Direct writing of fiber optic components in photonic crystal fibers and other specialty fibers

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ABSTRACT

Femtosecond direct laser writing has recently shown great potential for the fabrication of complex integrated devices in the cladding of optical fibers. Such devices have the advantage of requiring no bulk optical components and no breaks in the fiber path, thus reducing the need for complicated alignment, eliminating contamination, and increasing stability. This technology has already found applications using combinations of Bragg gratings, interferometers, and couplers for the fabrication of optical filters, sensors, and power monitors. The femtosecond laser writing method produces a local modification of refractive index through non-linear absorption of the ultrafast laser pulses inside the dielectric material of both the core and cladding of the fiber. However, fiber geometries that incorporate air or hollow structures, such as photonic crystal fibers (PCFs), still present a challenge since the index modification regions created by the writing process cannot be generated in the hollow regions of the fiber. In this work, the femtosecond laser method is used together with a pre-modification method that consists of partially collapsing the hollow holes using an electrical arc discharge. The partial collapse of the photonic band gap structure provides a path for femtosecond laser written waveguides to couple light from the core to the edge of the fiber for in-line power monitoring. This novel approach is expected to have applications in other specialty fibers such as suspended core fibers and can open the way for the integration of complex devices and facilitate miniaturization of optical circuits to take advantage of the particular characteristics of the PCFs.

Keywords: Femtosecond laser writing, Integrated waveguides, In-fiber waveguides, Photonic crystal fiber, Optical taps, Power monitors.

1. INTRODUCTION

Femtoscond laser direct writing of waveguides in transparent materials[1] have been the subject of much research and innovation over the years. The ability to micromachine and write three-dimensional integrated optical devices[2–7] has been a key characteristic that facilitated the demonstration of low loss waveguides[8] or point-by-point Bragg gratings,[9–11] and devices such as integrated lasers,[12–15] couplers,[16] data storage elements,[17] interferometers,[18] wave retarders,[19] polarization beam splitters,[20] or integrated quantum photonics devices.[21–23]

In optical fibers, femtosecond laser writing has proven to be an excellent means to prototype devices. Research has shown that this method is effective at both: altering or modulating the refractive index of the fiber core such as in the case of fiber Bragg gratings;[24–27] or producing optical circuits in the cladding of the fibers such as directional and cross couplers,[28,29] birefringent elements and optical retarders,[30,31] microfluidic elements for sensors,[32] or interferometers for sensing applications.[33]

The use of femtosecond laser writing techniques became commercially viable with the increased availability of stable and affordable femtosecond laser sources and the development of reliable and repeatable fabrication methods.[34–39] This paper presents the technical basis for a commercially successful product that takes advantage of the precision and miniaturization possibilities created by femtosecond writing technology, to manufacture an in-fiber device that relies on waveguides written through the fiber core and cladding to form a compact cross coupler that is used as an optical tap for power monitoring applications.

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2. FEMTOSECOND LASER DIRECT WRITING

The in-fiber devices presented in this paper were fabricated with a Coherent RegA femtosecond laser, operating at a repetition rate of 250 KHz, 75 fs of pulse duration at 800 nm wavelength and focused with a 0.1 NA lens. A three-dimensional translation stage controlled the position of the fiber relative to the focal plane of the lens as seen in Fig 1, producing waveguides by focusing approximately 4 µJ of energy per pulse and translating the fiber at a speed of 250 µm/s.

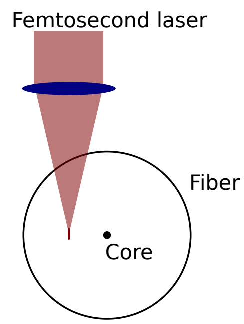

Figure 1. Schematic of the femtosecond laser writing principle with the laser focused inside an optical fiber. This illustration ignores other focusing, distortion, and aberration effects created by the cylindrical shape of the fiber itself.

With these fabrications conditions, regions of modified index of refraction, that is higher than the index of the cladding, can be defined inside the glass fiber and form waveguides that have the potential to interact with the light propagating in the fiber core. This method is independent of the type of fiber under test and, in principle, can be applied to produce integrated devices in multiple types of fibers including standard single mode (SM) fibers or polarization maintaining (PM) fibers with various core sizes and materials.

The index profile inside the fibers was measured non-destructively with an IFA-100 interferometric system[40,41] and the waveguides formed by the modified index region were used to produce couplers that were characterized by attaching a photodetector to the edge of the optical fiber cladding.

