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Five-ring hollow-core photonic crystal fiber with 1.8 dB/km loss

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A 19-cell hollow-core photonic crystal fiber reaching 1.8 ± 0.5 dB/km loss at 1530 nm is reported. Despite expanded corner holes in the first ring adjacent to the core, and only five cladding rings, the minimum loss is close to the previously published record of 1.7 dB/km at a comparable wavelength, achieved in a fiber with seven cladding rings. Since each additional cladding ring requires a significant increase in fabrication time and complexity, it is highly desirable to use as few as possible while still achieving low loss. Modeling results confirm that further reducing cladding deformations would yield only a small decrease in loss. This demonstrates that loss comparable to the previously demonstrated lowest-loss bandgap fibers can be achieved with fiber structures that are significantly simpler and faster to fabricate.

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Hollow-core photonic crystal fibers (HC-PCFs) guiding by the photonic bandgap effect have long held promise to reach lower propagation losses than standard silica solid-core fibers, which currently hold the low-loss record of ~0.18 dB/km at 1550 nm. Loss in hollow-core fibers is thought ultimately to be limited by frozen-in surface capillary waves causing scattering from surface roughness on the glass–air interfaces [1]. The currently lowest published losses in HC-PCFs are 1.2 dB/km at 1620 nm [1] and 1.7 dB/km at 1565 nm [2]. These fibers had seven rings of air holes in the cladding to reduce confinement loss, which as a rule of thumb can be expected to decrease by roughly an order of magnitude for each added ring [3]. Furthermore, the first cladding ring surrounding the core was made so that it resembles the rest of the cladding as much as possible, as this was considered the ideal case [1]. All the fibers mentioned had a hollow core formed by omitting 19 capillaries from the center of the periodic structure. For a fiber structured to have minimum loss at λ_c and where the loss is dominated by surface scattering, the minimum achievable loss scales as $1/\lambda_c^3$. Therefore, much recent work has been devoted to lowering the loss by structuring the fiber to guide at wavelengths longer than the standard telecom values, with an optimum for lowest loss expected at $\lambda_c \sim 2\ \mu\text{m}$ [1,4]. There has, however, not been much focus on reproducing the 2005 record-low loss, or achieving similar loss with simpler cladding structures.

Recently, we fabricated a series of 19-cell HC-PCFs, achieving a minimum loss of 1.8 ± 0.5 dB/km at 1530 nm despite using only five rings of air holes in the cladding [5]. This result was achieved even though the innermost cladding ring had six corner holes clearly enlarged with respect to the remaining cladding (see inset of Fig. 1). Numerical simulations show that it is the high air-filling fraction, i.e., small struts and comparably large junctions, that allows low loss to be achieved even when the cladding is deformed. From a physical viewpoint, this result is surprising because it indicates that increasing the air-filling fraction in the cladding structure has a stronger effect on the total loss than decreasing the confinement loss by adding rings and making a perfect cladding structure, at least for loss levels down to ~2 dB/km. The result is also technically interesting because it proves that reasonably low-loss HC-PCFs can be fabricated with significantly less time and complexity. For example, in a 19-cell HC-PCF, 102 fewer capillaries are needed for five cladding rings than for seven, not counting the small outer support capillaries added to make the final stack more circular than hexagonal, so that it fits better into the sleeving tube. We also note that a 19-cell HC-PCF with six cladding rings and 3.5 dB/km loss at 1500 nm was recently reported, the focus being on reducing coupling to surface modes using a thin surrounding core wall so as to obtain low loss over a wider bandwidth [6]. Interestingly, in this work, the inner cladding ring has enlarged corner holes, though the Letter does not discuss this.

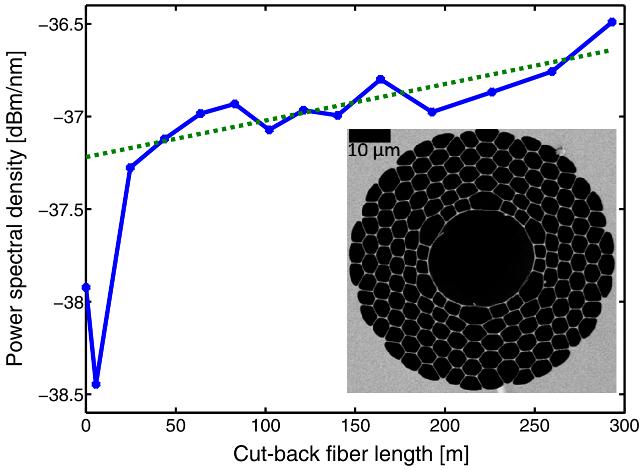

Fig. 1. Cut-back data points (blue points) at a wavelength of 1530 nm for PCF 1. The dotted green line was found using *robust* linear regression, and has a slope of 1.8 dB/km with a standard error of ±0.5 dB/km. Note that robust regression is inherently less sensitive than least-squares regression to outliers such as the first two data points. The initial fiber length was 505 m. Inset: scanning electron micrograph of PCF 1.

