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| Item Type   | Article |
|-------------|---------|
| Authors     | Bertoncini, Andrea; Liberale, Carlo |
| Citation    | Bertoncini, A., & Liberale, C. (2020). 3D printed waveguides based on photonic crystal fiber designs for complex fiber-end photonic devices. Optica, 7(11), 1487. doi:10.1364/optica.397281 |
| Eprint version | Publisher's Version/PDF |
| DOI         | 10.1364/OPTICA.397281 |
| Publisher   | The Optical Society |
| Journal     | Optica |
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| Download date | 2023-12-12 06:49:15 |
| Link to Item | http://hdl.handle.net/10754/665966 |
3D printed waveguides based on photonic crystal fiber designs for complex fiber-end photonic devices

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Received 12 May 2020; revised 12 September 2020; accepted 15 September 2020 (Doc. ID 397281); published 27 October 2020

Optical waveguide segments based on geometrically unbound photonic crystal fiber (PCF) designs could be exploited as building blocks to realize miniaturized complex devices that implement advanced photonic operations. Here, we show how to fabricate optical waveguide segments with PCF designs by direct high-resolution 3D printing and how the combination of these segments can realize complex photonic devices. We demonstrate the unprecedented precision and flexibility of our method by fabricating the first-ever fiber polarizing beam splitter based on PCFs. The device was directly printed in one step on the end-face of a standard single-mode fiber and was 210 μm long, offering broadband operation in the optical telecommunications C-band. Our approach harnesses the potential of high-resolution 3D printing and of PCF designs paving the way for the development of novel miniaturized complex photonic systems, which will positively impact and advance optical telecommunications, sensor technology, and biomedical devices.

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https://doi.org/10.1364/OPTICA.397281

1. INTRODUCTION

Photonic crystal fibers (PCFs), also known as microstructured optical fibers or holey fibers, are single-material optical fibers in which an array of microscopic longitudinal hollow channels enables light guidance [1,2]. The design of the geometry of the longitudinal hollow channels in PCFs is a powerful handle to control and tune the fiber waveguide parameters, such as optical mode size and shape, modal dispersion, birefringence, and nonlinearity. With the development of PCFs, unprecedented fine control of the fiber waveguide parameters across a wider range has become achievable, opening up unique possibilities like supercontinuum generation [3], fiber chromatic dispersion engineering [4], and ultrahigh birefringence [5]. Furthermore, PCFs are unique in allowing the creation of hollow-core fibers [6], which have important applications such as fiber propagation with ultralow nonlinearity or novel gas and optofluidic sensors [7].

Optical waveguides based on PCF designs could be exploited on the small scale as building blocks to create on-fiber complex miniaturized devices that implement advanced photonic operations including—but not limited to—mode conversion, Y-splitting, and polarization splitting. For such devices, the accurate and geometrically unbound manufacture of the designed PCF transverse hole patterns is of paramount importance. Additionally, precise control of the longitudinal variation of the PCF geometry allows the creation of elements such as ultrashort adiabatic tapers or periodic structures, which will pave the way for the development of novel miniaturized photonic devices. However, current PCF fabrication methods have important limitations in manufacturing PCF segments with the needed characteristics and for their union to create complex miniaturized photonic systems. PCFs are primarily fabricated by drawing a cylindrical “preform” of cm-scale diameter [8]. The preform has a cross-sectional geometry that corresponds to a scaled-up version of the desired final sub-mm-scale geometry of the fiber. Current methods to create the preform, however, grant only limited freedom in the design of the preform [9]. Additionally, during the drawing process, the preform geometry is generally not preserved due to material viscosity, gravity, and surface tension effects [10]. Therefore, obtaining the desired PCF cross-sectional structure is not a straightforward process, and can be especially difficult. Specific hole geometries are even impossible to realize [11]. The 3D printing of cm-scale PCF preforms has been recently proposed as a means to increase freedom of design, but the perturbing effects of drawing still present a major limiting factor that prevents the accurate realization of arbitrary PCF designs [9,12–14]. Lastly, μm-scale control of the length of PCF segments and of their longitudinal tapering, which is needed to create miniaturized photonic systems, is very difficult with standard preform-based methods.

Here, we show the use of high-resolution 3D printing [15–17] for the in situ single-step fabrication of stacked ultrashort
PCF-like segments with different geometries to create all-fiber integrated devices that perform complex optical operations in sub-mm lengths. Our approach entirely avoids the drawing process that introduces so many limitations and drawbacks, and grants unprecedented design flexibility and precision in the control of the transverse and longitudinal PCF geometry. We begin by demonstrating that our proposed approach can precisely replicate the hole array geometry for virtually any class of manufactured PCF designs described in the literature. We then establish the manifold advantages of our approach for the miniaturization of complex optical devices by fabricating a 210-µm-long broadband, all-fiber, and integrated polarization beam splitter (PBS), which is the first PCF PBS ever realized and described in the literature.

