

Fusion splice between tapered inhibited coupling hypocycloid-core Kagome fiber and SMF

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Abstract: We report for the first time on tapering inhibited coupling (IC) hypocycloid-core shape Kagome hollow-core photonic crystal fibers whilst maintaining their delicate core-contour negative curvature with a down-ratio as large as 2.4. The transmission loss of down-tapered sections reaches a figure as low as 0.07 dB at 1550 nm. The tapered IC fibers are also spliced to standard SMF with a total insertion loss of 0.48 dB. These results show that all-fiber photonic microcells with the ultra-low loss hypocycloid core-contour Kagome fibers is now possible.

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1. Introduction

The advent of Inhibited-Coupling (IC) guiding Hollow-Core Photonic Crystal Fibers (IC HC-PCF) [1] and the dramatic improvement in confinement loss have recently resulted from the fiber core-shaping by making a hypocycloid-like contour (*i.e.* negative curvature) [2]. Consequently, this new branch of HC-PCF outperforms their photonics band-gap (PBG) guiding counterparts both in term of transmission bandwidth and attenuation particularly in the visible and near-IR. For example, record loss figures of 17 dB/km at $\sim 1 \mu\text{m}$ [3], 70 dB/km at $\sim 780 \text{ nm}$ [4] and 70 dB/km at 500-600 nm wavelength range [5] have been achieved. In particular, it has been shown in a systematic experimental and theoretical study [3, 6] that both the transmission loss and the core optical power spatial overlap with the silica core-surround drop with increasing the negative curvature of contour cups at the interface of the core and cladding regions. The effect of the negative curvature on the loss reduction was observed even with a single ring cladding design [7,8] with transmission loss of $\sim 30 \text{ dB/km}$ around 3-4 μm wavelength range [9]. Due to these optical performances, such fibers became very attractive and it is thus worthy to be able to splice them to standard single mode fiber (SMF) for further application in gas photonics and integration via efficient photonics microcells (PMCs) [10]. However, achieving low-loss and mechanically robust splicing between IC Kagome HC-PCF to SMF remains technically challenging due to the large hollow-core size. This problem of mode-field mismatch (MFM) has previously been addressed by tapering down such Kagome fibers and then splicing to SMF [11]. The results obtained show insertion loss figures of as low as 0.6 dB for a hexagonal core-shape 1-cell Kagome fiber (core size of 45 μm) and 2 dB for a circular core-shape 19-cell Kagome fiber (core size of 65 μm). If the delicate core contour of hypocycloid-core Kagome HC-PCF is preserved during the post-processing process, specially applying tapering technique would make sense. In this paper, we report on tapering hypocycloid-core Kagome HC-PCF whilst preserving the delicate negative contour at the fiber-core interface and the aspect ratios of transverse cladding structure and fusing splicing it to a standard SMF. A systematic study on the transition lengths and down ratios have been investigated, resulting in a minimum down-taper loss of 0.07 dB at 1550 nm and a record SMF to Kagome splice loss of 0.48 dB combined with good mechanical fuse compatible with a tension of several hundred grams.

2. Tapering process and systematic study

The experimental post-processing study was made on IC HC-PCFs based on a 7-cell core defect and a Kagome-latticed cladding with 3 rings with strut thickness t equal to 550 nm. The core/clad interface presents a hypocycloid-shape (quantified by using the parameter b set here at 0.66 ± 0.02 and defined as d/r , where d is the distance between the top of the cups and the chord, r is the radius of the semicircle having its diameter set by the previous chord length [3]) with an inner and outer core diameter of 63.4 μm and 75 μm respectively. The fiber exhibits a fundamental guidance band with a cut-off wavelength at 1100 nm and a loss figure in the range 90 - 170 dB/km. The fiber tapering process consists of the following procedures [11]. Firstly, the cladding at one of the fiber-ends is collapsed while keeping the hypocycloid-core opened by heating the fiber-tip using a commercial filament fusion splicer. The second fiber-end is completely sealed. The fiber-end with the collapsed cladding is then inserted into mechanical chamber, which is connected to a vacuum pump and a pressure gauge. This allows applying a controllable vacuum pressure in the range of few mbar to the HC-PCF and thus compensating the inner wall surface-tension induced collapse during the tapering process. The fiber tapering is achieved by using the following sequence. A fiber section is heated and stretched to form a tapered section. The taper section comprises two regions, one descending in diameter and one ascending in diameter, separated by a section with uniform transverse dimensions. Notice that the descending and ascending sections are referred in this paper as the “down-taper” and “up-taper” respectively. The middle section with uniform diameter is referred to as the taper “waist” as indicated in Fig. 1(a). Figures 1(b) and 1(c) show two scanning electron micrographs (SEM) pictures of the un-tapered and tapered