2.1 Optical Taps in Single Mode Fibers

In single mode fibers, there has always been a need for reliable power splitters for monitoring transmission. Traditionally, this monitoring can be achieved using fused couplers with which light is split and collected into a power monitor in one of the output arms of the coupler, subsequently producing a measurement that is proportional to the optical power in the other arm. This approach is simple and cost effective, however, the final devices can be large (with a length on the order of tens of millimeters) and applications are limited since this method is not easily applicable to fibers with core sizes smaller than 4 µm or specialty fibers that employ multiple layers of materials in their composition.

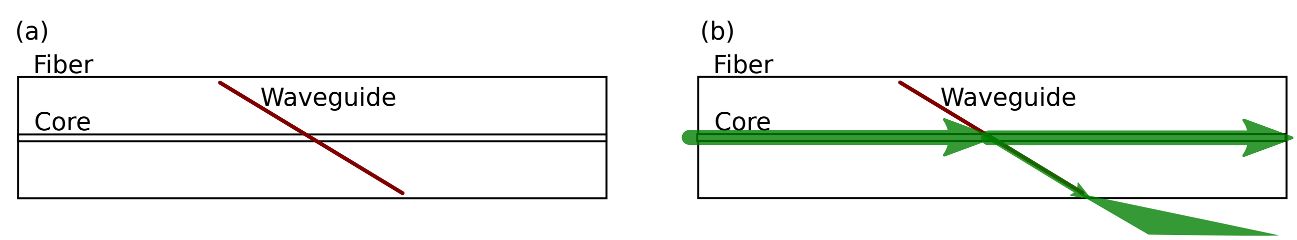

Figure 2. (a) Side view of a fiber with a femtosecond laser written waveguide crossing the core at an arbitrary angle; (b) Illustration of light propagating in the fiber from the left and a small portion being coupled into the cladding waveguide and exiting at the edge of the fiber. Similarly to Fig. 1 this illustration also ignores other focusing, distortion, and aberration effects created by the cylindrical shape of the fiber itself.

With the femtosecond laser writing method, a cross coupler can be directly written inside a fiber and produce sufficient coupling in order to monitor the optical power propagating in the fiber core. Figure 2 illustrates such a device with a waveguide seen from the top (a plane perpendicular to the writing laser propagation direction) crossing the fiber through the cladding and the core at a shallow angle. The induced loss in the fiber core and corresponding coupling ratio can be precisely controlled within ±0.005 dB by using accurate positioning of the fiber relative to the laser focus (±1 µm) and accurate control of the cross coupling angle (±0.002 rad).

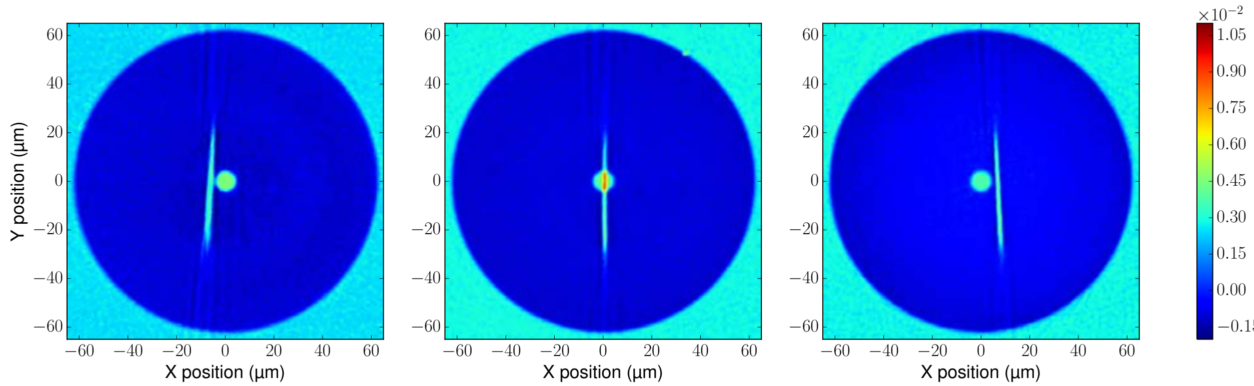

Figure 3. Tomographic images of a single mode fiber, taken at three distinct locations along the fiber axis, with a femtosecond written waveguide crossing the core.

