Liquid-core, liquid-cladding photonic crystal fibers

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Abstract: We experimentally demonstrate a simple and novel technique to simultaneously insert a liquid into the core of a hollow-core photonic crystal fiber (PCF) and a different liquid into its cladding. The result is a liquid-core, liquid-cladding waveguide in which the two liquids can be selected to yield specific guidance characteristics. As an example, we tuned the core-cladding index difference by proper choice of the inserted liquids to obtain control over the number of guided modes. Single-mode guidance was achieved for a particular choice of liquids. We also experimentally and theoretically investigated the nature of light confinement and observed the transition from photonic bandgap to total internal reflection guidance both with the core-cladding index contrast and with the PCF length.

OCIS codes: (060.4005) Microstructured fibers; (060.2270) Fiber characterization; (060.2400) Fiber properties

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1. Introduction

Liquid-filled photonic crystal fibers (PCFs) have received intense attention in recent years due to the wide range of potential applications they offer in a variety of fields. These applications can be separated into two main groups: those in which light-liquid interaction is exploited to study and/or characterize a liquid sample and those which use the light-sample interaction to manipulate the guiding properties of the PCF and to generate photonic devices. The first group is mostly composed of applications related to the very active field of chemical and biological sensing of liquids using infiltrated PCFs [1-6]. This is a very promising field since the microstructure allows for efficient light-sample interaction and requires nanoliter sample volumes. In one demonstration of PCF-based biological sensing, labeled antibodies were selectively detected [6]. The study of the nonlinear optical properties of liquids also fits this category, and stimulated Raman scattering was demonstrated in ethanol-core PCF [7].

A large number of reports has also described work that fall in the second application group. The change in cladding refractive index associated with the insertion of liquid material into the microstructure of a solid-core PCF, for instance, was shown to enable the creation of flexible photonic devices such as spectrally tunable gratings [8,9] and waveguides based on the photonic bandgap effect [10-12]. The introduction of liquid crystals both in solid- and hollow-core PCFs led to numerous demonstrations of thermally and electrically tunable fibers...
that are likely to find application as switches. More recently, the insertion of dye solutions into the core of PCFs and the use of an appropriate optical pump was shown to generate both conventional [15] and random laser [16] action. The efficient generation of supercontinuum spectra in PCFs whose cores were filled with liquids that simultaneously present high optical nonlinearity and low dispersion at the pump wavelength was also recently theoretically investigated [17]. In addition, it is possible to exploit the material dispersion of liquids to alter the overall dispersion of solid-core PCFs. Heavy water, for example, was used to change the dispersion of a fiber taper and to increase the bandwidth of the supercontinuum radiation generated in it [18].

A significant part of the applications mentioned above requires that the liquids be selectively inserted into specific PCF holes. A number of selective filling methods has been described for hollow-core PCFs that allows one to insert a single type of liquid either solely into its core or solely into its cladding microstructure [19-22]. However, to the best of our knowledge selectively filling the core of a PCF with one liquid and the microstructured cladding with a different liquid has not yet been demonstrated. All-liquid waveguides, in which two liquid components with different refractive indices flow along a single micro-channel and form core and cladding structures, have been demonstrated to allow for the design of totally reconfigurable guiding structures [23,24]. In a PCF, although the cross-sectional geometry is fixed, it is clear that the use of two liquids would lead to a more flexible control over the fiber’s guiding properties, leading to even more sophisticated photonic devices. Dispersion and number of guided modes are only two examples of parameters that can be finely tuned in doubly filled PCFs. In order to achieve double fiber filling, a specific selective filling method has to be developed.

Here, we propose and demonstrate an experimental method for simultaneously and selectively filling the core of a hollow-core PCF with one liquid and the cladding microstructure with a second liquid. As an example of the added design flexibility provided by the double fiber filling, we show control over the number of guided modes as well as single mode operation in a liquid-core, liquid-cladding PCF. We also experimentally and theoretically study the co-existence of bandgap- and index-guiding modes in such PCFs.

