

Octagonal Large-Mode-Area Leakage Channel Fiber with Reduced Bending Loss

Lorenzo ROSA^{1*}, Kunimasa SAITOH¹, Masanori KOSHIBA¹, Federica POLI², Annamaria CUCINOTTA², Stefano SELLERI², Luca VINCETTI³, Mrinmay PAL⁴, Mukul PAUL⁴, Debashri GHOSH⁴, and Shyamal BHADRA⁴

¹Graduate School of Information Science and Technology, Hokkaido University, Sapporo 060-0814, Japan

²Information Engineering Department, University of Parma, I-43124 Parma, Italy

³Information Engineering Department, University of Modena e Reggio Emilia, I-41100 Modena, Italy

⁴Fibre Optics Division, Central Glass & Ceramic Research Institute, Kolkata - 700032, India

*lrosa@ieee.org

Abstract: We investigate a novel design for high-power large-mode-area leakage channel fibers (LCFs) with a single octagonal dual-diameter air-hole ring encircling a nine-cell pure-silica core, having a tenfold differential mode loss and increased resistance to bending.

©2010 Optical Society of America

OCIS codes: (060.2280) Fiber design and fabrication; (060.2400) Fiber properties; (060.3510) Lasers, fiber; (060.5295) Photonic crystal fibers.

1. Introduction

Development and enhancement of fiber lasers and amplifiers with high power ranging from tens of watts to many kilowatts [1-3] have been driven by a strong industrial demand and fostered significant progresses in the development of Large-Mode-Area (LMA) single-mode optical fibers, aiming to solve the main problem of high-power Yb-doped fiber lasers, that is the suppression of nonlinear effects, such as self-phase modulation, Raman scattering, and Brillouin scattering. This can be partially overcome by deploying LMA fibers with reduced Numerical Aperture (NA) to suppress the multi-mode behavior, though this leads to a significant worsening of the macro-bending loss characteristics. The achievement of a suitable trade-off requires the employment of specially-designed fibers with high NA, where the Higher-Order Modes (HOMs) propagation can be impaired, obtaining an effectively single-mode operation. In standard fibers a maximum core diameter limit of 30 μm is fixed by the onset of multi-mode behavior [4], so it is useful to consider all-silica Photonic Crystal Fibers (PCFs), which permit very broad-band single-mode LMA operation. However, a very similar limit on core diameter has been discovered in PCFs, due to the increase of bending losses [5].

Recently, Dong *et al.* have proposed to address these issues by the adoption of LCFs [6-10], whose cladding is formed by a single air-hole ring. While inherently lossy, as only leaky guided modes can propagate, these fibers offer enough degrees of freedom to independently engineer the Confinement Loss (CL) of the different modes by tuning the air-hole pitch and diameters. In particular, the HOM CL can be greatly increased, while the Fundamental Mode (FM) CL can be kept low enough to allow almost unhindered propagation. Designs have been proposed which make use of both air-holes and down-doped silica rods as elements of the ring, where the doped-rod method has the advantage of easier construction and splicing with standard single-mode fibers, while the air-hole method has the advantage of a greater confinement due to the higher index contrast. Also, a quality criterion has been considered for defining an LCF as effectively single-mode, that of having the FM CL, CL_{fund} , equal or lower than 0.1 dB/m, while the LP₁₁-like HOM CL, $CL_{2\text{nd}}$, should be equal or larger than 1 dB/m [9]. However, this does not guarantee bending performance, as a recently-reported all-glass LCF design featuring a one-cell pure-silica core encircled by six down-doped silica rods, while fulfilling the aforementioned criterion, suffers too high bending losses to be suitable for the intended applications [10].

In this work we propose and numerically investigate a novel dual-diameter design for single-mode air-hole LMA LCFs with reduced bending loss, building on an approach already successfully employed with LCFs characterized by a single air-hole ring [11], where the solid core region size is increased by adding multiple pure-silica rods, and by increasing the polygonal order of the ring shape from hexagonal to octagonal. This approach trades off higher construction complexity for the ability to increase confinement by reducing the gap between the air-holes [12]. The simulations have been performed with a full-vector FEM (V-FEM) [13,14] solver using perfectly matched layers. From the V-FEM modal analysis we calculate the effective area, A_{eff} , and the loss variations as a function of the rod spacing, or pitch, Λ and the normalized rod diameter d/Λ . We show that the proposed air-hole LMA-LCF with a nine-cell core and two different sizes of air-holes achieves sufficient differential mode loss and lower bending loss,

as compared with the constant-diameter polygonal air-hole design, at the typical operating wavelength of 1064 nm for high-power Yb-doped fiber devices. This proves the new design criterion to be highly successful in reducing bending loss, while preserving the effectively single-mode condition.

2. Leakage Channel Fiber Design and Numerical Results

The octagonal LCF is designed by repeating an isosceles unit triangle with a vertex angle of 45° around the solid core, resulting in a hole-to-hole spacing inside the same ring different from the one between adjacent rings, which is assumed as the pitch Λ [12]. This originates an air-hole ring bearing an octagonal shape and the LCF studied, shown in Fig. 1(a), is named LCF9o, according to the number of unit cells contained in the core.

