EPJ Web of Conferences **266**, 11005 (2022) https://doi.org/10.1051/epjconf/202226611005
EOSAM 2022

Tapered hollow-core photonic crystal fibers

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Abstract. In this communication, we will first review the recent advances of hollow-core photonic crystal fibers. Then, the possibility offered to tailor their optical properties by making tapers will be discussed.

1. Introduction

The recent results on the technology of hollow-core photonic crystal fibers (HCPCF) consolidate them as building blocks for the new advances in photonics. Today, we distinguish two families of HCPCF, namely the photonic bandgap (PBG) [1] and inhibited coupling (IC) guiding ones [2]. Particularly, IC fibers have experienced tremendous progress in the latest years. The results concerned improvements in the fiber designs and fabrication procedures, which allowed attaining fibers with special properties and optimized transmission loss. Moreover, the unique properties of HCPCF can also be further optimized by using tapering process. Recently, several techniques have been developed to tailor specific parameters (*e.g.*, dispersion) and to efficiently integrate HCPCFs with the existing fiber devices and systems. Here, we present a review of such advances.

2. Recent advances in hollow-core fibers

The research endeavors on HCPCF have allowed identifying distinct limiting factors for loss decreasing depending on the spectral range of operation. For fibers working in the infrared (IR), the performances are limited by the fiber design. Conversely, for fibers working in the visible and ultraviolet ranges, the surface scattering loss (SSL) arising from the fiber core surface roughness hinders the loss decreasing. In the following sections, we discuss advances regarding IC fibers with ultralow loss in the short-wavelength range and a special fiber structure for low loss and effective single-mode operation.

2.1 Ultralow loss in the short-wavelength range

Since SSL limits the loss decreasing in fibers working at short wavelengths, improvements in the performances for the visible and ultraviolet (UV) ranges must rely on controlling the surface roughness of the fiber core. Considering this, we revisited the HCPCF fabrication methods and obtained a reduction of the core surface roughness levels. Fig. 1a presents comparative plots of the surface roughness profiles for fibers drawn via typical HCPCF fabrication methods and by using our innovative techniques. The reduction of the core surface roughness (peak-to-peak reduction by a factor ~3), allowed us to obtain new state-of-the-art HCPCF working at short wavelengths [3]. Fig. 1b shows, as an example, the loss spectrum of a single-ring tubular-lattice (SR-TL) HCPCF with record low loss at wavelengths <600nm. It is remarkable that the new record low values lie below the silica Rayleigh scattering limit, a fundamental restriction for solid-core fibers.

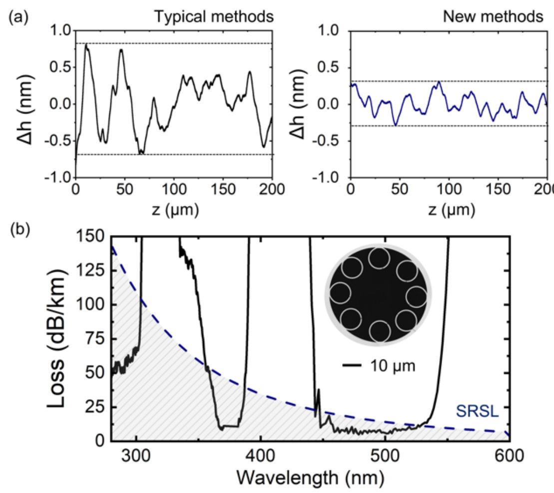

Fig. 1. Core surface profiles for HCPCF drawn by (a) typical and (b) innovative approaches. (c) Loss spectrum of a HCPCF with record low loss in the short-wavelength range. SRSL: silica Rayleigh scattering limit.

2.2 Robust single-mode operation

For fibers working in the IR, the design of the fiber cladding plays a crucial role in providing strong light confinement. Additionally, the judicious design of the fiber cladding allows tailoring the fiber modal properties for achieving robust single-mode operation. Remarkably, the six-tube SR-TL HCPCF design allows to efficiently filter the contaminating LP_{11}-like modes and provides effective single-mode operation. However, this design displays high loss. To circumvent this limitation, the confining power of the structure must be improved. An opportunity for having low loss and robust single-mode

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HCPCF is to use the so-called hybrid kagome-tubular (HKT) HCPCF [4]. Fig. 2a presents the cross-section of the HKT HCPCF, which exhibits an inner cladding formed by a ring of six tubes and an outer kagome one for confinement improvement. This structure allows having low loss (Fig 2b) and robust single-mode operation. Fig. 2c shows that the HKT HCPCF has a robust fundamental mode-like near-field output profile even if the light launching condition is shifted from its optimum (X=Y=0).