2. RESULTS

A. 3D Printing of Different Classes of Photonic Crystal Fiber Designs

In this section, we present scanning electron microscope (SEM) images and the optical guidance of 3D printed PCF-like segments with various solid or hollow-core geometries to demonstrate the accuracy and flexibility of the proposed method (see Appendix A for fabrication details). For demonstration, we replicated an assortment of known PCF designs based on radically different guiding mechanisms, core shapes, and sizes. Figure 1(a) shows a 3D printed segment with the typical design of a highly nonlinear (HNL) PCF [18], with a core diameter of 2 µm, an air-filling fraction—defined as the ratio of the air hole diameter d to the lattice spacing \( \Lambda \)—equal to 0.75, and a mode field diameter (MFD) of 1.8 µm. This type of PCF is typically characterized by a small core (few µm in diameter), with hexagonal holes and a high air-filling fraction. The guiding mechanism in HNL PCFs is based on modified total internal reflection (MTIR) [1]—analogous to that of a standard single-mode fiber—whereby the pattern of holes surrounding the central core acts as an effective cladding with a reduced refractive index [19]. We directly printed the HNL PCF segment on the end-face of a single-mode fiber with a 6 µm MFD. The large modal mismatch between the optical fiber and the 3D printed segment was easily compensated for by including a 70-µm-long PCF-like adiabatic taper in the 3D printed structure, similar to that described in [20], which resulted in a 1.7 dB insertion loss (see Supplement 1, Section S1). Figure 1(b) shows a 3D printed helically twisted core-less PCF segment with the same geometrical pattern proposed by [21]. Here, the twist of the fiber around its axis induces guidance next to the central hole, which is not twisted. Increasing the twist rate makes the guided mode more confined and less sensitive to perturbations. Thanks to the high resolution granted by our 3D printing method, we could easily achieve a very high twist rate of \( 10^9 \text{pi} \text{[rad/mm]} \) (corresponding to a twist period of 200 µm), which is higher than any twist rate previously reported in the literature. As expected for this type of PCF design, we obtained a well-defined hollow mode confined to the first ring around the central non-twisted hole, with an MFD of 6.57 µm. Next, we fabricated hollow-core PCF-like structures based on two different guiding mechanisms: photonic bandgap (PBG) hollow-core fibers and hollow-core anti-resonant fibers (HC-ARFs) [22]. In PBG hollow-core fibers, optical confinement is provided by the PBG mechanism, in which the periodic array of holes in the cladding acts as a photonic crystal that prohibits the propagation of light, which is then trapped in the hollow core. We fabricated a PBG PCF-like segment with a geometry that replicated a commercially available fiber (HC-1060-02, NTK Photonics), and the final structure showed the expected light guidance in the central hole satisfactorily [Fig. 1(c)], with an MFD of 8.2 µm. In HC-ARFs, the light is confined through a combination of inhibited coupling between the core and cladding modes and anti-resonant reflection at the air–fiber–material interfaces. The hollow-core region is defined by anti-resonant elements with negative curvature. We 3D printed a HC-ARF geometry that replicated a more recent design [13], where the anti-resonant elements are semi-elliptical. Semi-elliptical elements are typically problematic to manufacture using traditional preform drawing-based methods [13,23]. However, here we show that semi-elliptical structures can be easily and accurately reproduced by 3D printing. Figure 1(d) shows an accurate reproduction of the structure and the expected guidance in the central hollow core, with an MFD of 12.1 µm. Note that hollow-core PBG and HC-ARF fibers rely on guiding mechanisms that are very...
sensitive to the geometric precision of the structures. The optical guidance that we achieved here intrinsically demonstrates that our 3D printed PCF structures are geometrically accurate. Finally, Fig. 1(c) shows a fractal ring-core PCF-like segment [11], which supports a well-defined annular mode through an MTIR guidance mechanism. These types of structures are attracting increasing interest because they have been recently shown to support modes that carry orbital angular momentum [11].

Traditional PCFs manufactured by drawing require a final fiber cleavage step, which can eventually distort the final fiber surface or create non-flat output surfaces. Remarkably, 3D printing of PCF-like waveguides is not affected by this issue because the 3D printing process allows direct production of flat perpendicular or angled output surfaces.

We measured the propagation losses of the 3D printed PCF-like waveguides by fabricating segments of different lengths, up to 350 µm. For a solid-core PCF design with a core size of 12 µm and \( d/\Lambda = 0.4 \), we found an attenuation of 0.44 dB/mm at 1070 nm and of 0.79 dB/mm at 1550 nm. For comparison, a pure silica fiber with the same PCF geometry (ESM 12B, Thorlabs) has an attenuation of about 8 dB/km. The propagation losses of the 3D printed PCF segment closely match the extinction coefficient for the bulk polymerized photoresists that are 0.43 dB/mm at 1070 nm and 0.78 dB/mm at 1550 nm [24], which is then the dominant loss contribution (see also Section 3 and Supplement 1, Section S2). For the 3D printed waveguide with a PBG hollow-core PCF design presented in Fig. 1(c), we found an attenuation of 0.3 dB/mm at 1070 nm. This attenuation, while being lower than the intrinsic photopolymerized material losses, is not as low as expected for propagation in a hollow core. This could be explained with the fact that a dominant factor in hollow-core PCF losses is the surface roughness of the core wall. While pure silica hollow-core PCFs have typically a sub-nanometer root mean square (RMS) roughness value, in our case the 3D printing layer-by-layer fabrication introduced a larger RMS roughness of about 30 nm (estimated from SEM images). This roughness value is consistent to what was measured by other groups using the same 3D printing technology and material [25].