hypocycloid core shape Kagome fiber respectively. The fiber is tapered from an initial outer diameter (OD) of 300 μm down to 125 μm over few tens of mm. The insets of Figs. 1(b) and 1(c) clearly show that the curvature of the arcs of the core contour has been conserved as well as the aspect ratios of the fiber transverse structure. Indeed, the strut thickness was found reduced from 550 nm down to 220 nm. Therefore, the physical integrity of tapered IC fiber has been completely preserved with a down ratio as large as 2.4. The repeatability of our tapering process is found pretty good with a typical deviation of less than 5% on the physical properties.

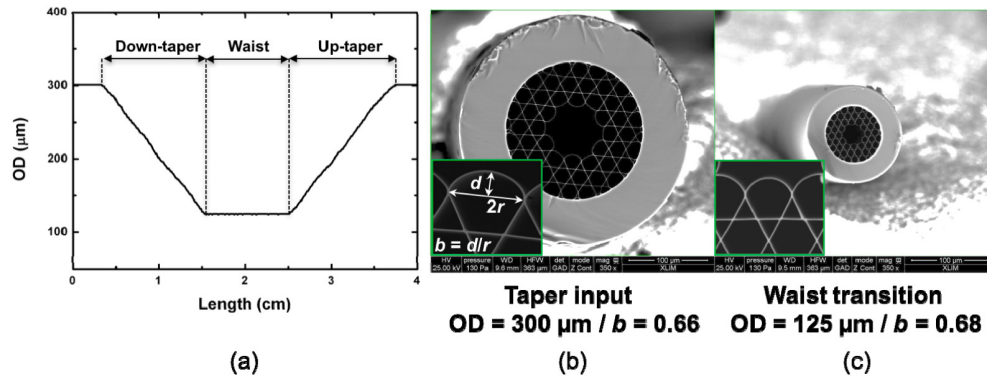


Fig. 1. (a) Experimental evolution of the taper section of fiber with length; (b) Cross section of un-tapered and (c) tapered IC Kagome HC-PCF fiber at the waist region with an outer (inner) diameter respectively of 300 μm (63.4 μm , MFD of 42.7 μm) and 125 μm (26.4 μm , MFD of 17.7 μm). In inset: zoom in of the core-contour showing the preservation of the curvature shape before and after the tapering. A definition of d and r is given to deduce the b parameter.

In a second step, the impact of the transition length (TL) and the down-ratio (DR) on the taper performances were investigated and optimized by carrying out a systematic study. Notice that the waist length is kept constant to 1 cm. The typical transmission and loss spectrum of a whole tapered fiber include down-taper and up-taper region is shown in Fig. 2. The losses were obtained using cut-back technique by launching a home made supercontinuum source. Near field was monitored by InGaAs IR camera to confirm the single mode guidance. The spectra show a taper loss response with values ranging between 0.2 and 0.5 dB in the analyzed IR range below 1680 nm. The recorded fluctuations in the loss spectrum are attributed to the power noise of the white light source and the limited resolution of the optical spectrum analyzer. The loss spectra were recorded for different TL and DR and show the same spectral trend.

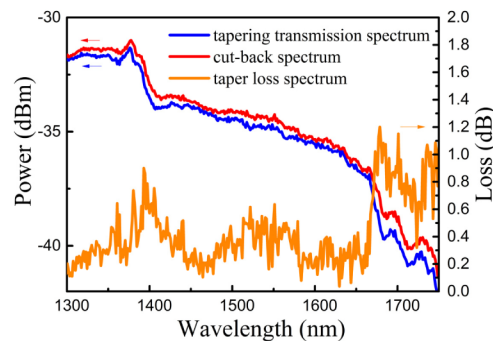


Fig. 2. Measured transmission spectra of 3 m long HC-PCF with a tapered section from an outer-diameter of 300 μm to 200 μm with a full length of 4 cm (TL = 15 mm and waist section length of 10 mm) (blue curve) and of the cut-back at the start of the tapered section (red curve). Full taper loss spectrum (brown curve).

