Hypocycloid-shaped hollow-core photonic crystal fiber Part II: Cladding effect on confinement and bend loss

M. Alharbi,[1,2] T. Bradley,[1,2] B. Debord,[1] C. Fourcade-Dutin,[1] D. Ghosh,[1] L. Vincetti,[3] F. Gérôme,[1] and F. Benabid[1,2,*]

[1]*GPPMM group, Xlim Research Institute, UMR 7252 CNRS, Université de Limoges, Limoges, France*
[2]*Department of Physics, University of Bath, Claverton Down, BA2 7AY, UK*
[3]*Department of Engineering "Enzo Ferrari", University of Modena and Reggio Emilia, I-41125 Modena Italy*
[*]*f.benabid@xlim.fr*

Abstract: We report on numerical and experimental studies on the influence of cladding ring-number on the confinement and bend loss in hypocycloid-shaped Kagome hollow core photonic crystal fiber. The results show that beyond the second ring, the ring number has a minor effect on confinement loss whereas the bend loss is strongly reduced with the ring-number increase. Finally, the results show that the increase in the cladding ring-number improves the modal content of the fiber.

OCIS codes: (060.5295) Photonic crystal fibers; (060.2280) Fiber design and fabrication.

References and links

1. P. Russell, "Photonic Crystal Fibers," Science **299**(5605), 358–362 (2003).
2. F. Couny, F. Benabid, P. J. Roberts, P. S. Light, and M. G. Raymer, "Generation and Photonic Guidance of Multi-Octave Optical-Frequency Combs," Science **318**(5853), 1118–1121 (2007).
3. F. Couny, F. Benabid, and P. S. Light, "Large-pitch kagome-structured hollow-core photonic crystal fiber," Opt. Lett. **31**(24), 3574–3576 (2006).
4. F. Benabid, J. C. Knight, G. Antonopoulos, and P. S. J. Russell, "Stimulated Raman Scattering in Hydrogen-Filled Hollow-Core Photonic Crystal Fiber," Science **298**(5592), 399–402 (2002).
5. Y. Wang, F. Couny, P. J. Roberts, and F. Benabid, "Low loss broadband transmission in optimized core – shaped Kagome Hollow Core PCF," in Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science, Postdeadline Papers (Optical Society of America, 2010), CPDB4.
6. Y. Y. Wang, N. V. Wheeler, F. Couny, P. J. Roberts, and F. Benabid, "Low loss broadband transmission in hypocycloid-core Kagome hollow-core photonic crystal fiber," Opt. Lett. **36**(5), 669–671 (2011).
7. Y. Cheng, Y. Y. Wang, J. L. Auguste, F. Gerome, G. Humbert, J. M. Blondy, and F. Benabid, "Fabrication and Characterization of Ultra-large Core Size (> 100 µm) Kagome Fiber for Laser Power Handling," in Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science, (Optical Society of America, 2011), CTuE1.
8. Y. Y. Wang, X. Peng, M. Alharbi, C. F. Dutin, T. D. Bradley, F. Gérôme, M. Mielke, T. Booth, and F. Benabid, "Design and fabrication of hollow-core photonic crystal fibers for high-power ultrashort pulse transportation and pulse compression," Opt. Lett. **37**(15), 3111–3113 (2012).
9. T. D. Bradley, Y. Wang, M. Alharbi, B. Debord, C. Fourcade-Dutin, B. Beaudou, F. Gerome, and F. Benabid, "Optical Properties of Low Loss (70dB/km) Hypocycloid-Core Kagome Hollow Core Photonic Crystal Fiber for Rb and Cs Based Optical Applications," J. Lightwave Technol. **31**(16), 3052–3055 (2013).
10. B. Debord, M. Alharbi, T. Bradley, C. Fourcade-Dutin, Y. Wang, L. Vincetti, F. Gérôme, and F. Benabid, "Cups curvature effect on confinement loss in hypocycloid-core Kagome HC-PCF," in *CLEO: 2013* (Optical Society of America, 2013), CTu2K.4.
11. B. Debord, M. Alharbi, T. Bradley, C. Fourcade-Dutin, Y. Y. Wang, L. Vincetti, F. Gérôme, and F. Benabid, "Hypocycloid-shaped hollow-core photonic crystal fiber. Part I: Arc curvature effect on confinement loss," Submitted for publication to Optics Express (2013).
12. A. V. V. Nampoothiri, A. M. Jones, C. Fourcade-Dutin, C. Mao, N. Dadashzadeh, B. Baumgart, Y. Y. Wang, M. Alharbi, T. Bradley, N. Campbell, F. Benabid, B. R. Washburn, K. L. Corwin, and W. Rudolph, "Hollow-core Optical Fiber Gas Lasers (HOFGLAS): a review [Invited]," Opt. Mater. Express **2**(7), 948–961 (2012).
13. A. D. Pryamikov, A. S. Biriukov, A. F. Kosolapov, V. G. Plotnichenko, S. L. Semjonov, and E. M. Dianov, "Demonstration of a waveguide regime for a silica hollow--core microstructured optical fiber with a negative curvature of the core boundary in the spectral region > 3.5 µm," Opt. Express **19**(2), 1441–1448 (2011).