B. Design and Fabrication of an All-Fiber Integrated PCF Polarization Beam Splitter

With proper design, PCFs can have high birefringence, and this has been used in the past to create fiber polarizers based on single-core highly birefringent PCFs [26]. Here, we present an on-fiber ultrashort PBS based on a dual-core PCF design to demonstrate the multiple strengths of our 3D printing approach. Several sub-mm dual-core PCF PBS designs have been proposed over recent years [27–30]; however, the limitations of current PCF fabrication methods have prevented their successful manufacture. Indeed, the dual-core geometries that have been proposed in the literature to date have all been generally asymmetric, with the inclusion of holes of different sizes and shapes, all factors that add significant complexity to the design of the preform. Moreover, these PCF PBS designs have a sub-mm length that requires precise control to a sub-µm level to create the desired output polarization split. These combined factors make it difficult to handle and cut segments to the required length from a long fiber that has been drawn. Furthermore, on-fiber integration of the PCF PBS requires rigid coupling to a standard fiber, e.g., by fusion splicing. This coupling also requires a small but critical lateral offset of a few micrometers in order to directly couple just one of the two cores of the dual-core structure. This integration step is also significantly challenging with PCFs manufactured by fiber drawing.

Figure 2(b) shows the design for a dual-core PCF PBS theoretically proposed by Jiang et al. [27], which we have chosen to implement here, with necessary modifications, as a demonstration. This design has many exceptional merits, such as featuring a very large bandwidth that includes the telecommunication C-band and an ultrashort length. Note that the ultrashort length is achieved thanks to the ultrahigh birefringence enabled by the PCF design. The dual-core PCF segment acts as a directional coupler (DC), and is characterized by a coupling length (CL) for each polarization, defined as the waveguide length for which there is a complete transfer of power from one core to the other. In particular, the CLs are given by

\[
CL_i = \frac{\lambda}{2 \ast (n_1^i - n_2^i)},
\]

where \( \lambda \) is the wavelength, \( n_1^i \) and \( n_2^i \) are the effective indices for the even and odd mode of the dual-core waveguide, respectively, and \( i = x, y \) is either of the two orthogonal polarizations. Because of the birefringence introduced by this PCF design, the two CLs are different, which allows the structure to act as a PBS for a proper tuning of its design parameters and at specific lengths [27]. The length of the dual-core DC PCF structure must be simultaneously an odd integer multiple of the CL for one polarization and an even integer multiple of the CL for the other polarization [27]. The shortest possible polarization splitting dual-core DC is obtained when the length of the structure is equal to the CL for one polarization and twice the CL for the other polarization, thus giving a CL ratio (CLR) of 2.

Efficient integration of the dual-core DC PCF structure on a standard single-mode optical fiber requires the addition of other elements. By leveraging one of the strengths of the 3D printing approach, we have embedded the dual-core DC PCF structure in a more complex photonic structure composed of three sequential waveguiding segments (Fig. 2): a PCF-like tapered coupler (down-taper), the dual-core DC birefringent PCF structure, and a final fan-out section that increases the spatial separation of the two cores. The down-taper [input cross section in Fig. 2(a); simulations in Supplement 1, Section S3] allows for efficient and alignment-free coupling of a 6 µm MFD single-mode fiber (1060XP, Thorlabs) to one of the two cores of the birefringent dual-core DC PCF segment [Fig. 2(b)]. The two cores of the latter are non-circular, relatively small (1 µm along the minor axis), and positioned close to each other (2.4 µm apart) to maximize the core inter-coupling and obtain the shortest possible CLs. The final segment is a fan-out structure with a PCF design, which rapidly spatially separates the two cores up to a 10 µm distance, to facilitate optical measurements of the PBS outputs [output cross section in Fig. 2(c)]. This segment also provides a simple solution for coupling to other optical fibers or for integration into optical chip components by allowing a modal reshape of the two orthogonally polarized output beams; in our case, an adiabatic transformation from an asymmetric \( 1 \times 2 \) µm mode to a 3-µm-diameter round mode (see Supplement 1, Section S4). We set the working spectral range for the PBS to be centered at 1550 nm, thus covering the optical communications C-band.

A design of an optimal (CLR = 2) dual-core DC PCF segment based uniquely on the calculation of the modal effective
indices, and the use of Eq. (1), cannot account for several aspects of the entire real-world design-to-fabrication process, such as the discretized geometry in the 3D printing system and possible anisotropic shrinkage of the structures during post-exposure development [31]. These effects could make the fabricated PCF-like structure geometrically deviate slightly from the wanted PCF design. Additionally, it is difficult to simulate the role of the transition from the dual-core DC PCF segment to the down-taper and the fan-out sections (see Supplement 1, S5). For this reason, we defined the final design of the complete PCF PBS structure using an iterative approach that involved modal analysis, fabrication, and optical measurements; this iterative approach was enabled by the fast turnover time achievable by 3D printing. We used the modal analysis to provide reliable guidelines on how the CLs change with size variations of different parts of the structure’s geometry. In each step of this iterative optimization process, we selected a different geometrical parameter of the dual-core PCF segment to be varied, based on its effect on the CLs for the two orthogonal polarizations, and hence on the CLR, as indicated by the numerical calculations with modal analysis. Then, we fabricated an array of different PBS structures on a glass coverslip, where each structure had a different value for the selected geometrical parameter. We generated the initial guess for the dual-core PCF geometry from modal analysis of a geometry very similar to the one presented in [27], while accounting for the refractive index of the used photopolymer (1.532 at 1550 nm, see Appendix A and [24]). The structures in each array were individually coupled with a focused free-space beam, and their output sections were imaged onto an InGaAs infrared camera to extract; for each polarization, the ratio between the powers was carried by the two cores (see Appendix A).