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Table 1. Structural and Loss Parameters of the Fibers Investigated Here (1–5), and the Fiber (6*) from [2]

PCF Number	Core Diameter D [μm]	Pitch Λ [μm]	Core-Diameter-to-Pitch Ratio D/Λ	Cladding Layers	Minimum Loss [dB/km]	Minimum Loss Wavelength [nm]	Air-filling Fraction
1	23	4.2	5.5	5	1.8 ± 0.5	1530	92%
2	24	4.4	5.5	5	3 ± 2	1580	92%
3	23	4.3	5.3	6	44 ± 6	1576	92%
4	31	5.1	6.1	6	111 ± 7	1613	94%
5	22	4.4	5.0	6	228 ± 12	1239	95%
6*	20	3.9	5.1	7	1.7	1565	

Here we present more details of the low-loss 19-cell HC-PCF structure, together with attenuation measurements and numerical simulations aimed at elucidating the effects of cladding deformations. The influence of morphology (pitch, core diameter, etc.) on the guidance properties of PCFs with undistorted cladding structures is well understood [7]. In practice, however, various deformations in the cladding can, e.g., shift the bandgap in a nontrivial way, as can be seen by comparing the structural parameters and loss for PCFs 1–5 in Table 1. We therefore also compare loss simulations between fiber structures with ideal and deformed claddings.

The fibers were fabricated using a two-step stack-and-draw technique. Capillaries were stacked into a primary preform, sleeved by a jacket tube, drawn into a cane, and sleeved again by a second jacket tube before finally being drawn to fiber. The fibers presented here had either five or six complete hexagonal cladding rings of hollow channels (the structural parameters are listed in Table 1).

As can be seen in the inset of Figs. 1 and 2, the first cladding ring typically has six significantly expanded air holes. The expansion of these corner holes could be controlled through balancing the pressures applied to the core and cladding during fiber drawing. One method of quantifying how much the corner holes are expanded is to consider the core-diameter-to-pitch ratio D/Λ, which by simple geometrical considerations equals 5 for a 19-cell HC-PCF with an undistorted cladding and a perfectly hexagonal core. This does not, however, provide a perfect measure of deformation because the cladding and/or core may still be deformed in such a way that the ratio is close to 5 (PCF 5 is an example of this).

The loss was measured by launching light from a broadband supercontinuum light source into the test HC-PCF, and coupling the output into a 30 m long single-mode fiber connected to an optical spectrum analyzer (OSA) (the single-mode fiber acts as a spatial filter, eliminating spurious signals from higher-order modes potentially present in the test fiber). The transmission spectrum was saved before cutting off a length of fiber and repeating the measurement. Since we considered a single cut-back of no more than a few hundred meters to be insufficient for evaluating losses of order 1 dB/km or lower, we made several cut-backs on the same fiber, performing *robust* linear regression for each series of data points associated with a narrow wavelength window (1 nm resolution on the OSA). This allowed us to determine the loss as the slope of the linear fit and calculate the fitting error to estimate the measurement uncertainty. An example of a series of data points and a linear fit is shown in Fig. 1, and the results of the loss measurements are plotted in Fig. 3 and summarized in Table 1.

The lowest loss previously reported in a 19-cell HC-PCF at 1565 nm is 1.7 dB/km, in a fiber (PCF 6* in the table) with seven cladding rings and nonexpanded corner holes in the first cladding ring, i.e., $D \approx 5\Lambda$ [2]. It is therefore remarkable that the lowest loss achieved in the current work (PCF 1) is 1.8 ± 0.5 dB/km, even though the fiber has only five cladding rings and enlarged corner holes due to an overexpanded core ($D > 5\Lambda$). It is interesting to ask whether the loss could have been even lower if the structure had been less deformed. To answer