14. C. Wu, M. G. Raymer, Y. Y. Wang, and F. Benabid, "Quantum theory of phase correlations in optical frequency combs generated by stimulated Raman scattering," Phys. Rev. B **82**(5), 053834 (2010).
15. L. Vincetti, "Numerical analysis of plastic hollow core microstructured fiber for Terahertz applications," Opt. Fiber Technol. **15**(4), 398–401 (2009).
16. Y. Y. Wang, X. Peng, M. Alharbi, C. F. Dutin, T. D. Bradley, F. Gérôme, M. Mielke, T. Booth, and F. Benabid, "Design and fabrication of hollow-core photonic crystal fibers for high-power ultrashort pulse transportation and pulse compression," Opt. Lett. **37**(15), 3111–3113 (2012).
17. F. Yu, W. J. Wadsworth, and J. C. Knight, "Low loss silica hollow core fibers for 3-4 μm spectral region," Opt. Express **20**(10), 11153–11158 (2012).
18. G. J. Pearce, G. S. Wiederhecker, C. G. Poulton, S. Burger, and P. St J Russell, "Models for guidance in kagome-structured hollow-core photonic crystal fibres," Opt. Express **15**(20), 12680–12685 (2007).
19. S. Février, B. Beaudou, and P. Viale, "Understanding origin of loss in large pitch hollow-core photonic crystal fibers and their design simplification," Opt. Express **18**(5), 5142–5150 (2010).
20. S. Selleri, L. Vincetti, A. Cucinotta, and M. Zoboli, "Complex FEM modal solver of optical waveguides with PML boundary conditions," Opt. Quantum Electron. **33**(4/5), 359–371 (2001).
21. L. Vincetti and V. Setti, "Confinement Loss in Kagome and Tube Lattice Fibers: Comparison and Analysis," J. Lightwave Technol. **30**(10), 1470–1474 (2012).
22. L. Vincetti and V. Setti, "Extra loss due to Fano resonances in inhibited coupling fibers based on a lattice of tubes," Opt. Express **20**(13), 14350–14361 (2012).
23. M. Heiblum and J. Harris, "Analysis of Curved Optical Waveguides by Conformal Transformation," J. Quantum Electron **QE-11**(2), 75–83 (1975).
24. L. Vincetti, M. Foroni, F. Poli, M. Maini, A. Cucinotta, S. Selleri, and M. Zoboli, "Numerical Modeling of S-Band EDFA Based on Distributed Fiber Loss," J. Lightwave Technol. **26**(14), 2168–2174 (2008).
25. Y. Tsuchida, K. Saitoh, and M. Koshiba, "Design of single-moded holey fibers with large-mode-area and low bending losses: the significance of the ring-core region," Opt. Express **15**(4), 1794–1803 (2007).
26. V. Setti, L. Vincetti, and A. Argyros, "Flexible tube lattice fibers for terahertz applications," Opt. Express **21**(3), 3388–3399 (2013).
27. A. F. Kosolapov, A. D. Pryamikov, A. S. Biriukov, V. S. Shiryaev, M. S. Astapovich, G. E. Snopatin, V. G. Plotnichenko, M. F. Churbanov, and E. M. Dianov, "Demonstration of CO2-laser power delivery through chalcogenide-glass fiber with negative-curvature hollow core," Opt. Express **19**(25), 25723–25728 (2011).

