Deliverable 4.5: HC-PCF with improved PER at 1µm (>20 dB)

Dissemination Level: Public

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Contents

1 Scope

The scope of this deliverable relates to the task to push the state-of-the-art of low loss Kagome HC-PCF by designing a fiber that has much better polarization maintaining capabilities. The aim is to have a PER>20 dB at the operating wavelength range around 1 µ. The task consists of designing and fabricating a new fiber structure. The fiber will be based on Kagome-like design, i.e. guiding via Inhibited-Coupling mechanism, so to keep the fiber specifications in terms of outer and core diameters, numerical apertures and transmission performance compatible with the current fiber design.

2 Introduction

In past few years, work on a type of HCPCF guiding via a new guidance mechanism, coined Inhbited-Coupling, emerged. Among the salient features that have been demonstrated with these fibers are their outstanding energy handling and low transmission loss. In HIPERDIAS project, we want to explore these properties to implement it as an integral part of the laser micro-machining system. Towards this aim, work on improving the polarization maintenance of the fiber is paramount. This task aim is to improve on the design of such fibers so to achieve PER higher than 20 dB.

3 Main body

3.1 Optimization of curvature and silica thickness core contour of inhibited-coupling hollow-core fibers

In this task, we first start with a theoretical study in order to optimize our current HC-PCF design based on a Kagome lattice and a hypocycloid core-contour (*i.e.* negative curvature). In particular, we focus on two geometrical parameters: the curvature (noted b) and the silica thickness (noted t) of this hollow-core contour. Indeed, our current state-of-the-art, although exhibiting record losses of 17 dB/km at 1 µm, presents some possible improvements. Especially, the transmission bandwidth is found to be relatively narrow (some tens of nm) which can be a limiting factor in some applications and the polarization extinction ratio (PER) value limited to 10-15 dB. As our fiber guides by the inhibited-coupling (IC) mechanism, the calculations demonstrate that reducing *t* while maintaining an optimum *b* close to 1 will improve the optical performances. Consequently, a careful optimization of such geometrical parameters has theoretically been calculated and then experimentally validated.

Figure 1 summarizes calculated confinement loss coefficient (α_{CL}) spectra of hypocycloid core-contour Kagome HC-PCF for different strut thickness t (Fig. 1(a)) and different negative curvature parameter b (Fig. 1(c)). The calculation was performed with a modal solver, and the CL spectra are presented in function of the normalized frequency $\mathrm{F} = (2\,\mathrm{t}/\,\lambda\,)\sqrt{\mathrm{n}^2 - 1}$. Furthermore, all the simulated fibers have the same inner core diameter of 45 µm. In Fig. 1(a), where *b* = 1, the results clearly show the strong effect of reducing the thickness in the CL reduction for each of the transmission bands. A decrease in *t* from 1400 to 300 nm results in CL reduction by ~ 4 orders of magnitude. Similarly, Fig. 1(c) shows the benefit of increasing *b* in reducing CL. Here, the HC-PCF strut thickness is fixed to *t* = 600 nm, and the results show a decrease in CL by ~ 2 orders of magnitude when the *b* is increased from 0.25 to 1.25.

We then fitted the CL data to empirically extract a scaling law of the CL with *t*, *b* and λ. Fig. 1(b) shows the CL spectra taken from Fig. 1(a) and presented as $\alpha_{CL}(A\,t\,\lambda^{4.3})^{-1}$ versus F, while Fig. 1(d) presents $\alpha_{CL}(A\,t\,\lambda^{4.3}\,b^{-2})^{-1}$ versus F from the data of Fig. 1(c). The results show that all the spectra are now superimposed. Each of these spectra curves is then high-frequency filtered to smoothen out the oscillating peaks (see black curve in Fig. 1(b) and Fig. 1(d)). This filtering was carried out for every CL spectra, and the resulting smoothed CL curves (only one curve is shown in Fig. 1(b) and 1(d)) are identical within 20%. **In conclusion**, the results shows that CL scales with *t*, *b* and λ as $\alpha_{CL} \propto t\,\lambda^{4.3} b^{-2}$, and the minimum loss for higher order bands to occur at $\mathrm{F} = \mathrm{l} + 1/2$; *i.e* at wavelength $\lambda_{\min} = \left(2\,\mathrm{t}/(\mathrm{l} - \frac{1}{2})\right)\sqrt{\mathrm{n}^2 - 1}$. As a result, and in corroboration with previous works, ultra-low loss and broad transmission windows is achieved by having large negative curvature parameter and thin silica struts.