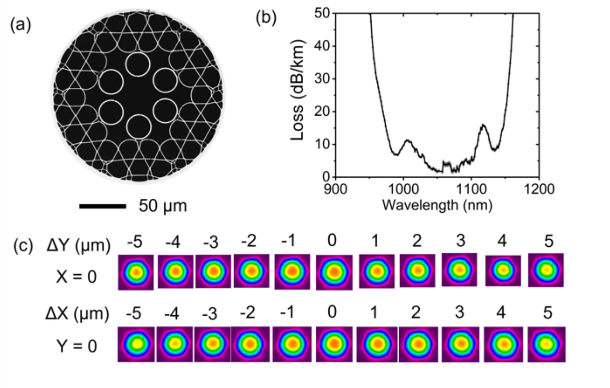

Fig. 2. HKT HCPCF (a) cross-section and (b) loss spectrum. (c) Robustness of the near-field output profile for varying input conditions.

3. Tapering process for tailoring the properties of hollow-core fibers

The optical performances of the HCPCFs can also be tailored by using tapering process. In fact, by varying the different geometrical parameters of the fiber along its length, it is possible to manage the characteristics of the guided mode. The tapered section can be managed over a few tens of mm to several meters combined with an evolution of the overall dimension of the fiber (*i.e.*, the outer diameter) by several factors, according to the need. To illustrate this, two examples are given.

The first one concerns the issue of HCPCF integration into systems. Indeed, due to the improved performances presented in the previous section, such fibers became today very attractive, and it is thus worthy to splice them to standard single mode fiber (SMF) for further application in gas photonics and telecommunications. However, achieving low loss and mechanically robust splicing between HCPCF to SMF remains technically challenging especially due to the large hollow-core size. Also, the delicate shape of the HCPCF (*i.e.*, negative curvature core contour) needs to be preserved during the post-processing to keep the waveguide performance. Thus, we proposed different tapering processes based on commercial splicers to answer this call. By tapering down a kagome-lattice HCPCF (core diameter: 61-75 μm, Fig. 3) from 300 μm to 125 μm outer diameter over an adiabatic length of 12 mm, a down-taper loss of 0.07 dB and a record SMF to kagome splice loss of 0.48 dB at 1550 nm was achieved [5]. However, the reverse splicing loss reached 3.5 dB due to the excitation of the HCPCF high-order modes in this scheme. More recently, by using a two-step reverse-tapering method, we could improve the control and the splicing loss in both directions. A record-low insertion loss of 0.88 dB for a SMF/HCPCF/SMF chain at 1310 nm was demonstrated [6].

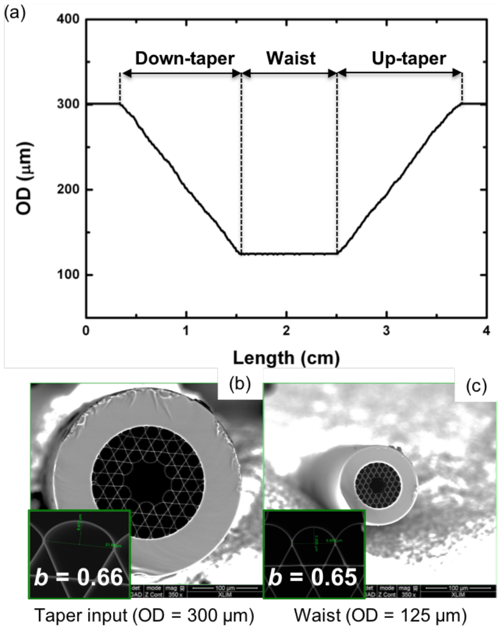

Fig. 3. (a) Experimental evolution of the taper diameter versus length; (b) Cross-section of untapered and (c) tapered kagome HCPCF fiber at the waist region. Inset: zoom in the core contour.

The second example concerns the use of long-tapered HCPCF specially designed to manage the dispersion profile of the fiber. Indeed, the position of the zero-dispersion wavelength and the value/slope of the dispersion curve are some of the key parameters in the nonlinear effects. Here, the tapering process is done directly during fiber fabrication by controlling the drawing speed. By using a homemade software integrated into the drawing tower, the variation of the fiber's outer diameter can be easily adapted in terms of shape and length. Such long-tapered HCPCFs were successfully fabricated. Adiabatic soliton pulse compression [7] and matched cascade frequency-conversion using stimulated Raman scattering have then been demonstrated [8].

To conclude, recent advances in HCPCF combined with tapering process open the way to a myriad of applications ranging from optical telecommunications, nonlinear and ultrafast optics, atom and quantum optics to plasma photonics.

The research was funded through PIA program 4F, Labex ΣLim and la région Nouvelle Aquitaine.

4. References

1. Birks *et al.*, *Electron. Lett.* **31**, 1941-1943 (1995).
2. Couny *et al.*, *Science* **318**, 1118-1121 (2007).
3. Osório *et al.*, CLEO Conference, SW4K.6 (2022).
4. Amrani *et al.*, *Light : Sci. Appl.* **10**, 7 (2021).
5. Zheng *et al.*, *Opt. Express* **2**, 14642-14647 (2016).
6. Wang *et al.*, *Opt. Express* **29**, 22470-22478 (2021).
7. Gérôme *et al.*, *Opt. Express* **15**, 7126-7131 (2007).
8. Beaudou *et al.*, *Opt. Express* **18**, 12381-12390 (2010).