Figure 3 shows the index profile of a single mode fiber with such a waveguide inscribed. The magnitude of the index variation of the region exposed by the femtosecond laser is $\approx 4 \times 10^{-3}$ and comparable to the index of the core, however, using the parameters described at the beginning of Sec. 2, most importantly the focusing power of the objective lens, the waveguides generated have a significantly different shape than the fiber core, forming an ellipse with a length of ≈ 40 µm on the vertical direction and ≈ 4 µm on the horizontal direction. The cylindrical shape of the fiber also creates distortions to a perfect, straight waveguide crossing the core. The focal plane is closer to the top of the fiber towards the edges and the major axis of the ellipsoidal waveguide forms an angle with the center propagation vector that is also higher towards the edges of the fiber and vertical at the center. Despite the distortions and waveguide ellipsoidal shape, this configuration produces single mode propagation and loosely confined light can be efficiently collected at the edge of the cladding (Fig. 2(b)) with low excess loss that is demonstrated by efficiencies of >80% of light coupled out of the core being effectively collected at the edge.

2.2 Optical Taps in Polarization Maintaining Fibers

Other useful target fibers for the femtosecond laser writing method are polarization maintaining fibers. In this case, in addition to the efficiency or low excess loss and controlled coupling between the core and cladding shown for standard single mode fibers, it is also critical that the the polarization maintaining characteristics of the fiber remain unaffected by the writing procedure.

Figure 4 shows examples of two index profiles obtained from two different types of polarization maintaining fibers. The fiber on the left is a germanium doped core fiber with Panda type PM stress rods and fused silica cladding. The fiber on the right is a fused silica core, fluorine doped depressed cladding fiber, also with Panda type PM stress rods. In both cases the waveguide is shown at the position where it crosses the core and the cross coupling waveguide plane is aligned with the fast axis of the fiber (perpendicular to the plane formed by the stress rods), this alignment contributes to maintaining the extinction ratio between the fast and slow axes of the fiber, i.e. it provides low coupling between the two proper polarization axes and therefore does not disturb the original polarization characteristics of the fiber. Extinction ratio values typically above 35 dB can be obtained after the femtosecond laser inscription which shows that the modification does not significantly interfere with the normal mode propagation in the fiber.

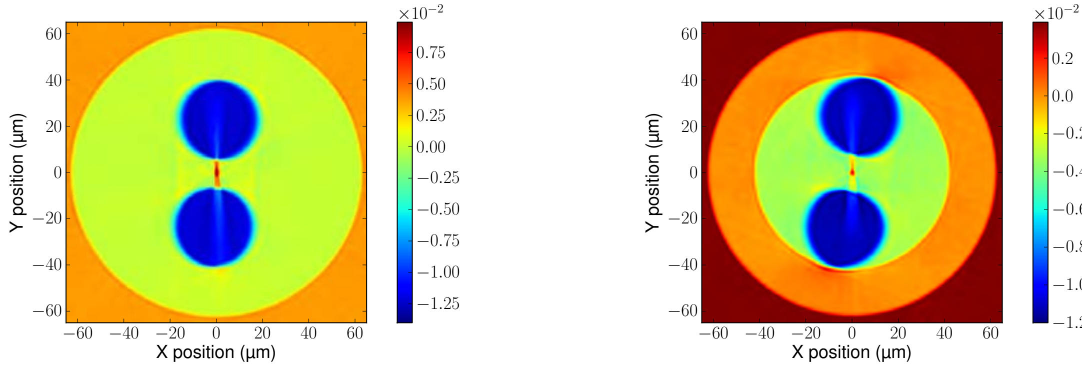

Figure 4. Tomographic images of two polarization maintaining fibers, with femtosecond written waveguides crossing the core and shown at the core location. (Left) germanium doped core, Panda type PM stress rods and fused silica cladding. (Right) fused silica core, Panda type PM stress rods and fluorine doped depressed cladding.

2.3 Optical Taps in Photonic Crystal Fibers

Initially photonic crystal fibers (PCFs) presented a concrete challenge for the femtosecond laser writing technique. The air holes responsible for creating the photonic band gap (shown in Fig. 5) were obviously unaffected by the laser writing process and therefore made it impossible to break the core confinement and couple light from the core to the cladding of the fiber. Even simply reaching the core with femtosecond laser light might be a problem[42] as the air holes distort and prevent the laser light from focusing and creating an meaningful index modification. To overcome this problem an additional step was developed by partially collapsing the photonic band gap structure, allowing coupling from the core to the cladding. For this demonstration the fiber used was a polarization maintaining, large area mode, and endless single mode photonic crystal fiber with an internal structure similar to the illustration in Fig. 5(b).