1. Introduction

Two families of hollow-core photonic crystal fibers (HC-PCF) have emerged in the previous decade. The first one guides via photonic bandgap (PBG) [1] and the second one guides via inhibited coupling (IC) between the core modes and the cladding modes [2]. Recently, the confinement loss in IC guiding HC-PCF, represented by Kagome-lattice HC-PCF has been reduced from 1 dB/m level [3,4] to a few tens of dB/km with the introduction of hypocycloid-like shaped fiber core [5–9]. The role of the hypocycloid shape in decreasing the confinement loss (CL) was pioneered and explained in 2010 by an enhancement of the inhibited coupling via the dramatic decrease in the spatial overlap between the slow-varying transverse-phase core modes and the fast-varying transverse-phase silica modes of the core-surround [5]. Furthermore, a recent relationship between the negative curvature and the confinement loss in the HC-PCF family was experimentally and theoretically demonstrated [10,11]. In this work, it was shown that the increase of the curvature of the core-surround contour inward arcs (labeled as b in [10,11]) influences the optical properties of the fiber in three ways. Firstly, the transmission loss decreases almost exponentially with the increase of b. Secondly, the spatial optical overlap of the fundamental core mode with the silica core-surround drops by almost two orders of magnitude when the core-contour is changed from circular to hypocycloid with $b>1$. Finally, when b exceeds the value of 0.5 the modal content approaches that of a single-mode, despite the core diameter being as large as 30 μm. This led to development of a $b = 1$ negative curvature Kagome HC-PCF with a record loss at 1064 nm of 17 dB/km [11] and while operating in a single mode fashion.

Conversely, such a low attenuation-level with a hypocycloid-shaped core has been predicted and demonstrated to be achieved even with a single ring [12–15]. For example a 30-40 dB/km loss figure in the IR and Mid-IR domains was achieved in fibers with both 3-ring cladding [16] and in a single ring cladding fibers [12,17]. However, the role of the cladding in light confinement is not fully understood. This is also illustrated in the prior numerical simulations that considered the cladding contribution to light confinement in circular or hexagonal core-shape Kagome HC-PCF, and which led to differences in conclusions [2,6,18,19]. For example in [19], the authors claim that the cladding has an adverse effect on light confinement, whilst in [2,6] the authors show that adding a cladding with three rings shows lower loss than a single anti-resonant ring hollow-fiber. The combination of the lack of a clear understanding in the cladding role in such fibers on one hand and of the recent ultra-low transmission loss reported in IC guiding HC-PCF with hypocycloid core-contour, which put this class of HC-PCF as an excellent waveguide candidate in spectral ranges where the PBG guiding HC-PCF failed to perform, call for a comprehensive investigation on how the cladding affects the optical performance of IC guiding HC-PCF.

Here, we report on experimental and theoretical systematic study of the effect of the cladding ring number on confinement and bend losses in hypocycloid-core shaped Kagome cladding lattice HC-PCF. Firstly, we report on how the transmission loss evolves with the cladding ring number in these fibers. Secondly, we investigate the bend loss dependence on the ring number, and finally we show how the cladding ring number affects the modal content and the physical mechanism underlying the bend loss.