Figure 3 shows an example of an optimization iteration step. Here, we exploited the dependence of the CLR on the ellipticity of the central hole in the dual-core DC PCF segment. We printed an array of structures with four different ellipticities, and for each ellipticity, we printed a further three structures with different lengths, increasing from left to right in Fig. 3, for a total of 16 structures in the array. By fitting the variation in the ratio of powers carried by the two cores at different lengths, we could extrapolate the two CLs, hence giving the CLR for each different ellipticity (see Supplement 1, Fig. S6). We used the structure with the geometry that gave a CLR closest to 2 as a starting point for the next round of the iteration, where we changed a different geometrical parameter using the guidelines provided by the simulations (see Supplement...
Fig. 4. Experimental optimization of the PCF PBS geometry. (a) Progression of the best CLR in each step of the optimization process toward CLR → 2. The geometrical elements that have been changed in each iteration step are highlighted in blue (only the important central holes are displayed); (b) complete cross-sectional PCF geometry of the optimized PCF PBS design.

1. From the new fabricated array, we identified a new geometry that achieved a CLR even closer to 2. The complete optimization process involved four steps and the variation of three geometrical parameters [Fig. 4(a) and Supplement 1, Section S7], concluding with the optimized design shown in Fig. 4(b), which gave a satisfactory CLR of 1.97. The optimized design has a 140-µm-long dual-core DC PCF segment and a total length of 210 µm for the complete structure. We directly printed this finalized PCF PBS structure on the end-face of a single-mode fiber [Fig. 5(a)] and characterized its broadband polarization splitting performance. This PCF PBS 3D printed on fiber had an extinction ratio of more than 10 dB over a bandwidth of 100 nm and centered around 1550 nm [Fig. 5(c)]. Both cores had an extinction ratio above 12.6 dB in the fiber optics communication C-band (1530–1565 nm). At 1550 nm, we achieved a minimum extinction ratio above 12.6 dB [Figs. 5(b) and 5(c)]. The insertion loss at 1550 nm was 1.18 dB for the horizontal polarization and 1.35 dB for the vertical polarization. These insertion losses could be further improved by using a longer down-taper section, to make it adiabatic according to the length-scale criterion [32]. The bandwidth of our PCF PBS was very broad, but not as broad as that predicted by Jiang et al. [27] (i.e., 150 nm at 10 dB extinction ratio). We can attribute this difference to three main factors: (1) accurate modal analysis of the dual-core DC PCF geometry shows the existence of higher order modes that were neglected in [27], but whose contribution degrades the PBS extinction ratio; (2) the final CLR of the 3D printed structure is not exactly equal to 2; (3) some residual scattering from the photopolymerized material may lead to inter-core cross talk.

