillary of diameter similar to that of the hollow core of a PCF can evaporate in a such way that the capillary is emptied at a rate of around 1 μm/s, thereby severely affecting optical coupling and guidance in just a few minutes. This corroborates the observations of a previous work conducted by some of us [6], which investigated supercontinuum generation in a distilled water-core PCF, pumped by 60 fs pulses at a repetition rate of 1 kHz. In this case, the evaporation rate is even larger, due to thermal effects at high optical intensity levels. Indeed, although a maximum spectral width of ~500 nm has been achieved, we registered a spectral narrowing after about 10 minutes, due to water evaporation from the fiber tips, leading to diminished light coupling.

A few methods to prevent evaporation in liquid-core PCFs have already been described in the literature. The most often used technique requires the use of liquid-filled reservoirs at one (or both) of the fiber tips [5], [7], [13]. It is also necessary to seal the air holes in the cladding to prevent their undesired filling. Another possibility is the production of end-capped fiber ends [4], [11]. In one example of such an approach, the filled fibers are dipped in a viscous solution of a transparent polymer [11]. Although efficient, this method, as well as those that use liquid reservoirs, require the use of fairly cumbersome and bulky apparatus connected to the fiber tips, thereby preventing easy butt-coupling to conventional fibers and the development of fully integrated devices and sub-systems. In addition, it has been suggested [4] that end caps consisting of a short capillary silica fiber spliced to PCFs, primarily used to allow for selective hole filling, can later be spliced or butted to conventional fibers. However, the potential problem of evaporation during splicing/butting is yet to be investigated.

In this letter, we address the issues above, by proposing a new technique to seal the liquid-filled core of PCFs. By using the technique, it was possible to achieve very stable supercontinuum generation in a water-core PCF, keeping the same spectral width (~280 nm) for at least two hours.

II. Technique Description

The sealing technique consists of using a micropipette to deploy a micro-droplet of a UV curable polymer adhesive in both core inputs, after the hollow core has been filled with the desired liquid using the method detailed in [10]. We used an optical quality polymer with good transmission properties in

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R. M. Gerosa and C. J. S. de Matos are with Grupo de Fotônica, Universidade Presbiteriana Mackenzie, São Paulo 01302-907, Brazil (e-mail: rodrigo.mgerosa@gmail.com; cjsdematos@mackenzie.br).

A. Bozolan is with Universidade de São Paulo, São Carlos 13564-250, Brazil, and also with Grupo de Fotônica, Universidade Presbiteriana Mackenzie, Sao Paulo 01302-907, Brazil (e-mail: bozolan@sel.eesc.usp.br).

M. A. Romero is with Universidade de São Paulo, São Carlos 13564-250, Brazil (e-mail: murilo.romero@usp.br).

C. M. B. Cordeiro is with Instituto de Física, Universidade Estadual de Campinas, Campinas 13083-970, Brazil (e-mail: cmbc@ifi.unicamp.br).

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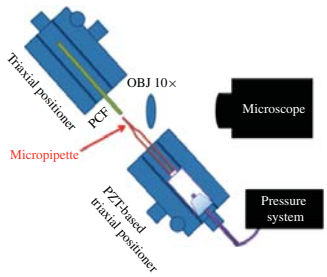

Fig. 1. Schematic view of the experimental setup.

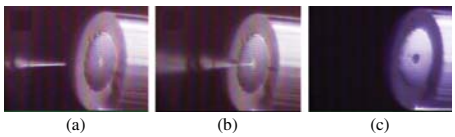

Fig. 2. Optical microscope imaging of the sealing sequence in a water-core PCF. (a) Alignment and (b) insertion of the micropipette. (c) Polymer plug undergoing UV curing.

the spectral range of 0.4–2.0 μm (Norland Optical Adhesives, NOA 61; refractive index 1.56) and the experimental arrangement depicted in Fig. 1. The micropipettes used to introduce the polymer droplet at the core input, without damaging the surrounding fiber cross section, are produced from borosilicate glass capillaries. The resulting micropipette end tips present an outer diameter which can be tailored from one up to four microns (while the inner diameter ranges from a few hundred nanometers up to one micron), according to the size of the air hole to be sealed. The micropipette is then attached to a syringe, which contains the polymer and is, in turn, connected to a pressure system. This syringe is placed over a PZT-controlled micropositioner, while the liquid-core fiber is placed over another triaxial positioner. The positioners are arranged in such a way as to face each other, while making a 45° angle with the axis of an optical microscope, used for monitoring purposes. An extra 10× objective lens is used to provide further magnification and to allow for a longer working distance.