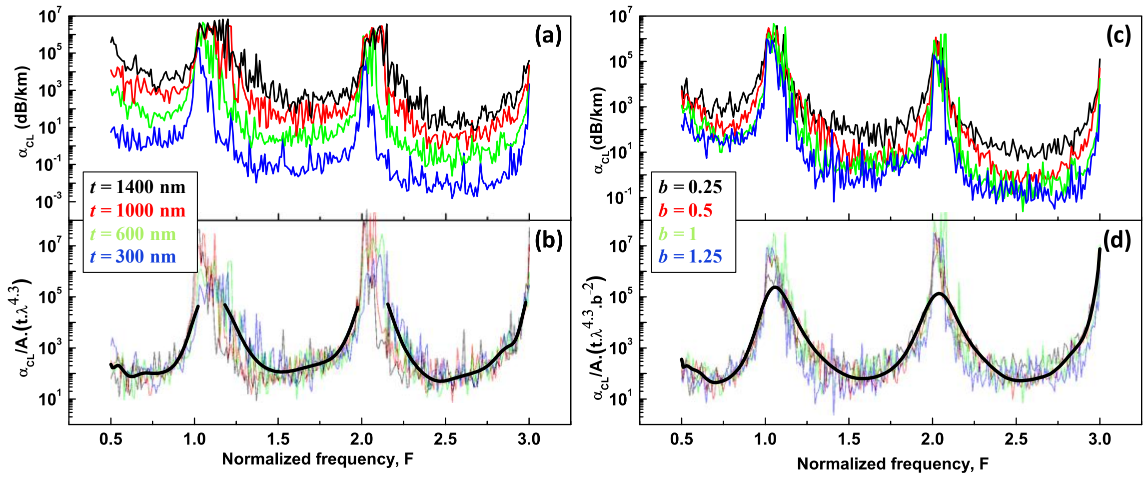

Fig. 1. (a) Calculated CL spectra for different hypocycloid core-contour Kagome HC-PCF with t ranging between 300-1400 nm and for b = 1 versus the normalized frequency. (b) CL normalized by the equation $t\,.\,\lambda^{4.3}$. (c) Calculated CL versus b ranging between 0.25-1.25 for a fixed t = 600nm. (d) CL normalized by adding b^{-2} to the scaling law. A is a normalizing constant whose value $(1/800)\times(1/1750)^{4.3}$ has been chosen to have normalized loss in the same range of loss (b) and (d). The inner core diameter is fixed to 45 μm for all the simulated fibers.

Then, the experimental work was carried out. Figure 2 summarizes the results of representative fabricated hypocycloid core-contour Kagome HC-PCF. Figure 2(a) shows the loss spectra and the scanning electron micrographs (SEM) of six HC-PCFs with different strut thickness.

The loss spectrum of each fiber has then been measured by cut-back technique on 100 m-long pieces with a coupling efficiency between the fiber and the white light source superior to 90%. Notice that the fundamental band is plotted in black color and the first high-order band in grey in the Fig. 2(a). As expected, making the strut thinner results in a broader transmission band associated with a decrease of the attenuation level, except at wavelengths shorter than 1 µm, which is mainly due to the surface scattering loss (SSL). In particular, the attenuation exponentially increases for shorter wavelengths as shown in the first high order band when it is shifted towards the visible spectral range; reaching values around 180 dB/km when t = 400 nm.