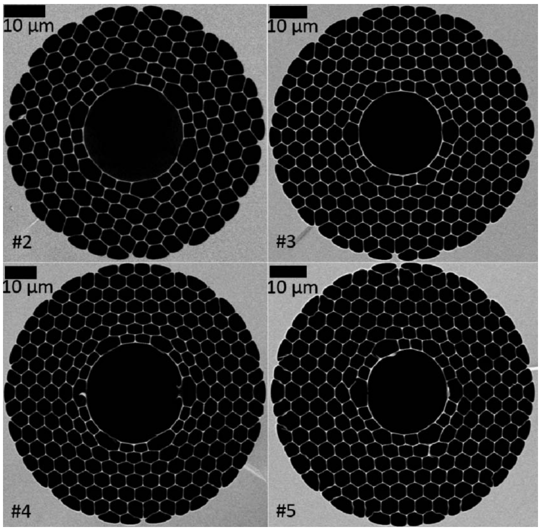

Fig. 2. Scanning electron micrographs of PCFs 2–5. Note that some defects (broken or deformed glass walls) are caused by cleaving.

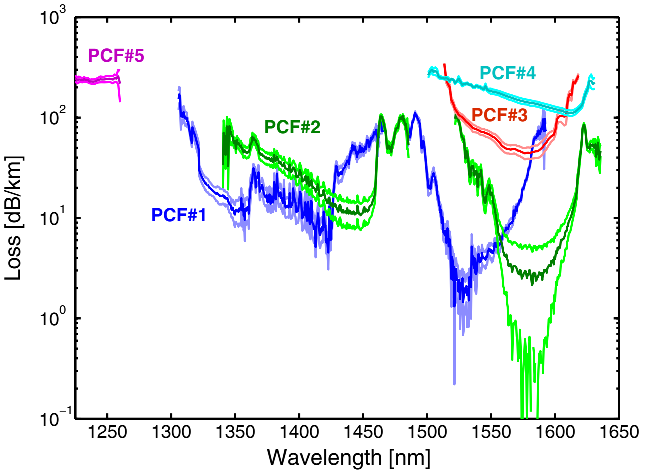

Fig. 3. Loss measured from cut-back measurements of PCFs 1–5. The lighter colored lines above and below each darker line indicate the estimated measurement error range.

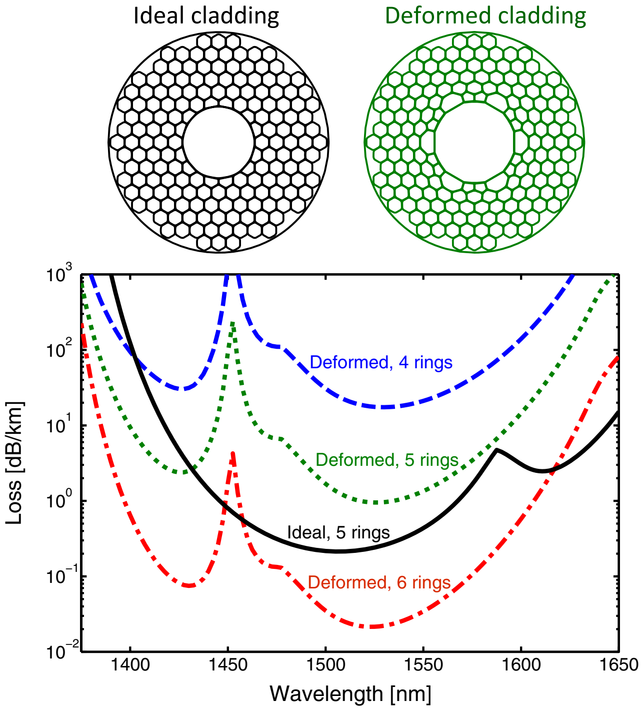

Fig. 4. Top: two of the five-ring structures used for the loss calculations shown below. The glass wall thicknesses are exaggerated for visual clarity. Bottom: calculated loss for the ideal structure (black, solid), and deformed structure with four (blue, dashed), five (green, dotted), and six (red, dash-dotted) cladding rings. The structural parameters are chosen to closely match those of PCF 1: pitch is 4.2 μm, and cladding strut thickness is 110 nm. Core surround thickness in ideal fiber is 110 nm; in the deformed fiber it is 40 nm at the corner holes and 170 nm elsewhere, and the junction radius is 210 nm, while the corner radii may vary.

this, we carried out finite element modeling of fibers with both ideal and deformed cladding structures. Cladding deformations were introduced by starting with an ideal structure and only slightly adjusting the radii of the glass blobs and the thickness of the struts after changing the spatial positions of the glass junctions in the cladding.