2. Transmission loss evolution with cladding ring number

Figure 1(a) shows computed confinement loss (CL) spectra of Kagome cladding-lattice HC-PCF with different cladding ring-numbers. The fibers are taken to have a hypocycloid-shape core with a constant *b* curvature parameter of 0.3 (see [10,11] for the definition of *b*), and a constant inner diameter of 32.5 μm. The thickness of the silica web forming the cladding is set to 450 nm and the pitch equal to 20 μm. The computation was carried out using a commercial software (COMSOL Multiphysics) based program on the finite-element-method (FEM) with anisotropic perfectly matched layer [20], and which was successfully applied to the analysis of loss and dispersion properties of several IC HC-PCFs [21]. The spectral range of the computed CL was limited to the first transmission band (i.e λ>900 nm) and spans from 900 nm to 2.4 μm. It is noteworthy that for a single ring structure the CL obtained with b = 0.3 negative-curvature core HC-PCF is lower than its circular single-ring counterpart (i.e. an anti-resonant ring) [16]. Indeed, here the loss in a single ring reaches a minimum of ~50 dB/km in the 1200-1400 nm spectral range, which is almost three orders of magnitude lower than that of a circular ring with comparable core-size and silica thickness [6]. This loss figure is in qualitative agreement with the ones experimentally observed in the fabricated single-ring hypocycloid-core HC-PCF [9,12], and which was explained by the decrease of CL with increasing *b* [9]. Furthermore, the results show two distinct trends in the confinement loss evolution with the cladding ring number. Firstly, there is little overall variation in the confinement loss by increasing the cladding ring-number from two to four rings. This trend is similar to the one found with circular or hexagonal core Kagome HC-PCF [18]. For fibers with a ring-number of 2 or larger, the average base-line of the loss is about 20 dB/km in 1200nm-1400nm spectral range. Secondly, the CL reduces significantly when the cladding ring number is increased from 1 (i.e. single-ring cladding fiber) to 2 (i.e. 2-ring fiber), with the average base-line loss figure dropping from 60 dB/km to 20 dB/km. In addition to these trends, the modulation depth of the peaks and dips that structure the CL spectrum is significantly increased with the cladding ring-number. As a matter of fact some dips exhibit a CL of less than 2 dB/km, whilst for some peaks, the CL increases above 100 dB/km. The origin and the dynamics of these peaks and dips are beyond the scope of the present paper. Furthermore, the origin of such oscillations were attributed to the structural cladding features [2], and in some cases they exhibit behavior akin to Fano resonances [22].

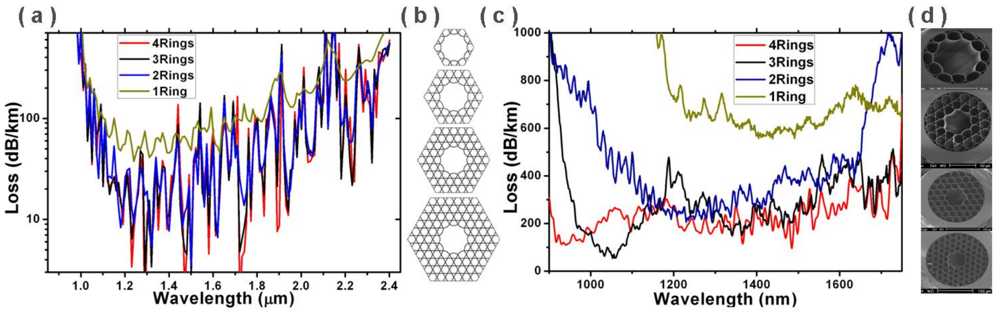

Fig. 1. (a) Simulated loss spectra for four different cladding ring numbers; (b) Structure fiber profile, (c) Measured loss spectra for four fabricated hypocycloid-core Kagome HC-PCF (one, two, three and four cladding rings), and (d) corresponding SEM images.

Table 1. Physical parameters of the fabricated hypocycloid-shaped core HC-PCF.

	b-curvature parameter	*Pitch (μm)*	*Silica thickness (nm)*	*Core inner diameter (μm)*	*Representative loss (@ 1500 nm) (dB/km)*
1-ring HC-PCF	0.45	19.5	480	58	610
2-ring HC-PCF	0.34	20.3	405	48	373
3-ring HC-PCF	0.52	19.2	450	55	251
4-ring HC-PCF	0.45	18.8	440	47	171

The overall trends of the CL spectra are qualitatively corroborated experimentally. Figure 1(c) shows the measured loss spectra for four fabricated fibers with a ring-number varying from one to four. The fibers whose scanning electron micrograph are shown in Fig. 1(d), were fabricated with similar pitch (~20 μm) to within a relative difference of less than 8%, and strut thickness (~450 nm), core diameter (~52 μm) and hypocycloid-core shape (*b*~0.45). Care was taken so the curvature of the hypocycloid-core arcs is kept the same for all the fibers and close to the computed one. Table 1 lists the physical parameters of each drawn fiber along with a representative loss figure measured at 1500 nm. The loss spectra of the fibers were obtained by a cut-back measurement on ~50 m long fiber. The curves of Fig. 1(c) show that the four, three and two ring fibers present comparable loss-figures; in the range of ~150 dB/km and 300 dB/km, which is in good qualitative agreement with the numerical results. Similarly, 600 dB/km loss level measured for the single-ring HC-PCF confirms the numerical results that the single-ring fiber contrasts with the larger cladding ring-number fibers by a relatively higher transmission loss [6].