As it can be seen in Fig. 2, during the sealing process the positioners are moved so as to introduce the micropipette tip inside the PCF core. Next, the polymer is pumped into the fiber by means of the pressure system connected to the syringe. Special care is taken to prevent the formation of air bubbles as the polymer fills the fiber input surface, which is accomplished by pressing the pipette against the inner wall of the core. Finally, the polymer is UV cured and the process is repeated at the other fiber end.

By using the above technique, sealed liquid-core PCFs have been produced from commercially available HC-1550-02 fiber samples (NKT Photonics, core diameter 10.9 μm). It should be mentioned that the technique can also be used to seal specific air holes in the PCF cladding, and holes with diameters ranging from 2 to 20 μm have been sealed. In fact, by combining this sealing technique with a post-processing method based on differential pressure and heating, we have recently demonstrated the production of compact all-fiber interferometers [14].

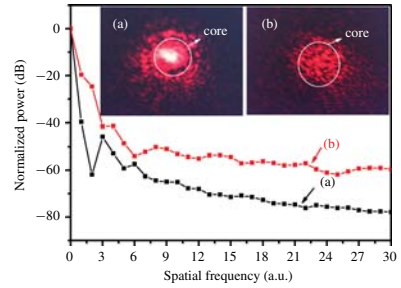

Fig. 3. FFT results for the output light intensity distributions (insets) considering two distinct plug geometries in sealed water-core PCFs. (a) Concave surface. (b) Convex surface.

III. Optical Characterization and Applications

Next, the sealed liquid-core PCFs were experimentally characterized by launching a He-Ne laser beam (633 nm) into the fiber core. One of the primary goals was to determine if the final shape of the polymer plug surface had any effect on the excited modes. The laser beam was focused and subsequently extracted by objective lenses (20× and 40×, respectively) and the output power distribution was imaged in a charge-coupled device (CCD) camera. For output power measurements, the camera was replaced by a power meter. We characterized several water-core HC-1550-02 PCFs, all samples approximately 7 cm long, and observed that the output light intensity distribution across the core is indeed a function of the plug shape, through lensing effects. Careful control of the polymer insertion process allowed the formation of a concave surface, which was found to favor lower-spatial-frequency (i.e., lower-order) modes, as can be seen in inset (a), Fig. 3.

On the other hand, for convex surfaces, produced when the polymer plug protrudes from the fiber end, higher-spatial-frequency (higher-order) modes were observed, as it can be seen in inset (b), Fig. 3. This conclusion is supported by an FFT (Fast Fourier transform) analysis of the central pixel line across the output power images (Fig. 3).

We observed that convex plugs, favoring the excitation of higher-order modes, resulted in lower losses. In this case, ∼15% of the launched power reached the output end, corresponding to an insertion loss of about 8.2 dB. By using concave plugs, optical transmission was about one order magnitude smaller. Concave plugs are, nonetheless, recommended for applications such as supercontinuum generation (to be discussed next), which require primary excitation of the fundamental mode.

In both cases, concave and convex plugs, optical losses are mainly due to the lack of flatness at the plug surfaces, because water-absorption losses are negligible in such short fiber samples at the red wavelength. In any case, comparable values, at the same order of magnitude, were achieved for the coupling and transmission losses in nonsealed PCFs during the first minutes after filling, indicating that our technique is indeed useful.