The SEMs show also a close-up of the fiber around its hollow-core and of a representative cup of the hypocycloid core-contour. The SEMs are presented from top to bottom with decreasing thickness from 800 to 300 nm. The cup negative curvature b decreases with decreasing t. Indeed, the curve of the top of Fig. 2(b) shows b of 0.45 at t = 310 nm and increases with t to reach asymptotically the value of 1 when t is larger than 800 nm. Here, the fibers were achieved by first setting a strut thickness target, and then maximize b by controlling the pressurization of the fiber air holes during the draw. This is done to avoid the surface-tension induced collapse of the holes, and to inflate the core-surround holes to the maximum curvature whilst avoiding the distortion of the cladding structure such as degrading the silica thickness uniformity or increasing the relative size of the connecting struts. The latter affects both the maximum achievable negative-curvature parameter b and the fiber-transmission performance (see below). The limit on the maximum achievable b is set by a larger surface-tension at the connecting strut, which results in pulling the negatively-curved silica-cups toward the nodes and thus in flattening them somewhat. Moreover, this effect cannot always be compensated by further hole-pressurizing without disturbing the thickness uniformity. The thinner the struts are the more difficult the hole-pressure compensation gets. These rheological effects also alter the connecting strut geometrical shape as is readily illustrated in the close-up of the SEM pictures, which show the connecting strut shapes evolution with thinner struts.

By virtue of IC optical guidance, such a change in the connecting strut shape with strut-thinning affects the transmission loss via two mechanisms. First, the increase in the node length with decreasing *t* induces an enhancement in coupling between the core modes and the node low-azimuthal-number modes. Second, by limiting the maximum achievable *b*, it is set to a lower-limit on the confinement loss. This is summarized in Fig. 2(b).

The top of the figure shows the resulted change in *b* with the strut thickness. The results show a *b* of 0.45 at *t* = 310 nm and an increase with *t* to reach asymptotically the value of 1 when *t* is larger than 800 nm. The impact of the achieved *b* value on the CL is illustrated by the bottom curves of Fig 2(b). They show the fundamental band minimum loss as they are measured (black joined-squares) and simulated (red joined-squares) for the different drawn fibers. Comparing these two curves, we can draw the conclusion that for *t* > 600 nm, the measured losses are very close to the simulated CL, thus indicating that the measured transmission loss is set by the confinement loss with no significant contribution from the scattering loss or other source of loss. Furthermore, for *t* < 400 nm, the measured loss is ~10X larger than the calculated CL, which is due to enhanced contribution of surface scattering loss (SSL) with thinner strut and for shorter wavelengths. The figure also shows the calculated minimum CL for the fabricated HC-PCF if they had *b* = 1 (red dashed curve). Here, we clearly see the impact of the difficulty