2. The doubly selective filling method

The method to selectively fill the core and cladding of a PCF with two different liquids is schematically explained in Fig. 1 and relies on the fact that air is significantly more compressible than liquids. In one extremity of a hollow-core PCF the cladding microstructure is closed through the application of an electric arc with a conventional fiber fusion splicer [20]. Air pressure is then reduced in this extremity while the opposite fiber end is dipped into a polymer melt. The polymer is selectively sucked into the core and then UV cured so as to form a solid plug [19]. As a consequence, different types of holes are blocked in opposite fiber ends. The liquid selected to fill the core is then pressurized into the PCF from the side where the cladding holes are blocked, while the liquid chosen to fill the cladding is pressurized from the opposite side. The air trapped inside the fiber holes is then compressed and the liquids move into the fiber until the internal air pressure balances the external applied pressure. With syringes, it is trivial to manually apply a pressure that is, for example, five times the atmospheric pressure. This means that the trapped air will compress to occupy 20% of the total fiber length, with the remaining 80% section being filled with the liquid. As different liquids are inserted from different sides, it is seen that they will overlap in the central part of the PCF, generating a doubly-filled fiber section, in this case, with 60% of the total fiber length. Finally, this central section is cut generating a liquid-cladding, liquid-core PCF. Note that the doubly-filled length is proportional to the total fiber length and that the only restriction to the longest achievable doubly-filled PCF extension is given by the viscous resistance of the fluids within the holes. Also, larger fractions of the fiber can be doubly filled with the application of higher pressures.

In the proof-of-principle experiments, the silica hollow-core PCF depicted in the inset of Fig. 1 was employed. It has a core diameter of 10.7 μm, and average cladding pitch and hole
diameter of 2.2 \( \mu \text{m} \) and 1.9 \( \mu \text{m} \), respectively. For optical experiments \(~5\)-cm lengths of doubly-filled samples were utilized.

3. Controlling the number of modes in liquid-core, liquid-cladding PCFs

To show one example of the increased flexibility generated by the double filling of a hollow-core PCF, control over the number of index-guided modes is demonstrated by the appropriate choice of core and cladding liquids. In particular, the achievement of single- and few-mode guidance is shown. A complete analysis of the single-mode fiber, as well as the demonstration of its applicability for interferometric liquid sensing was reported elsewhere [5].

To obtain the desired number of modes, the refractive indices of both liquids are selected so that the core-cladding index contrast yields the appropriate normalized frequency (\( V \) parameter). To obtain single-mode guidance this frequency should be tuned (by raising the cladding refractive index) to a value that is below the cutoff of the second mode. Note that this approach for obtaining single-mode guidance in a liquid-core PCF is alternative to that demonstrated by Fini [2] in which the fiber microstructure is specifically designed to result in a single-mode liquid core. The advantage of the method demonstrated here is that it obtains mode number control via a post-fabrication fiber processing. In our experiments, distilled water (refractive index of 1.332 at 633 nm) was used to fill the cladding microstructure while a water-glycerin mixture was inserted into the core. To obtain a variable number of guided modes, the glycerin volume fraction in the mixture was varied from 10\% to 60\%, which tuned the mixture refractive index from \(~1.347\) to \(~1.417\) at 633 nm. To analyze the modal properties of the doubly-filled PCF, the beam of a He-Ne laser was launched into it and a near-field image of the output light was obtained in a CCD camera.

![Near field images of guided light exiting a PCF with a water-filled cladding and a liquid core with refractive indices of 1.353 (a), 1.390 (b), and 1.417 (c).](image)

Figure 2(a) shows the near-field image obtained at the PCF output with a core index of 1.353 (15\% glycerin mixture). The clear profile of a fundamental fiber mode is observed. No other modes could be excited with this core mixture, indicating the PCF is a single-mode waveguide. The same profile could be observed with a 1.360 (20\% glycerin mixture) core index. However, in this case an \( LP_{11} \)-like mode could be observed by deliberately angling the launched laser beam with respect to the fiber axis. The \( LP_{11} \)-like mode was more easily observed with a 1.390 core index (40\% glycerin mixture), the near-field image of which is...
seen in Fig. 2(b). Further core index increases led to complicated intensity distribution, indicating several modes were guided. Figure 2(c) shows one of such profiles obtained with a core index of 1.417 (60% glycerin mixture). On the other hand, when the core index was dropped to 1.347, no guided modes were observed, indicating that the cladding index was higher than the core index.

All the results above were obtained with fiber lengths of ~5 cm. A number of additional modes, identified as photonic-bandgap modes, could be observed when fiber lengths below ~4 cm were used. In what follows, an experimental and theoretical study is described of the two guiding mechanisms in liquid-core, liquid-cladding PCFs.