Furthermore, the loss was measured by launching single wavelength laser at 1550 nm to get more accurate loss-figures. The full taper and the down-taper transmission losses at 1550 nm with different TL and DR are shown in Figs. 3(a) and 3(b). Here, the loss data were obtained by repeating ten times the measurements of the transmitted powers through ten fiber samples with the taper and its cut back at the start of the full taper for the whole taper loss [Fig. 3(a)] and at the middle of the waist for the down-taper loss [Fig. 3(b)]. The solid points in Fig. 3 plots represent the obtained average loss and the error bar heights corresponds to the standard deviation of the repeated measurements. As expected for such low loss HC-PCF, the tapering induced loss decreases with the TL and inversely proportional to the DR. For example, the taper transmission loss drops 8 fold, from 1.6 dB down to 0.2 dB for a fixed TL of 5 mm when DR is changing respectively from 300/125 to 300/200. Also, when the TL is increased to 20 mm for a fixed DR of 300/125, the loss for the whole tapered fiber can be reduced to 0.4 dB. A further investigation on the propagation loss dynamics along the taper was carried out by performing loss measurement for the up-taper section by cutting the fiber at the middle of the taper waist [see Fig. 3(b)]. The deviation of position cleaving at the waist is inferior to 1 mm. Whilst the loss evolution with TL and DR is similar to the full taper, the minimum up-taper loss is found to be 0.07 dB. This asymmetry between the propagation losses in the up-taper compared to the down-taper is likely due to excitation of higher order modes in the up-taper section (un-adiabatic taper). However, this asymmetry is reduced when the TL is increased from 5 to 20 mm, as well as the loss difference between the up and down section of the taper as it is shown by the whole taper transition loss of 0.14 dB for TL of 20 mm. Furthermore, for the taper with the lowest DR, the loss varies little. This evolution reveals that for a DR of 300/125, the adiabatic transition is obtained only for a TL higher than 20 mm [12,13]. This is confirmed by the near field recorded at the tapered IC fiber output [see Fig. 3(c)] showing the same guiding mode than the un-tapered case with 98.4% light transmission.

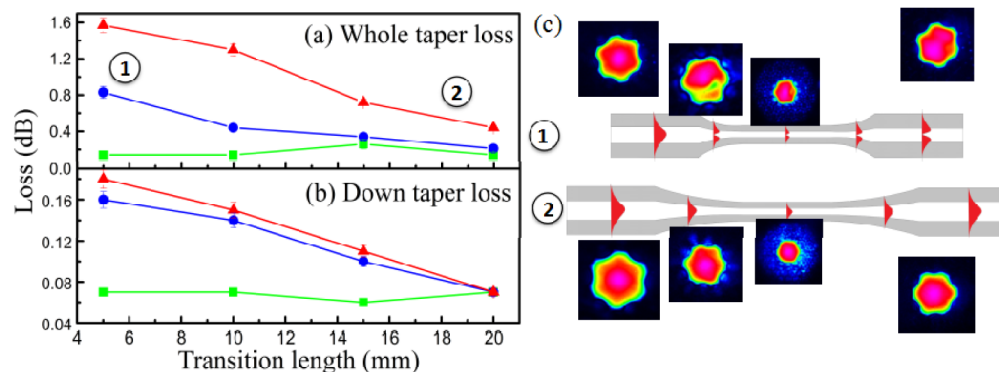


Fig. 3. (a) Evolution of the loss at 1550 nm of several independent whole tapered fibers for three different DR (300 μm to 200 μm : green line, 300 μm to 150 μm : blue line and 300 μm to 125 μm : red line) and for different TL (5 mm, 10 mm, 15 mm and 20 mm) and (b) for only the down-tapered fiber section; (c) Evolution of the near field for two tapers differentiated by different TL, referred by 1 (TL = 5 mm and DR = 300/125) and 2 (TL = 20 mm and DR = 300/125) recorded by launching 1550 nm laser source.