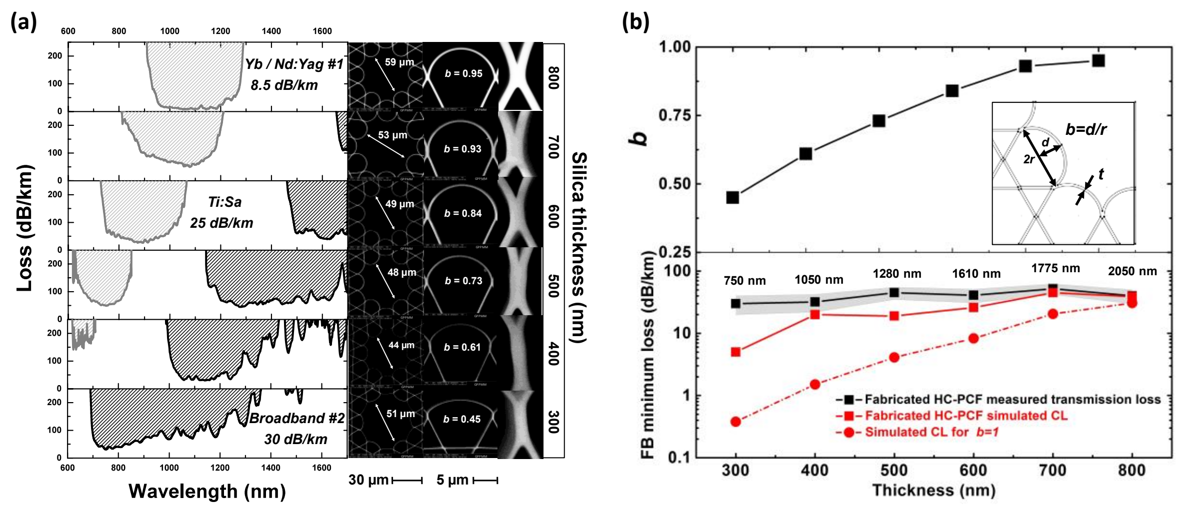

Fig. 2. (a) Loss spectra evolution versus the wavelength for several fabricated IC Kagome HC-PCFs with different *t*. The SEM images of the fibers and the geometrical parameters are added. (b) Evolution with *t* of the core negative curvature *b* (top), of the fibers measured minimum loss (bottom, black joined squares), and simulated CL (red joined-squares) at the fundamental band (FB). The wavelengths corresponding to this minimum loss are indicated on top of each point. The grey filled region in the measured loss curve corresponds to the measurement uncertainty. The red joined-discs curve shows the simulated CL of fibers similar to the fabricated one but with *b* = 1.

in maintaining *b* = 1 on the transmission performance for HC-PCF with strut thickness *t* < 600 nm. The *b* "degradation" induces a factor 2 in loss increase for *t* = 700 nm and up to more than 100 times loss increase when *t* = 300 nm.

3.2 Improvement of the PER value (> 20 dB)

3.2.1 Design #1: Hollow-core fiber based on Kagome lattice

For the case of the thickest strut fiber (referred to fiber #1 on Fig. 2), the geometrical parameters are *t* = 810 nm, a core diameter of 59 µm, a pitch of 24 µm and an outer diameter of 320 µm. The loss spectra plotted in Fig. 3(b) obtained by a cut-back measurement using a homemade supercontinuum white light source from 106 m down to 3.8 m with a bending curvature of 35 cm-radius exhibits its first high order band centered around 1 µm ranging from 900-1280 nm. In this 1st order transmission window, the minimum loss results in a value which is for the first time below the 10 dB/km level (8.5 dB/km at 1030 nm). Notice that for each recording, ten transmission spectra were taken with different cleaves of the fiber output to estimate the measurement uncertainty, which was found to be 0.5 dB/km in our case. An additional measurement has been performed by using a stable 1030 nm laser which confirms this loss figure. The associated 3-dB bandwidth is measured to be 225 nm wide, which is almost doubled compared to the current state-of-the-art. Finally, the loss spectrum was compared to the earlier fiber exhibiting *b* = 1 but with thicker silica struts to highlight these improvements. The associated chromatic dispersion is estimated to be +0.45 ps/(nm.km) around 1030 nm and the mode field diameter (MFD) of 45 µm.

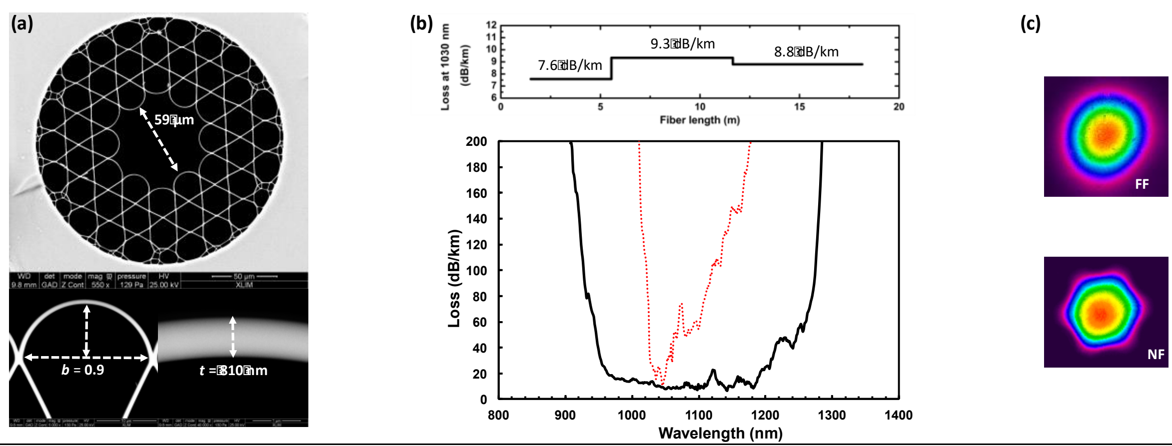

Fig. 3. (a) SEM images on the fiber #1. (b) Loss spectra curves of fiber #1. A comparison with our previous fiber fabrication exhibiting an optimum *b* is added (red curve). (c) Mode field profiles (near and far field) are also indicated at 1 µm.