3. DISCUSSION

In this work, we first demonstrated the successful direct 3D printing and optical guidance of a selection of optical waveguides with PCF-like designs that rely on different guiding mechanisms. By successfully fabricating these PCF designs, we verified that our method can achieve the fabrication precision and optical quality required for obtaining the final desired cross-sectional PCF geometry considerably faster than current PCF fabrication methods. We then demonstrated that our method is capable of fabricating PCF-like waveguides with geometries that were previously impossible to manufacture because of their complexity. Specifically, we succeeded in fabricating the first-ever PCF PBS. This PCF PBS is the first example of miniaturized complex structures made of stacked segments with PCF designs, presenting fast longitudinal tapers and precisely controlled lateral offsets. Finally, through the realization of the PCF PBS, we showed how direct 3D printing of PCF-like waveguides allows for a comprehensive optimization process that is significantly faster than current PCF fabrication methods based on the drawing of a preform. Besides demonstrating the strengths of our approach, the PCF PBS that we fabricated is significant in itself, as miniaturization and fiber integration of polarization splitting devices are highly desirable features, especially in optical communication systems. Polarizing beam splitters 3D printed on optical fibers have been already reported in the literature [33,34]; however, they are based on diffraction mechanisms, and a further integration in a fiber optical system could be complicated by their intrinsic free-space output. In addition,
we anticipate that a similar dual-core PCF structure such as ours could be optimized to perform wavelength demultiplexing or all-optical switching [35,36]. Based on current high-resolution 3D printing technology, the maximum length that can be achieved for a PCF-like waveguide is in the order of a few mm because of limitations in the fabrication speed and in the configuration of 3D printing machines. However, we foresee that advances in multi-photon lithography fabrication performance [37,38] will soon allow for the fabrication of longer segments and at faster speeds. 3D printing fabrication also opens up the possibility to fabricate the bulk parts of the structures that are not used in light propagation (e.g., the outer part of the waveguide cladding) as a wireframe mesh. With this approach, lighter and faster fabrication of robust structures is achievable, potentially leading to the design of unique opto-mechanical properties [39]. Such wireframe structuring is not currently achievable with traditional drawing-based methods. The current propagation losses for 3D printed solid-core PCF-like waveguides are relatively high, and are contributed mainly by the extinction coefficient of the polymerized photoresist [24], which is significantly higher than that of standard fiber optic materials such as fused silica. We expect that future improvement in multiphoton polymerizable materials will lead to more favorable propagation losses. Additionally, an approach described recently for high-resolution 3D printing of glass–ceramics could allow the use of less lossy materials [40], which could also provide better mechanical and thermal properties to the printed PCF segments than what is offered by polymers. The propagation losses of 3D printed hollow-core PCF designs are also relatively high, in this case mainly because of the intrinsic roughness of longitudinal surfaces, which is 2 orders of magnitude higher than typical values for drawn glass PCFs. This roughness is determined by the chosen slicing step-size that, while allowing for a reasonable fabrication time, was nevertheless not optimal for reducing propagation losses. As fabrication speeds and methods improve in the future, smaller slicing steps will become more viable, leading to smoother surfaces and lower propagation losses. Nevertheless, even if the current propagation losses of the 3D printed waveguides based on PCF designs are a little too high for long propagation distances, they are still suitably low enough to achieve unique and well-performing miniaturized photonic devices. We expect that our approach will open up new possibilities to enhance optical fiber end-faces with miniaturized hybrid complex photonic systems based on segments having PCF designs, as well as their easy combination with other 3D-printable refractive, reflective, diffractive, and metamaterial-based elements [31,33,41–43]. These structures may find application in orbital angular momentum, optical tweezers, and quantum technologies. New, more sophisticated fiber-end probes for biomedical applications may also emerge. We also foresee the development of novel fiber end-face sensors that use 3D printed hollow-core PCF designs for bioanalytics and optofluidics [44]. These applications could benefit from new photoresists with low autofluorescence that are being developed. The inclusion of metals and liquids in high-resolution 3D printed structures has already been demonstrated [45,46]; this technology could be combined with our method to create multi-material hybrid PCF-like structures [47]. We also expect that optical and fiber-optic engineers could benefit from the unprecedented possibilities offered by the freedom of design of PCF geometries in several ways: (a) the easier fabrication of previously difficult-to-produce PCF geometries could unlock new designs, including not-yet-proposed designs that were hitherto considered impossible to fabricate; (b) several properties (e.g., mode shape, mode size) of special PCF designs could be experimentally tested without concern for long turnaround times to achieve the desired fiber geometries fabricated. We also predict that our technology could be applied in the development of twisted optical fibers. In addition to the very high twist rates achievable, a finely controlled transverse and/or axial modulation of the twist rate, as is easily achieved by 3D printing, could lead to new optical effects [48]. Finally, our 3D printing approach to create optical waveguides that exploit the unique properties of PCF designs could easily integrate/complement other recently proposed methods that share the same printing technology, for creating and coupling optical waveguides and photonic chips [25,49–51].

We anticipate our method will unleash the creativity of PCF designers and enable a new generation of miniaturized on-fiber photonic structures for enhancement of the fiber end-face, positively impacting and advancing optical telecommunications, sensor technology, and biomedical devices.

**APPENDIX A MATERIALS AND METHODS**

**A. Fabrication**

3D printing through two-photon lithography offers sub-μm resolution [52], 3D design freedom, and has been recently exploited in several fields, including micro-optics [25,31,41–43]. In two-photon lithography, a focused near-infrared femtosecond laser beam induces the highly localized polymerization of a photopolymer [53]. All the structures presented in this work were 3D printed by a commercially available two-photon lithography system (Photonic Professional GT, Nanoscribe). The photopolymer used here was the proprietary IP-Dip (Nanoscribe GmbH), which is the one that provides the highest fabrication resolution among those available from Nanoscribe. This photoresist is mainly composed of pentaerythritol triacrylate [54], and its absorption spectrum can be found in [24]. We used this resist with a 63× 1.4 NA microscope objective (Zeiss), and in dip-in [55] lithography configuration—in which the microscope objective is directly dipped into the photoresist. In our printing configuration, the polymerized voxel has an ellipsoidal shape, with a typical size of ∼0.3 μm × 1 μm. The writing laser is a near-infrared femtosecond fiber laser with a pulse duration of ∼100 fs, a 780 nm wavelength, and a 80 MHz repetition rate. It uses galvano metric mirrors for beam steering in the system, which allowed a high linear writing speed up to 100 mm/s. The 3D printing was executed layer by layer, with the transverse (x−y) scanning performed by the galvo system while the axial (z) movement was carried out by a piezo actuator. The distance between the different exposed lines is usually referred to as “hatching” in the case of the x−y plane and as “slicing” for the z axis. We used a 0.3 μm slicing distance, a 0.2 μm hatching distance, a scan speed of 10 mm/s, and a laser power of 13.5 mW. Under these settings, the total fabrication time of the complete structure printed on fiber, which was 210 μm long, was around 25 min.

Following completion of the 3D printing, the structures were developed in the mr-Dev 600 developer. To ensure the complete development of the very high aspect ratio hollow channels of the PCF-like waveguides—140 μm long and 0.7 μm in diameter in the case of the dual-core DC PCF segment—we adopted a multi-step strategy. We began with a 5 min development step to remove the bulk of the unpolymerized photoresist. Then we proceeded with two 20 min development steps to remove any remaining...
unpolymerized photoresist from the hollow channels. We then immersed the sample in isopropanol for 25 min to remove any remaining developer, and allowed the sample to air-dry. We used fluorescence confocal laser scanning microscopy to assess if the hollow channels were completely developed (see Supplement 1, Section S8). We fabricated the structures either on glass slides using a standard Nanoscribe substrate holder, or directly on the end-face of single-mode optical fibers (Thorlabs 1060XP) using a custom-designed holder. To guarantee optical fiber alignment and stability during 3D printing, we inserted the fiber in a ferrule, and then terminated and connectorized the fiber. Using this approach, the fiber is more stable compared to using a v-groove-based fiber holder.