3. Bend loss and modal content evolution with cladding ring number

A further characterization of these different cladding ring-number fibers is made by measuring the macro bending behavior. Figure 2 shows the bend-loss spectra for different bend radii (5 cm, 4 cm, 3 cm and 2 cm) measured with the four fiber designs. The bend was carried out by coiling the fiber four turns for each measurement run.

#197710 - $15.00 USD Received 16 Sep 2013; revised 2 Nov 2013; accepted 5 Nov 2013; published 13 Nov 2013

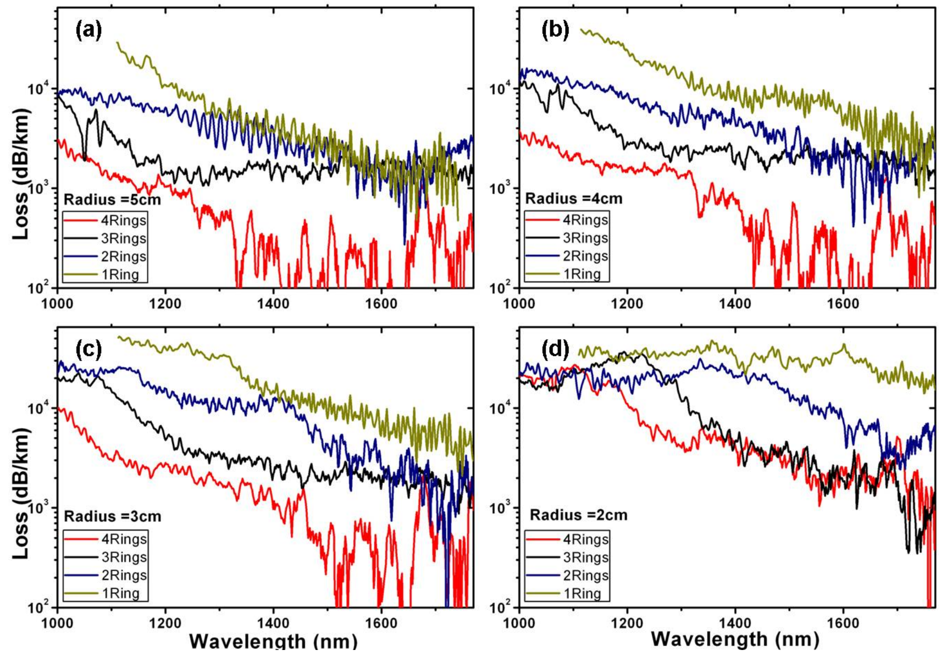

Fig. 2. Bending loss spectrum measured for four hypocycloid-core Kagome HC-PCF (with one, two, three and four cladding rings) at different bending radii (a) 5 cm, (b) 4 cm, (c) 3 cm and (d) 2 cm.

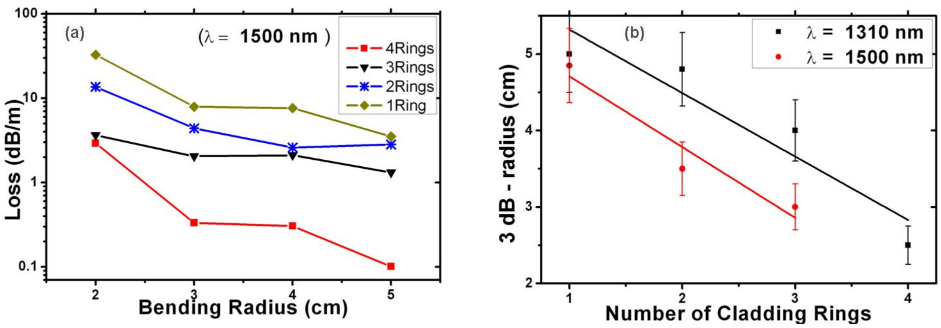

Fig. 3. (a) Zoom-in of measured bending loss evolution at the particular wavelength 1500 nm. (b) Critical radius versus number of cladding rings at 1310 nm and 1500 nm.