The modal performances were then studied, especially focused at Yb-Nd:Yag region where the fiber aimed to have record level transmission properties and the HIPERDIAS project is focus on. The polarization extinction ratio (PER) has been measured over the fiber length. For this part, a linearly polarized laser emitting at 1064 nm was launched into the fiber associated with a half-wave plate for polarization control. At the output of the fiber, the transmitted beam passed through a polarizing beam-splitter (PBS) and each of its two output beams is recorded by a power-meter and a camera imaging its reconstructed near-field beam profile. The results are plotted in Fig. 4 indicating a maximum PER of 26 dB for fiber lengths shorter than 3 m. The evolution with the fiber length of the PER has also shown a constant decrease in PER with a rate of 0.6 dB/m. The 20 dB is then kept for fiber length up to 10 m, which is in agreement with the length used for BDS (typically between 3 to 5 m-long).

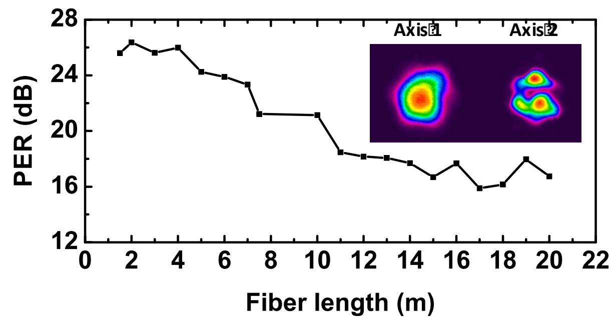

Fig. 4. Linear characterizations of the fiber #1 on the evolution of the PER versus the fiber length.

This result validates the deliverable D4.5. Consequently, this fiber was selected and then transferred to GLOphotonics for integration into the BDS. These results have been published in *Optics Letters* this year.

3.2.2 Design #2: Hollow-core fiber based on Tubular lattice

In parallel to this work, we have investigated, within another publicly funded project [Agence Nationale de la Recherche (ANR) (Photosynth); Air Force Office of Scientific Research (AFOSR) (HOFGAS); Σ_LIM Labex Chaire, Maturation, region Limousin], another hollow-core fiber design that fully fulfils the mentioned features for IC guidance. It relies on a tubular lattice with a one ring of isolated (with no connecting nodes) thin glass tubes. Here also, a systematic study was carry out resulting in fabrication of record tubular lattice IC HC-PCFs with one demonstrating a loss range of 10-20 dB/km over one octave from 600 to 1200 nm and guidance down to 220 nm. This result has been published for publication in the high impact journal *Optica* and is summarized on Fig. 5.