For direct 3D printing of the PBG PCF-like waveguide shown in Fig. 2(c), we precisely replicated the geometry of the commercially available fiber HC-1060-02 (NTK Photonics), starting with the SEM image of the output face as given in the manufacturer data-sheet. We processed the SEM image to obtain a 2D binary mask that we used directly as the desired transverse geometry in the 3D printer slicing software. Finally, we extruded this adopted 2D design to the desired length and 3D printed it.

B. Optical Characterization

We assessed the performance of the structures that were 3D printed on a planar glass substrate, e.g., those shown in Fig. 3. The structures were optically coupled by focusing the collimated output of a tunable laser beam (SuperK COMPACT supercontinuum laser with SuperK SELECT tunable filter, NTK Photonics) with a $20 \times 0.4$ NA microscope objective (Nikon). The polarization of the input beam was defined by using a linear polarizer and a half-wave plate. The output beams from the PCF-like waveguides were collected with a $40 \times 0.6$ NA microscope objective (Nikon) and imaged on a InGaAs camera (Xeva 320, Xenics) with a $500 \text{mm}$ tube lens, after passing through a linear polarizer to select either of the two orthogonal polarizations. We collected the images of the PCF PBS output beams with the same integration time for the two orthogonal positions of the output linear polarizer. We then processed them in MATLAB to obtain the output power for each core by spatially integrating the image on the respective core areas. We calculated the extinction ratio for each core from $ER_A = 10 \log 10(P_{Ax}/P_{Ay})$ for core A and $ER_B = 10 \log 10(P_{Bx}/P_{By})$ for core B, where $P_{Ax}$ and $P_{Ay}$ are the output powers on core i (with $i = A, B$) for the x and y polarization, respectively.

To assess the optical performance of the PCF structures 3D printed directly on the end-face of single-mode fibers, we used a FC/PC fiber connector to directly couple the optical fiber to the fiber delivery unit of the supercontinuum laser, and we controlled the input polarization with a fiber polarization controller (FPC030, Thorlabs). See Supplement 1, S6 for details on the calculations of the CLR.

Funding. King Abdullah University of Science and Technology (BAS/1/1064-01-01).

Disclosures. The authors declare no conflicts of interest.