For a bend radius of 5 cm, the loss spectra in 1500nm-1750nm spectral range are comparable for the fibers with cladding ring number up to 3, all exhibiting a bend loss figure of ~2 dB/m. However, as the wavelength gets shorter towards the high-frequency transmission edge of the fundamental band, the loss in the single-ring fiber increases at a much higher rate than the rest of the fibers, indicating that the cladding layers act as a barrier to bend-induced mode-coupling between the core modes and radiation modes. This corroborated with the 4-ring fiber which bend loss figure reaches ~0.1 dB/m level in 1500nm-1750nm spectral range. Furthermore, for radii shorter than 5 cm, the spectra clearly show that the bending loss decreases with the cladding ring number. For example in the case with a bend radius of 3 cm, the spectra show that fibers with more than two layers exhibit a bend loss which is lower than the single ring design by more than one order of magnitude. Figure 3(a) shows the evolution of the bend loss at a representative wavelength from the center of the transmission band (chosen to be 1500 nm) with the bend radius. The results show that when the fibers are bent with a bend radius of 5 cm, the bend loss is as low as 0.1 dB/m for a 4-ring

#197710 - $15.00 USD Received 16 Sep 2013; revised 2 Nov 2013; accepted 5 Nov 2013; published 13 Nov 2013

HC-PCF, whilst it is ~50 dB/m for a single-ring fiber. Figure 3(b) shows the evolution of the deduced 3-dB radius (i.e. the bend radius at which the transmission is attenuated by 3dB upon a one full turn coil) at 1500 nm and at another wavelength from a spectral range that is closer to the short-wavelength transmission (chosen to be 1300 nm). For both wavelengths, the 3dB-radius is decreased by 1 cm per one ring addition to the cladding.

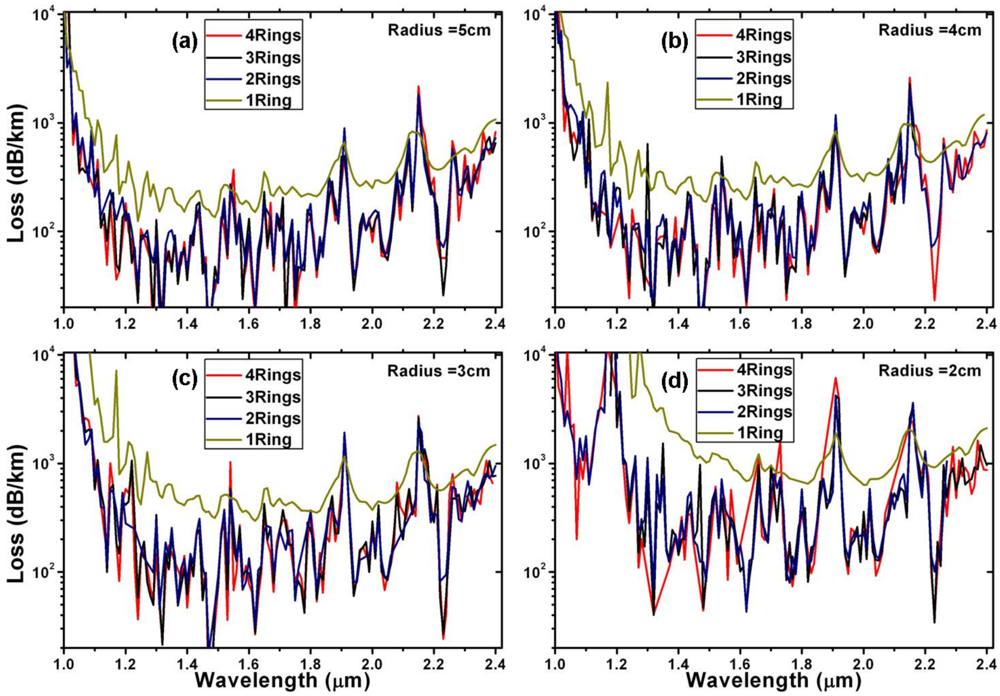

Fig. 4. Calculated bend loss spectra for four fibers with different cladding ring numbers (1, 2, 3 and 4 rings) at different bending radii (5, 4, 3, and 2 cm).