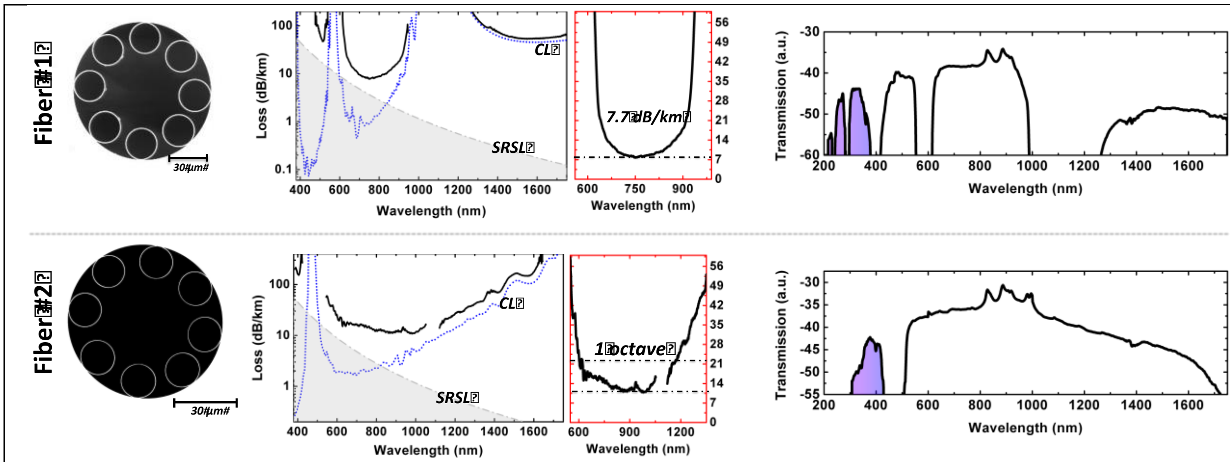

Fig. 5. First column: SEM pictures of fabricated tubular lattice HC-PCFs. Second column: experimental (black curve) and theoretical (blue dotted line) confinement loss (CL) curves. Third column: Measured transmission of a 2 m-long piece with purple-filled curve highlighting UV/DUV guidance.

However, on this kind on design, the PER is still limited to 15 dB. Therefore, in a second step, an optimization of the tubular cladding was performed within the HIPERDIAS project and the modal properties were investigated following the same protocol as mentioned above. The result is summarized on the Fig. 6. By carefully adjusting the cladding of the tubular matrice, a PER value up to 30 dB which corresponds to the current limitation of our characterization set-up. More surprisingly, this PER figure was found almost constant with the fiber length (test done on a piece of 20 m). This unusual behavior seems to be linked with the arrangement of the tubes. Theoretical and experimental works is under investigation for future dissemination and possible integration. Finally, we believed that, this result not expected at the initial plan, represents an added value to the project.

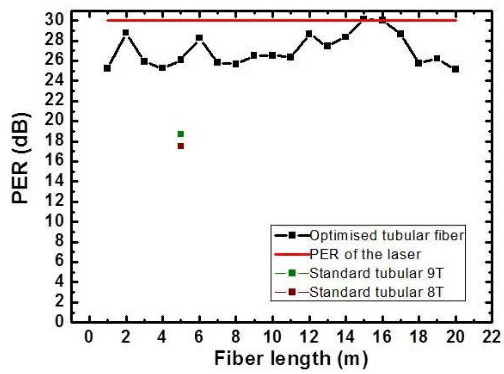

Fig. 6. Linear characterizations of the fiber #2 on the evolution of the PER versus the fiber length.

4 Results and Conclusions

4.1 Summary

In conclusion, several fibers were made and characterized in order to improve PER values at the operating wavelength 1 µm. The target value for the D4.5 deliverable was fixed to be superior to 20 dB. Notice that the current value is around 10-15 dB. For this work, two fiber designs were investigated. One based on the classical Kagome matrice and a second one on a new tubular arrangement. For both cases, fibers were designed and fabricated with performances > 20 dB, which met the requirement of the objectives.

In a more detailed report, the Kagome matrice fiber show a dependence of the PER versus the fiber length as expected, i.e. a linear decrease of 3 dB/5m. The 20 dB of PER can then be preserved up to 10 m associated with a new state-of-the-art attenuation reaching for the first time losses inferior to 10 dB/km at 1 µm (*i.e.* 8.5 dB/km at 1 µm). This fiber was selected and then transferred to GLOphotonics for integration into the BDS. Also, several international communications and papers were published with the acknowledgement of Hiperdias project as required. The second design based on the tubular matrice presents a PER up to 30 dB (the current limitation of our characterization set-up) with a figure almost constant with the fiber length (test done on a piece of 20 m). This unusual behavior seems to be linked with the arrangement of the tubes. Theoretical and experimental works is under investigation for future dissemination and possible integration. This unexpected result presents an added value to the initial plan of the project.