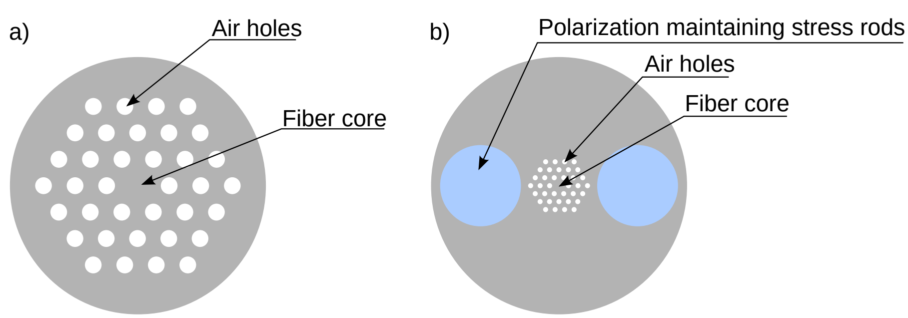

Figure 5. Example of two photonic crystal fiber configurations. (a) A simple honeycomb structure with a solid core surrounded by air holes that produce band gap confinement. (b) A solid core photonic crystal fiber with Panda style polarization maintaining rods.

In oder to be able to break the band gap of the PCF (Fig. 6(a)), and couple light from the core to the cladding, a small defect was introduced via an electrical fusion arc (Fig. 6(b)) that partially collapsed the air holes and created a small leak (Fig. 6(c)). This process introduced losses on the order of ≈0.02 dB. A waveguide was then written in the collapsed structure location (Fig. 6(d)) to guide the leaked light directionally towards the edge of the fiber where it can be collected and measured similarly to what was done for SM and PM optical taps.

This process resulted in an efficiency of ≈ 60%, smaller than the efficacy obtained for single mode fibers but nevertheless still sufficient for the purpose of monitoring the light propagating in the photonic crystal fiber. The defect and loss associated with the process was enough to provide a stable power monitoring signal (with ≈ 0.1%

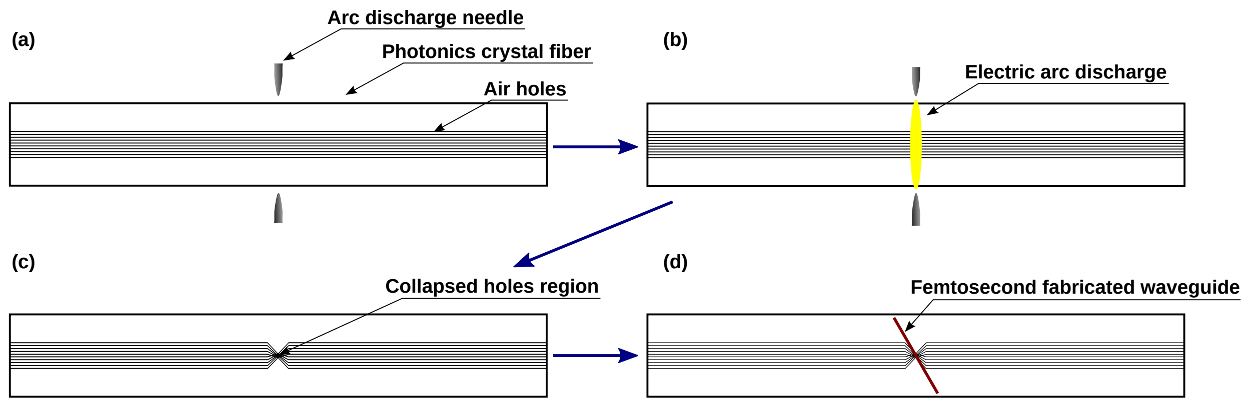

Figure 6. Diagram of the fabrication method for waveguide couplers in photonics crystal fibers. (a) Photonic crystal fiber structure before inscription. (b) Electrical arc softening delivered perpendicular to the fiber. (c) Photonics crystal fiber with the illustration of partially collapsed air holes. (d) Femtosecond inscription of a waveguide in the location where the partially collapsed air holes created a perturbation in the photonics band gap structure.

tap ratio) but small enough not to interfere with the mode propagation and with the intrinsic characteristics of the PCF. This method is expected to be applicable in other specialty fibers, such as suspended core fibers, where air holes are also a key component of the fiber structure and therefore a similar partial collapsing might be suitable in order to effectively access the core and couple light into the cladding. Moreover, photonic crystal fibers with hollow cores offer a similar challenge and may therefore present an opportunity to interact locally or distributedly with the light traveling in the core, enabling the opportunity to use the sensing potential of hollow core fibers in a completely new way. However, this has not been demonstrated yet and remains a subject for future work.