The results in Fig. 4 show that for the deformed cladding structure the wavelength range of the experimentally observed bandgap and the magnitude of the minimum loss are both reasonably well reproduced; the calculated minimum loss for the deformed five-ring structure is 1.0 dB/km at 1525 nm. The increase in loss resulting from deforming the cladding structure, so that it is more similar to the experimentally realized PCF 1, is, however, not as severe as one might have expected. The undeformed cladding structure results in 0.2 dB/km loss at 1510 nm—only 0.8 dB/km lower loss than in the deformed structure. It is also seen that removing one cladding ring increases the loss by a factor of ~20, whereas adding one cladding layer would reduce the loss by a factor of ~50, so each added cladding layer reduces the loss by roughly an order of magnitude, as expected [3]. Of course other loss mechanisms, such as scattering at surface capillary waves, may start to dominate when the number of cladding rings is increased from five to six [1]. For the PCF 1 with five cladding rings, the measured minimum loss is 1.8 ± 0.5 dB/km and the simulated minimum loss is 1.0 dB/km, so it cannot be said with certainty whether the loss is dominated by confinement loss or surface scattering, since the second is not included in the simulations. On the other hand, it should be noted that no HC-PCFs have yet been reported with losses lower than ~1 dB/km (0.8 dB/km was achieved in work unpublished by BlazePhotonics [8]) even when more cladding rings are added.

Comparing PCF 1 with the previously published PCF 6*, we note that PCF 1 has a much broader bandgap (~250 nm) than PCF 6* (~120 nm), both measured as the wavelength separation between the outermost 25 dB/km edges of the loss spectrum, neglecting the losses due to surface modes in the middle of the bandgap. Furthermore, the pitch of PCF 1 is bigger than that of PCF 6*, but the bandgap center of PCF 1 is downshifted ~120 nm compared to that of PCF 6*. Considering that, in general, the bandgap shifts to shorter wavelengths when the pitch is decreased and/or the air-filling fraction is increased [7], it is clear that PCF 1 must have a significantly higher air-filling fraction than PCF 6*. This could explain why PCF 1 has almost the same loss as PCF 6*, despite visible cladding deformations and only five cladding rings instead of seven. As seen in Table 1, achieving an even higher air-filling fraction than in PCF 1 is experimentally possible, but avoiding structural deformations becomes more challenging.

In conclusion, we have demonstrated a hollow-core photonic bandgap fiber with minimum loss similar to the current low-loss record, and a guidance band more than twice as wide, despite having two less rings of air holes in the cladding, and deformed cladding holes. The simpler cladding structure makes it faster to stack and draw the fiber preform, while the high air-filling fraction brings the loss down to a level comparable to the previous lowest-loss fibers with additional cladding rings.

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References

1. P. J. Roberts, F. Couny, H. Sabert, B. J. Mangan, D. P. Williams, L. Farr, M. W. Mason, A. Tomlinson, T. A. Birks, J. C. Knight, and P. St. J. Russell, Opt. Express **13**, 236 (2005).
2. B. J. Mangan, L. Farr, A. Langford, P. J. Roberts, D. P. Williams, F. Couny, M. Lawman, M. Mason, S. Coupland, R. Flea, H. Sabert, T. A. Birks, J. C. Knight, and P. St. J. Russell, in *Optical Fiber Communication Conference* (Optical Society of America, 2004), paper PDP24.
3. J. Pomplun, L. Zschiedrich, R. Klose, F. Schmidt, and S. Burger, Phys. Status Solidi A **204**, 3822 (2007).
4. M. N. Petrovich, N. K. Baddela, N. V. Wheeler, E. Numkam, R. Slavík, D. R. Gray, J. R. Hayes, J. P. Wooler, F. Poletti, and D. J. Richardson, in *Optical Fiber Communication Conference* (Optical Society of America, 2013), paper OTh1J.3.
5. M. H. Frosz, J. Nold, T. Weiss, A. Stefani, S. Rammler, F. Babic, and P. St. J. Russell, in *Frontiers in Optics Postdeadline Session III* (Optical Society of America, 2012), paper FW6C.5.
6. F. Poletti, N. V. Wheeler, M. N. Petrovich, N. Baddela, E. N. Fokoua, J. R. Hayes, D. R. Gray, Z. Li, R. Slavik, and D. J. Richardson, Nat. Photonics **7**, 279 (2013).
7. F. Benabid and P. J. Roberts, J. Mod. Opt. **58**, 87 (2011).
8. H. Sabert, Taylor & Francis Ltd., 4 Park Square, Milton Park, Abingdon OX14 4RN, Oxon, England (personal communication, 2011).