4.2 Dissemination

Thanks to the results achieved in the optimization of hollow-core photonic crystal fibers including loss record, new tubular design and high PER, several publications have been done. A list is available below:

2 Journals:

- MAUREL M., CHAFER M., AMSANPALLY A., ADNAN M., AMRANI F., DEBORD B., VINCETTI, L., GÉRÔME F., BENABID F.: « **Optimized inhibited-coupling Kagome fibers at Yb-Nd:Yag (8.5 dB/km) and Ti:Saph (30 dB/km) ranges** », *Optics Letters*, Vol. 43, Issue 7, pp. 1598-1601, 2018.
- DEBORD B., AMSANPALLY A., CHAFER M., BAZ A., MAUREL, M., BLONDY J-M., HUGONNOT E., SCOL, F., VINCETTI L., GEROME F., BENABID F.: « **Ultra-low transmission loss (7.7 dB/km at 750 nm) inhibited-coupling guiding hollow-core photonic crystal fibers with a single ring of tubular lattice cladding**», *Optica*, Vol. 4, Issue 2, pp. 209-217, 2017.

7 International conferences:

- DEBORD B., AMSANPALLY A., CHAFER M., BAZ A., VINCETTI L., BLONDY J-M., GEROME F., BENABID F.: « **7.7 dB/km losses in inhibited coupling hollow-core photonic crystal fibers** », *CLEO US*, Postdeadline, JTh4C.8, San Jose, California, 5 - 10 June 2016.
- BENABID F.: « **Hollow core photonic crystal fibre: Novel light guidance and myriad of gas-photonic applications** », *XXI Rinem conference*, invited paper, Parma, Italy, 12 - 14 September 2016.

- DEBORD B., MAUREL M., AMSANPALLY A., ADNAN M., BEAUDOU B., BLONDY J.-M., VINCETTI L., GÉRÔME F., BENABID F.: « **Ultra-low loss (8.5 dB/km @ Yb-laser region) inhibited-coupling Kagome HC-PCF for laser beam delivery applications** », *Photonic West,* Paper 10094-58, San Fransisco, California, 28 January - 2 February 2017.
- MAUREL M., GORSE A., BEAUDOU B., LEKIEFS Q., DEBORD B., GÉRÔME F., BENABID F.: « **Kagome fiber based industrial laser beam delivery** », *Photonic West*, Paper 10094-57, San Fransisco, California, 28 January - 2 February 2017.
- DEBORD B., AMSANPALLY A., CHAFER M., BAZ A., MAUREL M., BLONDY J.-M., HUGONNOT E., SCOL F., VINCETTI L., GEROME F., BENABID F.: « **7.7 dB/km transmission loss at 750 nm inhibited-coupling guiding hollow-core photonic crystal fibers** », *CLEO Europe*, CJ-8.4, Munich, Germany, 25 - 29 June 2017.
- DEBORD B., MAUREL M., AMSANPALLY A., ADNAN M., GORSE A., BEAUDOU B., BLONDY J.-M., VINCETTI L., GEROME F., BENABID F.: « **Experimental optimization of curvature and silica thickness core contour of inhibited-coupling Kagome fibers** », *CLEO Europe*, CJ-3.5, Munich, Germany, 25 - 29 June 2017.
- RÖHRER C., GÉRÔME, F., DEBORD, B., ABDOU AHMED, M., GRAF, T., BENABID, F. : « **Analysis of polarization maintaining behavior in inhibited coupling hollow-core photonic crystal fibers (IC-HC-PCF)** », *CLEO Europe*, CI-P.5, Munich, Germany, 25 - 29 June 2017.

2 National workshop/conferences:

- MAUREL, M., DEBORD, B., DUBROUIL A., HUSAKOU, A., GÉRÔME, F., BENABID, F.: « **Giant compression of high energy optical pulses using a commercially available Kagome fiber** », Symposium LAPHIA, Pessac, 22 - 23 septembre, 2016.
- CHAFER M., MAUREL M., AMSANPALLY A., GORSE A., BEAUDOU B., BLONDY, J.-M., DEBORD B., GEROME F., BENABID F.: « **Développements récents de fibres à coeur creux à couplage inhibé** », *37èmes Journées Nationales d'Optique Guidée,* Limoges, 3-6 Juillet 2017.