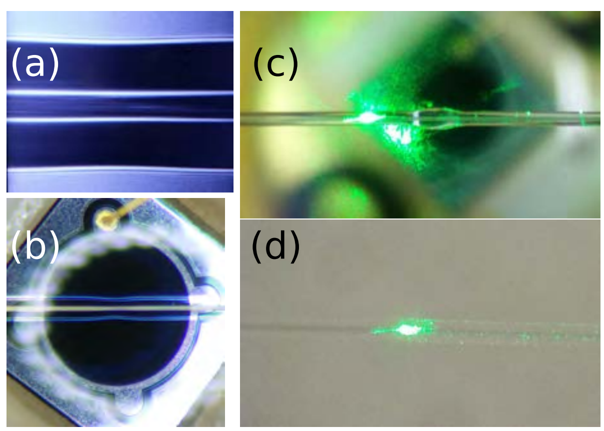

Figure 7. Microscope images of the photonics crystal fiber demonstrating the end result of the fabrication method. (a) Fiber with partially disturbed core and tapered cladding after electrical arc exposure. (b) Same fiber as in (a) with a photodetector in the background. (c) and (d) Fiber lit by green laser light, showing scattering at the waveguide location.

An image of the partially collapsed core region can be seen in Fig. 7(a) with the same fiber photographed on top of a photodetector in Fig. 7(b). The process using an electrical arc to partially fuse the glass and collapse the air holes inside the fiber also tapers the cladding diameter around the modified location and this can be seen in both Fig. 7(a) and Fig. 7(b). Based on this picture, it can be estimated that the affected region is on the order of 100 µm, similar to the 125 µm of diameter of the fiber. Figure 7(c) and Fig. 7(d) show the scattering of green light at the waveguide location. In these figures, the waveguide can also be seen highlighted by the same green scattered light and it is expected that this amount of scattering is partially responsible for the lower efficiency seen in this fiber when compared to the case of a standard single mode fiber presented in Sec. 2.1.

2.4 Higher intensity fabrication with oil immersion writing

The shape of the femtosecond written waveguides and the cylindrical aberrations introduced by focusing inside an optical fiber can both be corrected, or at least substantially mitigated, by changing the numerical aperture of the focusing objective and using a 1.25 NA oil immersion objective lens. Figure 8 shows a comparison between the low NA focusing (left) with an elliptical waveguide written ≈ 40 μm from the core, and high NA oil immersion focusing (right) where three waveguides were written around the core. Here it is clear that stronger focusing considerably reduces the elongation along the laser propagation axis, making the waveguides smaller and better suited for high density integration and for reduced component size. The high NA focusing created a larger laser intensity at the focal spot, which introduces a negative index region above the positive index volume. This effect can potentially increase confinement, reduce the mode size, and allow for a smaller curvature radius on S-bend or circular waveguides. The characteristics and advantages of oil immersion writing with femtosecond lasers is not new and has been explored by many other researchers in past. Nevertheless, it is shown here to be an viable alternative for commercial applications, improving the prospects of higher integrations density and enhanced device complexity at the expense of tighter alignment precision requirements.

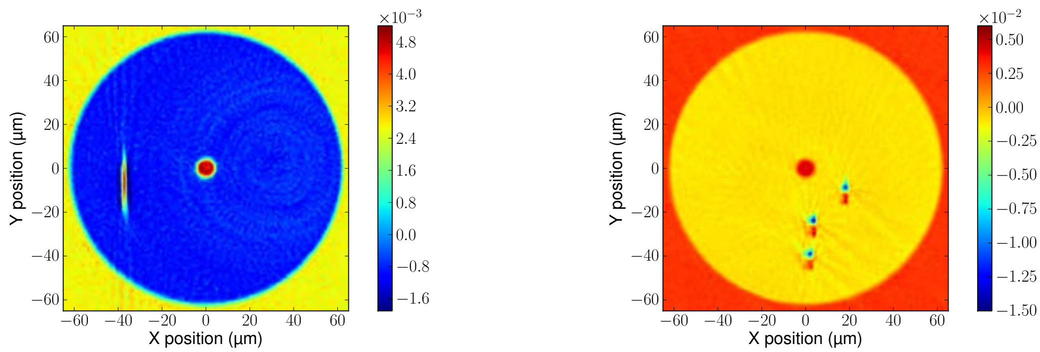

Figure 8. Comparison between waveguides generated with a 0.1 NA (left) and a 1.25 NA (right) objective lenses.