3. Kagome-SMF splice and characterization

Using the above Kagome fiber tapering results, we have undertaken splicing of tapered IC Kagome fiber to standard SMF. This is done by making a whole taper as described above, and then cleaving it at the waist. The chosen Kagome fiber taper characteristics are TL = 20 mm and DR = 300/125. The total insertion loss spectrum of the fiber section composed by 1m-long piece of 300 μm -OD Kagome fiber, tapered and then splice to a SMF fiber is obtained for both light propagation direction Kagome fiber-to-SMF, and SMF-to-Kagome fiber (see Fig. 4). During the fiber alignment stage before splicing, the light coupling is monitored

through an InGaAs IR camera at the output of the 300 μm -OD Kagome fiber to preferentially select the fundamental mode (FM) of core mode. Also, transition loss and modal power of the modes excited by input field have been numerically estimated by computing the overlap integrals [14].

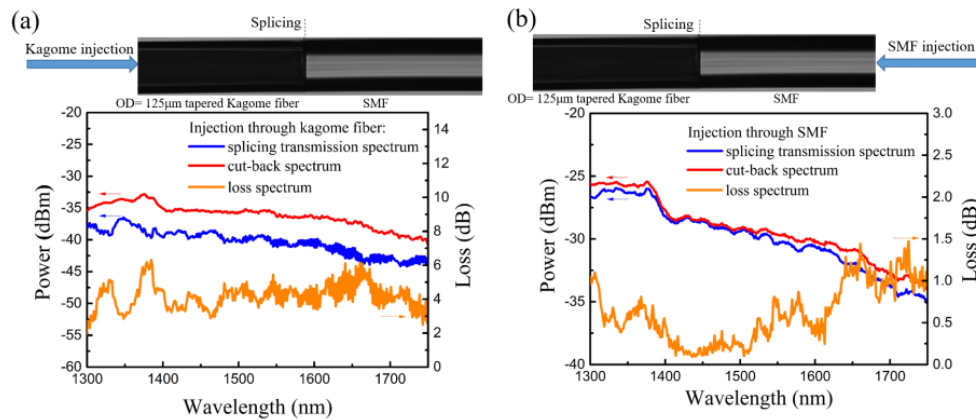


Fig. 4. Show the measured splicing transmission spectrum of tapered Kagome-SMF (blue line), the cutback (red line) and the insertion loss spectrum (black line) for the two sides launching. (a) Light is injected from 300 μm -OD Kagome section by a SMF; (b) Light is injected from SMF to the 125 μm -OD Kagomé section. In inset the images of the splice are shown.

For the case of SMF-to-Kagome configuration, the splice loss adding to the previous 0.07 dB of the taper transition is measured to 0.48 dB at 1550 nm. This total loss figure presents a standard deviation of few percent for ten made splices. Also, this value is in good agreement in comparison with the theoretical loss prediction of 98.3% light coupling due to mode field mismatch (MFM). In more detail, this corresponds to 76.7% of the power coupled supports by the fundamental mode, and 21.6% in the first higher order mode (HOM) which can be excited in case of zero axis offset between the two fibers (here HE_{12}). Here only 1.7% is coupled to highly lossy HOMs, which can be considered lost. For the reverse case, *i.e.* light is injected at the 300 μm -OD Kagome fiber end, the experimental loss figure is measured to be 3.5 dB at 1550 nm, and which is much higher than the MFM theoretical limit of 1.15 dB when only the FM is excited in the Kagome fiber. The difference is likely due non-negligible guided power in HOM present at the tapered section. Indeed, since the power is experimentally injected into Kagomé fiber through a SMF, additional loss at the SMF to 300 μm -OD Kagomé transition must be considered. Calculations demonstrate 18.6% of the power is coupled to fundamental mode and 30.3% to the HOM HE_{12} . The remaining 51.1% of power is coupled to highly lossy HOMs and thus considered lost. According to transition loss numerically estimated, this results in 3.1 dB of additional loss which explains why experimental loss is 3.02 dB higher than the previous case. Notice that changing the SMF by a better solid-core fiber in order to improve the MFM with the Kagome fiber will permit to reduce this 3.5 dB splice insertion loss if the application requires.

4. Conclusion

In conclusion, for the first time, tapering an inhibited coupling Kagome fiber while maintaining hypocycloid-core shape using a core vacuum compensation method is reported. The physical integrity has been preserved, and the taper presents an adiabatic evolution with a record value of 0.07 dB at 1550 nm. Finally, splicing this family of fibers to conventional SMF was also successfully demonstrated with minimum value of 0.48 dB. The splice was found mechanically robust as typical PBG-SMF joint. This result is the first step toward integrated IC Kagome fiber to telecommunication systems and other all-fiber optical devices.

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