REFERENCES

1. P. St. J. Russell, “Photonic crystal fibers,” Science 299, 358–362 (2003).
2. J. C. Knight, “Photonic crystal fibres,” Nature 424, 847–851 (2003).
3. J. M. Dudley and J. R. Taylor, “Ten years of nonlinear optics in photonic crystal fibre,” Nat. Photonics 3, 85–90 (2009).
4. K. Saitoh, M. Koshiba, T. Hasegawa, and E. Sasaoka, “Chromatic dispersion control in photonic crystal fibers: application to ultra-flattened dispersion,” Opt. Express 11, 843–852 (2003).
5. A. Ortopa-Blanch, J. Knight, W. Wadsworth, J. Amiga, B. Mangan, T. Birks, and P. St. J. Russell, “Highly birefringent photonic crystal fibers,” Opt. Lett. 25, 1325–1327 (2000).
6. R. Cregan, B. M. Johnson, J. Knight, T. Birks, P. St. J. Russell, P. Roberts, and D. Allan, “Single-mode photonic band gap guidance of light in air,” Science 285, 1537–1539 (1999).
7. A. M. Cubillas, S. Unterkofler, T. G. Euser, B. J. Etzold, A. C. Jones, P. J. Sadler, P. Wasserscheid, and P. St. J. Russell, “Photonic crystal fibres for chemical sensing and photochemistry,” Chem. Soc. Rev. 42, 8629–8648 (2013).
8. P. St. J. Russell, “Photonic-crystal fibres,” J. Lightwave Technol. 24, 4729–4749 (2006).
9. G.-D. Peng, Y. Luo, J. Zhang, J. Wen, Y. Chu, K. Cook, and J. Canning, “3D silica lithography for future optical fiber fabrication,” in Handbook of Optical Fibers (Springer, 2019) pp. 1–17.
10. A. Bjarklev, J. Broeng, and A. S. Bjarklev, “Fabrication of photonic crystal fibres,” in Photonic Crystal Fibres (Springer, 2003), pp. 115–130.
11. A. Tandjé, J. Yammine, M. Dossou, G. Bouwmans, K. Baudelle, A. Vianou, E. R. Andresen, and L. Bigot, “Ring-core photonic crystal fiber for propagation of OAM modes,” Opt. Lett. 44, 1611–1614 (2019).
12. K. Cook, J. Canning, S. Leon-Saval, Z. Reid, M. A. Hossain, J.-E. Comatti, Y. Luo, and G.-D. Peng, “Air-structured optical fiber drawn from a 3D-printed preform,” Opt. Lett. 40, 3966–3969 (2015).
13. L. D. van Putten, “Design and fabrication of novel polymer antiresonant waveguides,” Ph.D. thesis (University of Southampton, 2019).
14. W. Talataisong, R. Ismael, T. H. Marques, S. A. Mousavi, M. Beresna, M. Gouveia, S. R. Sandoghchi, T. Lee, C. M. Cordeiro, and G. Brambilla, “Mid-IR hollow-core microstructured fiber drawn from a 3D printed PETG preform,” Sci. Rep. 8, 5113 (2018).
15. S. Kawata, H.-B. Sun, T. Tanaka, and K. Takada, “Finer features for functional micro-devices,” Nature 412, 697–698 (2001).
16. M. Malinauskas, A. Žukauskas, S. Hasegawa, Y. Hayasaki, V. Miezikis, R. Buividas, and S. Juodkazis, “Ultrafast laser processing of materials: from science to industry,” Light Sci. Appl. 5, e16133 (2016).
17. L. Jonušauskas, D. Mackevičiūtė, G. Kontenis, and V. Purlys, “Femtosecond lasers: the ultimate tool for high-precision 3D manufacturing,” Adv. Opt. Technol. 8, 241–251 (2019).
18. S. Leon-Saval, T. Birks, W. Wadsworth, P. St. J. Russell, and M. Mason, “Supercontinuum generation in submicron fibre waveguides,” Opt. Express 12, 2864–2869 (2004).
19. J. C. Knight, T. A. Birks, P. St. J. Russell, and D. M. Atkin, “All-silica single-mode optical fiber with photonic crystal cladding,” Opt. Lett. 21, 1547–1549 (1996).
20. A. Bertonacci, V. P. Rajamanickam, and C. Liberale, “On-fiber 3D printing of photonic crystal fiber tapers for mode field diameter conversion,” in The European Conference on Lasers and Electro-Optics (Optical Society of America, 2017), paper CE_6_2.
21. R. Beravat, G. K. L. Wong, M. H. Frosz, X. M. Xi, and P. St. J. Russell, “Twist-induced guidance in coreless photonic crystal fiber: a helical channel for light,” Sci. Adv. 2, e1601421 (2016).
22. B. Debord, F. Amrani, L. Vinceti, F. Gérôme, and F. Benabid, “Hollow-core fiber technology: the rising of ‘gas photonics’,” Fibers 7, 16–58 (2019).
23. S. Chaudhuri, L. D. Van Putten, F. Poletti, and P. J. Sazio, “Low loss transmission in negative curvature optical fibers with elliptical capillary tubes,” J. Lightwave Technol. 34, 4228–4231 (2016).
24. M. Schmid, D. Ludescher, and H. Giessen, “Optical properties of photoresists for femtosecond 3D printing: refractive index, extinction,
luminescence-dose dependence, aging, heat treatment and comparison between 1-photon and 2-photon exposure,” Opt. Mater. Express 9, 4564–4577 (2019).
25. P.-I. Dietrich, M. Blaicher, I. Reuter, M. Billah, T. Hoose, A. Hofmann, C. Caer, R. Dangel, B. Offrein, U. Troppenz, M. Moehrle, W. Freude, and C. Koos, “In situ 3D nanoprinting of free-form coupling elements for hybrid photonic integration,” Nat. Photonics 12, 241–247 (2018).
26. H. Kubota, S. Kawanishi, S. Koyanagi, M. Tanaka, and S. Yamaguchi, “Absolutely single polarization photonic crystal fiber,” IEEE Photon. Technol. Lett. 16, 182–184 (2004).
27. H. Jiang, E. Wang, J. Zhang, L. Hu, Q. Mao, Q. Li, and K. Xie, “Polarization splitter based on dual-core photonic crystal fiber,” Opt. Express 22, 30461–30466 (2014).
28. H. Wang, X. Yan, S. Li, G. An, and X. Zhang, “Ultra-short polarization beam splitter based on dual core photonic crystal fiber,” J. Mod. Opt. 64, 445–450 (2017).