Further characterization, at the 980 nm wavelength (the same used in the supercontinuum experiments to follow) showed much reduced coupling losses, with 17% coupling efficiency estimated for a water-core PCF using concave polymer

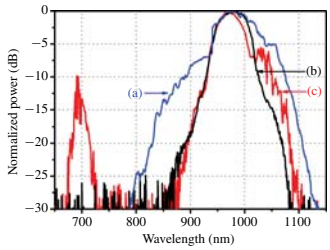

Fig. 4. Output spectra in sealed, (a) and (b), and unsealed, (c), water-core PCFs. Average powers before the PCF were 3 mW, (a), and 500 μW, (b) and (c).

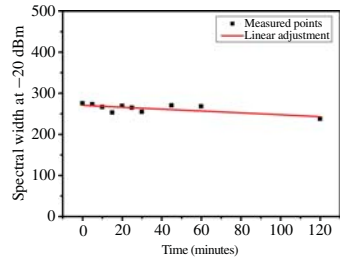

Fig. 5. Time evolution of the supercontinuum spectral width.

plugs. The measurement was carried out by recording input and output optical powers and accounting for the water attenuation loss at the operating wavelength. The improvement, which is also observed in unsealed PCFs, can tentatively be attributed to the increased core-cladding refractive index contrast at 980 nm, which results in a larger numerical aperture.

As a proof-of-principle demonstration for our technique, we carried out an experiment to assess the long-term stability of a supercontinuum source based on a sealed water-core PCF. The experimental setup was already described in [6]. The pump is an optical parametric amplifier (OPA) with a repetition rate of 1 kHz, tuned at 982 nm to produce pulses of ~60 fs with a spectral width (taken 20-dB below the peak value) of 76 nm. The pump was then launched into a 7-cm long water-core PCF (HC-1550-02). Fig. 4(a) shows the widest spectrum obtained, ~280 nm at −20 dB, using an average pump power of 3 mW. It is worth mentioning that, without our sealing process, this pump power cannot be used because it would cause immediate water evaporation. The average power leaving the fiber is 15 μW, from which a coupled average power of ~530 μW can be estimated (taking into account water attenuation only).

Fig. 4 also displays a comparison between two water-core PCFs, both 7 cm long, one sealed [Fig. 4(b)] and the other unsealed [Fig. 4(c)]. In both cases, the average power before coupling into the fiber was 500 μW (~70 μW into the PCFs, considering water attenuation), with output powers of 2.7 μW and 3.0 μW being obtained for the sealed and unsealed cases, respectively. It is noted that the similar losses observed are a direct consequence of evaporation in the unsealed PCF, which had its coupling loss increased by the time the experiment could be undertaken. The obtained spectral widths were essentially the same for the sealed and unsealed fibers (180 nm and 190 nm, respectively). A peak centered about 700 nm is, however, observed in the unsealed PCF and can tentatively be attributed to differences in the modal excitation obtained in the two fibers, due to their distinct input facets.

Nevertheless, we stress that the main advantage of the use of a sealed-core fiber is the much longer time stability of the obtained spectrum. In our previous work [6] stability was maintained only for about ten minutes (limited by water evaporation and provided the average power before the PCF was kept below 1 mW). Here, we monitored the spectral width for two hours and the result can be seen in Fig. 5. A maximum width variation of 23 nm (~8%) was observed during the first hour. After this, mechanical instabilities in the experimental setup affected the coupling into the fiber and reduced the spectral width and output power to 245 nm and 10 μW, respectively. Nevertheless, it is clear that a stable spectral broadening is still observed.

IV. Conclusion

In this letter we describe a simple and effective technique to prevent evaporation in liquid-core photonic crystal fibers (PCFs). Processed fibers remained liquid-filled for at least six weeks. As a proof of concept, we conducted a supercontinuum generation experiment in a sealed water-core PCF, to demonstrate a 120-minutes spectral width stability. Similar experiments, carried out with nonsealed fibers, produced supercontinuum spectra lasting no longer than 10 minutes. The sealed fiber also allowed for higher input powers to be employed.

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