The trends of the above experimental results are qualitatively corroborated numerically. Figure 4 shows the computed bend loss spectra for four fibers with different cladding ring-numbers, varying from one to four rings, at different bending radii. The numerical results were obtained through joint use of the FEM modal solver and of the conformal mapping technique [23], which allows the replacement of the bent fiber with refractive index $n(x,y)$ with a straight one having an equivalent index profile $n_{eq}(x,y) = n(x,y)e^{\xi/R_b}$ where $\xi = x,y$ is the transverse bending direction and R_b the bending radius. The combined use of the FEM and conformal mapping have already been successfully used to analyze bending loss in solid core step index fibers [24], microstructured fibers [25], and HC tube lattice fibers [26]. Similar to the experimental results, these results show that passing from one ring to two rings the confinement loss is significantly reduced, whereas a further increase in the number of cladding rings has a minor effect on the bend loss. This is confirmed by Fig. 5, where the confinement loss versus the bend radius for two wavelengths (λ = 1.5 μm and λ = 1.55 μm) for different ring numbers are plotted. The discrepancy between the experimental data and the numerical data are likely due to micro-imperfections in the fabricated fibers and mechanical deformations which are not taken into account in the numerical model. Furthermore, the experimental results show stronger insensitivity to bend when the cladding ring-number is increased, indicating further the limit of our numerical model.

Furthermore, the evolution of the transmission loss with bend radius doesn't show a uniform decrease but exhibits a resonant loss for a bend radius at 1.16 cm, and an oscillatory behavior shows a structured curve in the radial range of 2-8 cm. The loss resonant peaks are

#197710 - $15.00 USD Received 16 Sep 2013; revised 2 Nov 2013; accepted 5 Nov 2013; published 13 Nov 2013

explained by the coupling between the fiber core HE_{11} mode and that of cladding hole (see Figs. 5(c)-5(f)) [9,26]. The origin of the oscillatory behaviour near 2-8 cm radial range is more complicated to trace back. We believe that it is due to a bending dependence of the Fano resonances [27].

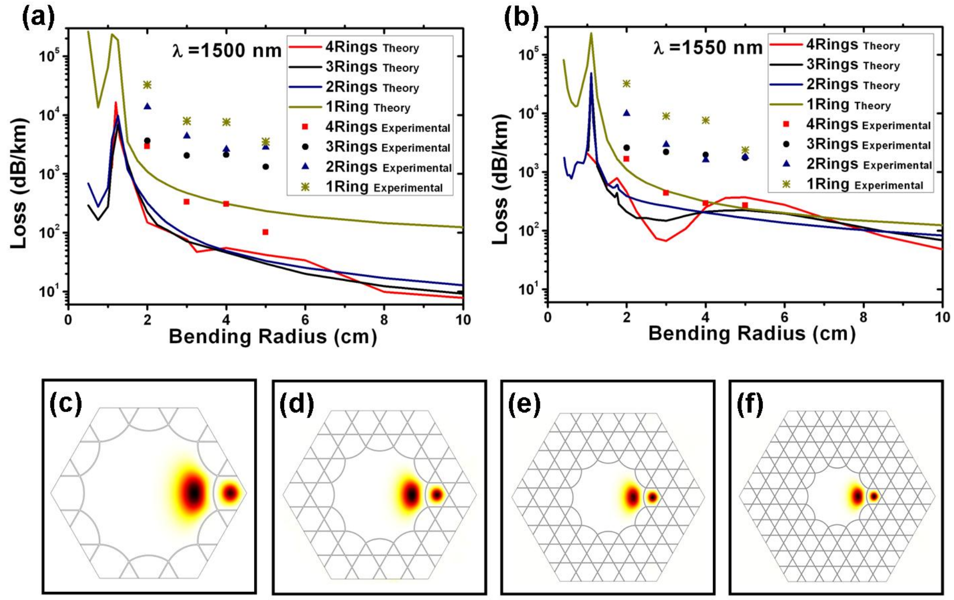

Fig. 5. Confinement loss versus the bend radius for two wavelengths (a) λ=1.5µm and (b) λ=1.55µm for different ring numbers. (c) - (f) Simulated fundamental mode profile at bend radius 1.1 cm at λ = 1.5µm.