29. B. M. Younis, A. M. Heikal, M. F. O. Hameed, and S. S. A. Obayya, “Highly wavelength-selective asymmetric dual-core liquid photonic crystal fiber polarization splitter.” J. Opt. Soc. Am. B 35, 1020–1029 (2018).
30. M. T. Rahman and A. Khaleque, “Ultra-short polarization splitter based on a plasmonic dual-core photonic crystal fiber with an ultra-broad bandwidth,” Appl. Opt. 58, 9426–9433 (2019).
31. T. Gissibl, S. Thiele, A. Herkommer, and H. Giessen, “Two-photon direct laser writing of ultracompact multi-lens objectives,” Nat. Photonics 10, 554–560 (2016).
32. J. Love, W. Henry, W. Stewart, R. Black, S. Lacroix, and F. Gonthier, “Tapered single-mode fibres and devices. Part 1: adiabaticity criteria,” IEEE Proc. J. Optoelectron. 138, 343–354 (1991).
33. V. Hahn, S. Kalt, G. M. Sridharan, M. Wegener, and S. Bhattacharya, “Polarizing beam splitter integrated onto an optical fiber facet,” Opt. Express 26, 33148–33157 (2018).
34. H. Wei, F. Callewaert, W. Hadibvita, V. Velev, Z. Liu, P. Kumar, K. Aydin, and S. Krishnaswamy, “Two-photon direct laser writing of inverse-designed free-form near-infrared polarization beamsplitters,” Adv. Opt. Mater. 7, 1900513 (2019).
35. A. Betlej, S. Suntsov, K. G. Makris, L. Jankovic, D. N. Christodoulides, G. I. Stegeman, J. Fini, R. T. Bise, and D. J. Digiovanni, “Air—optical switching and multifrequency generation in a dual-core photonic crystal fiber,” Opt. Lett. 31, 1480–1482 (2006).
36. M. Vieweg, S. Pricking, T. Gissibl, Y. V. Kartashov, L. Torner, and H. Giessen, “Tunable ultrafast nonlinear optofluidic coupler,” Opt. Lett. 37, 1058–1060 (2012).
37. V. Hahn, F. Mayer, M. Thiel, and M. Wegener, “3-D laser nanoimprinting,” Opt. Photon. News 30, 28–35 (2019).
38. S. K. Saha, D. Wang, V. H. Nguyen, Y. Chang, J. S. Oakdale, and S.-C. Chen, “Scalable submicrometer additive manufacturing.” Science 366, 105–109 (2019).
39. T. Frenzel, M. Kadic, and M. Wegener, “Three-dimensional mechanical metamaterials with a twist,” Science 358, 1072–1074 (2017).
40. D. Gailevičius, V. Padolskiytė, L. Mikoliūnaitė, S. Ā. Akirzanovas, S. Juodkazis, and M. Malinauskas, “Additive-manufacturing of 3D glass-ceramics down to nanoscale resolution,” Nanoscale Horiz. 4, 647–651 (2019).
41. M. Malinauskas, A. Žuakauskas, V. Purlys, K. Belazaras, A. Momot, D. Paipulas, R. Gadonas, A. Piskarskas, H. Gilbergas, and A. Gaidukevičiūtė, “ Femtosecond laser polymerization of hybrid/integrated micro-optical elements and their characterization,” J. Opt. 12, 124010 (2010).
42. C. Liberale, G. Cojoc, P. Candeloro, G. Das, F. Gentile, F. De Angelis, and E. Di Fabrizio, “Micro-optics fabrication on top of optical fibers using two-photon lithography,” IEEE Photon. Technol. Lett. 22, 474–476 (2010).
43. A. Bertocci and C. Liberale, “Polarization micro-optics: circular polarization from a Fresnel Rhomb 3D printed on an optical fiber,” IEEE Photon. Technol. Lett. 30, 1882–1885 (2018).
44. M. De, T. K. Gangopadhyay, and V. K. Singh, “Prospects of photonic crystal fiber as physical sensor: an overview,” Sensors 19, 464 (2019).
45. J. K. Gansel, M. Thiel, M. S. Rill, M. Decker, V. Bade, V. Saile, G. von Freymann, S. Linden, and M. Wegener, “Gold helix photonic metamaterial as broadband circular polarizer,” Science 325, 1513–1515 (2009).
46. A. Toulouse, S. Thiele, H. Giessen, and A. M. Herkommer, “Alignment-free integration of apertures and nontransparent hulls into 3D-printed micro-optics,” Opt. Lett. 43, 5283–5286 (2018).
47. C. Markos, J. C. Travers, A. Abdolvand, B. J. Eggleton, and O. Bang, “Hybrid photonic-crystal fiber,” Rev. Mod. Phys. 89, 045003 (2017).
48. R. Beravat, “Twisted photonic crystal fibers,” Ph.D. thesis (Friedrich-Alexander-Universität Erlangen-Nürnberg, 2018).
49. N. Lindenmann, G. Balthasar, D. Hillerkuss, R. Schmogrow, M. Jordan, J. Leuthold, W. Freude, and C. Koos, “Photonic wire bonding: a novel concept for chip-scale interconnects,” Opt. Express 20, 17667–17677 (2012).
50. A. Landowski, D. Zepp, S. Wingert, G. von Freymann, and A. Widera, “Direct laser written polymer waveguides with out of plane couplers for optical chips,” APL Photon. 2, 106102 (2017).
51. O. A. J. Gordillo, S. Chaitanya, Y.-C. Chang, U. D. Dave, A. Mohanty, and M. Lipson, “Plug-and-play fiber to waveguide connector,” Opt. Express 27, 20305–20310 (2019).
52. Z. Gan, Y. Cao, R. A. Evans, and M. Gu, “Three-dimensional deep sub-diffraction optical beam lithography with 9 nm feature size,” Nat. Commun. 4, 2061 (2013).
53. H.-B. Sun and S. Kawata, “Two-photon photopolymerization and 3D lithographic microfabrication,” in NMR—3D Analysis—Photopolymerization (Springer, 2004), pp. 169–273.
54. G. Sentiunas, A. Weber, C. Padeste, I. Sakellari, M. Farsari, and C. David, “Beyond 100 nm resolution in 3D laser lithography — post processing solutions,” Microelectron. Eng. 191, 25–31 (2018).
55. T. Bückmann, N. Stenger, M. Kadic, J. Kaschke, A. Frölich, T. Kennerknecht, C. Eberl, M. Thiel, and M. Wegener, “Tailored 3D mechanical metamaterials made by dip-in direct-laser-writing optical lithography,” Adv. Mater. 24, 2710–2714 (2012).