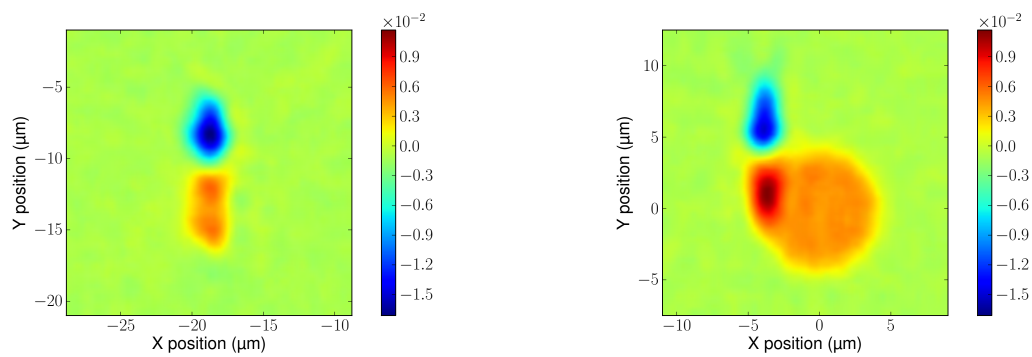

Figure 9. Detailed index profile of femtosecond written waveguides with high NA oil immersion lens on the cladding (left) and partially overlapping with the core (right).

The low NA written waveguide on Fig. 8(left) was written parallel to the core but on the same plane as the core, relative to the femtosecond laser propagation direction which was vertical on the figures shown in this paper. Defocussing and aberrations effects prevent this method from writing waveguides above or below the core, relative to the position of the focusing lens. The oil immersion method also overcomes this limitation as seen in Fig. 8(right), where waveguides can be arbitrarily positioned anywhere in the fiber volume for a true three-dimensional writing method.

A detailed refractive index profile of femtosecond written waveguides with a high NA oil immersion lens is shown in Fig. 9. With the exception of the objective lens, all the other writing parameters are similar to what was described in the beginning of Sec. 2. These conditions result in a positive index increase of $\approx 6 \times 10^{-3}$, shown in Fig. 9(left), which is similar to the step index of the germanium doped core. If the positive index modification region partially overlaps the core, then the index is further increased to $\approx 1 \times 10^{-2}$ as shown in Fig. 9(right). The negative region has a magnitude of $\approx -1.5 \times 10^{-2}$ and the waveguides are ≈ 5 µm in the laser propagation (vertical) direction and ≈ 3 µm in the horizontal direction.

3. CONCLUSION

Waveguides written with a femtosecond laser were successfully used to form a coupler inside photonic crystal fibers to produce an effective and stable optical tap for power monitoring purposes. These established techniques, detailed in Sections 2.1 and 2.2 for the fabrication of optical taps in single mode fibers and polarization maintaining fibers, were expanded with the addition of a method to controllably and locally collapse the photonic crystal structure and break the light confinement in the core in order for coupling to be possible from the core to the cladding of the fiber. This method is believed by the authors to be unique and the first time such demonstration was performed. The couplers showed more than 60% efficiency in converting the loss created by the coupler into an electric signal generated by the photodetector. These devices are expected to have a significant impact in applications that rely on the properties of photonic crystal fiber, such as supercontinuum generation. Power monitoring can now be done without the need to interrupt the fiber continuity and can even be implemented at multiple locations along a given fiber length which could enable monitoring of different stages of the supercontinuum generation process.

The addition of oil immersion, which has been explored by many other researchers in past, is shown here to be a viable way forward for the fabrication of smaller and more complex devices. The combination of all the technique variations shown in this paper and the study of its results demonstrated the flexibility inherent to the femtosecond laser writing method and suggest these mechanisms can effectively be harnessed for almost any type of optical fiber, while maintaining the original fiber integrity and adding functionality to perform complex optical processes in a small and stable package.

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