4. Index- and bandgap-guiding modes in the doubly-filled PCFs

To test whether the more complex modal structures observed for fiber samples shorter than 4 cm arose due to lossy bandgap guidance, both the core and cladding of the PCF was filled with water. In this configuration, total-internal reflection is inhibited, and bandgap guidance becomes the only possible mechanism for light confinement. Note that any observed bandgap in this experiment is also expected to exist if the core refractive index is changed but the cladding remains filled with water (experiments described in section 3). The transmission spectrum of a 2.3-cm-long sample was obtained with the use of a supercontinuum source and is shown in Fig. 3(a). As can be seen, transmission peaks appear at a number of wavelengths, indicating a complex cladding bandgap structure. Figures 3(b) and 3(c) show near-field images of light at 633 nm exiting 22-mm- and 53-mm-long samples, respectively. It is noted that while for shorter lengths light is guided within the core, for longer lengths light at the core virtually vanishes but remains guided via surface modes (ring structure in Fig. 3(c)). Figure 3, thus, shows that a lossy bandgap exists at 633 nm, which then gives rise to additional modes that, in the experiments of section 3, co-exist with the index-guiding modes. These extra modes were not observed in those experiments due to the longer lengths used.

![Normalized transmission spectrum obtained in a 23-mm water-core, water-cladding PCF exhibiting bandgap structures; (b) and (c) near-field images of the light exiting a 22 mm (b) and a 53 mm (c) sample of the water-core, water-cladding PCF.](image)

To further characterize guidance in liquid-core, liquid-cladding PCFs, numerical simulations were undertaken based on the finite difference method. The wavelength was 633 nm and a waveguide model was developed that is based on a commercially available hollow-core PCF (Crystal Fibre’s HC-1550-02). The model consisted of a microstructured cladding with pitch and hole diameter of 3.80 μm and 3.78 μm, respectively, which surrounded a 9.5-μm diameter core. A simulation of an infinite water-filled cladding structure (index of 1.332 at 633 nm) was also undertaken, leading to an expected cladding effective refractive index of ~1.375 (corresponding to the fundamental space-filling mode of this structure).

In one set of simulations the cladding microstructure was filled with water and the core index was varied between 1.33 and 1.38. Several modes were observed with all of the tested...
core indices indicating that photonic bandgaps existed in the cladding (modes were also observed for a core index of 1.00). Nevertheless, an abrupt change in the light intensity distribution occurred as the core refractive index was increased, as depicted in Fig. 4. Figure 4(a) shows this intensity distribution (in log scale) for a core index of 1.373. It is seen that even points that are 4 pitches away from the core still present intensities that are more than 1% the peak intensity. The same behavior was observed for lower core indices. In contrast, slight core index changes to 1.375 and beyond, leads to a much tighter intensity confinement to the core. For a core index of 1.375 the intensity falls to ~100dB below the peak intensity in points that are 4 pitches away from the cladding. Such an abrupt change in light confinement matches the point at which the core index exceeds the cladding index and, thus, total internal reflection becomes an additional guiding mechanism. Due to the much lower losses observed with this mechanism, the cladding photonic bandgap is expected to negligibly contribute to the mode formation. A smooth transition between the two guiding methods is, thus, observed.

Figure 4 shows how, for the simulated PCF, the guiding mechanism of the fundamental mode can be determined through investigation of the intensity distribution. The same investigation is applicable to other modes. Indeed, with a 1.375 core index the LP_{11}-like mode was found to present intensity distributions that are considerably more spread (intensities ~40 dB below peak value 4 pitches away from the core) than that of the fundamental mode (Fig. 4(b)). This suggests that only the fundamental mode is index guided. The higher losses associated with the higher-order modes (~3 dB/cm for the LP_{11}-like mode) mean that this PCF is expected to effectively present single-mode guidance even for relatively short samples. This is the same trend observed in the experiments described in section 3. It is worth noting that, in practice, bandgap modes can be avoided in the spectral region of interest [5].

5. Conclusion

We have demonstrated an experimental method for filling a hollow-core PCF with double selectivity, resulting in a liquid-core, liquid-cladding fiber in which core and cladding liquids can be individually selected. This development leads to further flexibility in the design and construction of infiltrated PCF, and control over the number of guided modes has been shown. In addition the coexistence of bandgap- and index-guiding modes has been experimentally and numerically investigated.

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