Finally, we observed that the increase of the cladding ring-number affects the modal content of the fiber. Figure (6) shows a set of reconstructed near field images taken by a CCD camera of the light output for the different 5m-long piece of fibers considered here and for different bend radii. A strong multimode guidance is found for the 1st ring design which contrasts with the other configurations. The coupling of the HE_{11} mode with the air-cladding modes is here playing a key role as it is demonstrated in Figs. 5(c)-5(f). Indeed, the loss level at the coupling point is strongly dependent of the distance between the first layer of the microstructure and the outer silica cladding jacket. The results clearly show that an increase in cladding ring-number improves the modal content and lessens the fiber sensitivity to bend. This study is an original way to confirm the main role played by the inhibiting coupling mechanism in such microstructured fibers.

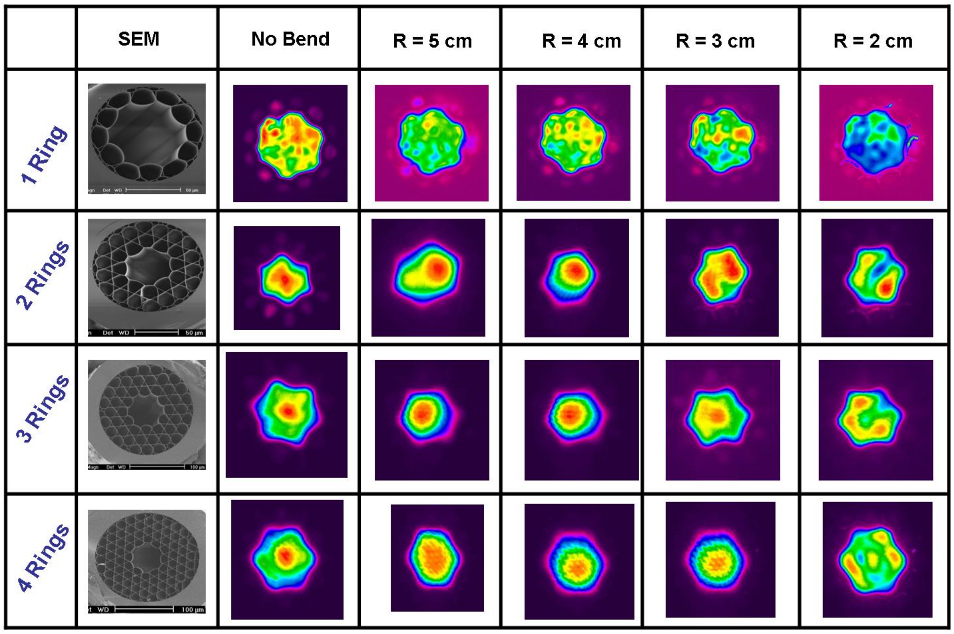

Fig. 6. Near filed mode profile for four fibers (1, 2, 3, and 4 ring) at no bend and different bend radii (5, 4, 3, and 2 cm).

Discussion and conclusion

We reported on an experimental and numerical study on the cladding effect in hypocycloid-core Kagome HC-PCF. The results showed that significant decrease in confinement loss is observed only when the ring-number is increased from 1 to 2. Additional rings to a 2-ring fiber have minor effect upon confinement loss. However, increasing the ring-cladding number resulted in a strong reduction in the measured bend loss, and an improved modal content is observed with the increase in number of cladding rings.

The trend observed in the evolution of CL and bend loss with cladding ring-number increase, and the presence of several resonant peaks and dips in the CL spectra reveal a more intricate dynamics in the light confinement and call for further work to elucidate whether the CL is enhanced via coherent effect (i.e. Bragg interference) or whether the cladding acts as an index layer whose dimension and effective index are the physical parameters to control for further improving the CL. Furthermore, the resonant peaks and their coupling dynamics are also worthy of further exploration.

Acknowledgment

This research is funded by Agence Nationale de la Recherche through grants PHOTOSYNTH and ∑_LIM Labex Chaire. The authors thank the PLATINOM platform for technical assistance in the fiber fabrication.