Fig. 2(a) shows the contour plots of the effective area (color map) of the FM at 1064 nm, as a function of Λ and d/Λ for the LCF9o, where the solid white curve depicts the $A_{\text{eff}} = 1400 \mu\text{m}^2$ condition, while the dashed and solid black curves correspond to $CL_{\text{fund}} = 0.1 \text{ dB/m}$ and to $CL_{2\text{nd}} = 1 \text{ dB/m}$ at 1064 nm, respectively. This last value is enough to guarantee the suppression of HOM propagation in practical devices, while the maximum CL_{fund} limit of 0.1 dB/m ensures negligible transmission loss. We can see that, as the solid curve lies below the dashed one, the LCF9o designed with equal-sized holes cannot fulfill both constraints at the same time. In particular, when $CL_{2\text{nd}} = 1 \text{ dB/m}$ for $\Lambda = 17.03 \mu\text{m}$ and $d/\Lambda = 0.377$, we have $CL_{\text{fund}} = 0.22 \text{ dB/m}$, which is considered too high to achieve effectively single-mode operation.

The LCF9o fiber can fulfil this condition if we employ two different hole diameters, which increases the HOM leakage loss while keeping the FM one low enough. Fig. 1(b) shows the cross-section of a LCF9o fiber formed by sixteen air-holes with diameters d_1 and d_2 ($d_1 > d_2$), called LCF9o-2. In Fig. 2(b), we show the FM effective area contour plots at 1064 nm as a function of Λ and d_2/Λ for the LCF9o-2, where we have set $d_1/\Lambda = 0.7$ to decrease the bending loss. For symmetry reasons, the effective index of the LCF9o-2 FM depends on polarization, but, due to the large core size, the birefringence is expected to be negligible at 1064 nm. For the LCF9o-2, the dashed curve is slightly above the solid one. However, at the intersection point where $CL_{2\text{nd}} = 1 \text{ dB/m}$ for $A_{\text{eff}} = 1400 \mu\text{m}^2$, we obtain $CL_{\text{fund}} = 0.11 \text{ dB/m}$, thus for all practical purposes the fiber can achieve effectively single-mode operation. The corresponding geometrical parameters are $\Lambda = 17.68 \mu\text{m}$, $d_1/\Lambda = 0.7$, and $d_2/\Lambda = 0.371$. This compares favorably with the hexagonal air-hole ring designs [11], where the effectively single-mode condition was defined with a 0.3 dB/m limit on CL_{fund} .

Lastly, in Fig. 3(a) we present the FM bending loss at 1064 nm as a function of bending radius, comparing LCF9o and LCF9o-2 using V-FEM in a local cylindrical coordinate system [14], for the A-A' (solid) and B-B' (dashed) bending planes indicated in Fig. 1. The LCF9o-2 bent parallel to the A-A' plane has the lowest bending loss of less than 0.2 dB/m up to a 15-cm bending radius, while the B-B' plane curve is only slightly higher than the symmetric curve of the LCF9o. It compares also very favorably with the hexagonal designs, which require a 24 air-hole ring to achieve a loss around 2 dB/m at 15 cm bending. Finally, in Figs. 3(b) and 3(c) we plot the optical field distributions at 1064 nm in the curved LCF9o and LCF9o-2, respectively, for a 15 cm A-A' plane bending radius, noting how the larger holes of the LCF9o-2 fiber offer smaller gaps to the outer cladding, permitting to keep the field better confined into the solid core.

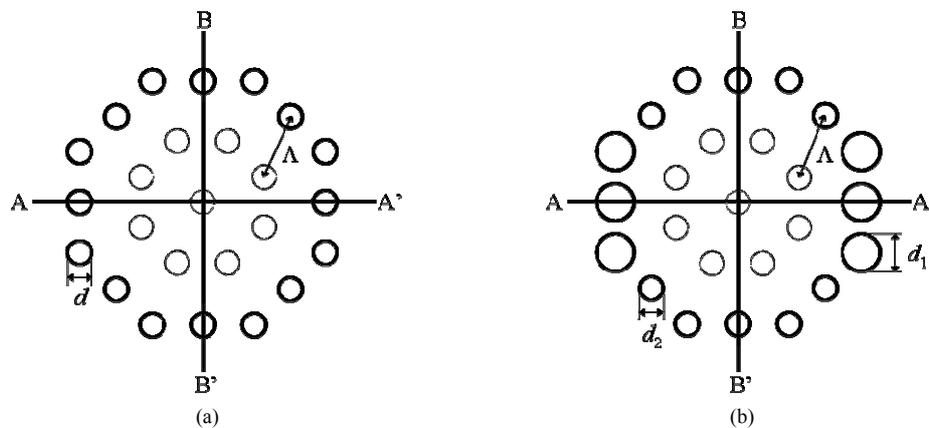


Fig. 1. Cross-section of octagonal air-hole LCFs formed by (a) 16 air holes around a nine-cell silica core (LCF9o), and (b) 16 air holes of two different diameters d_1 and d_2 around a nine-cell core with dual-diameter (LCF9o-2) symmetry.

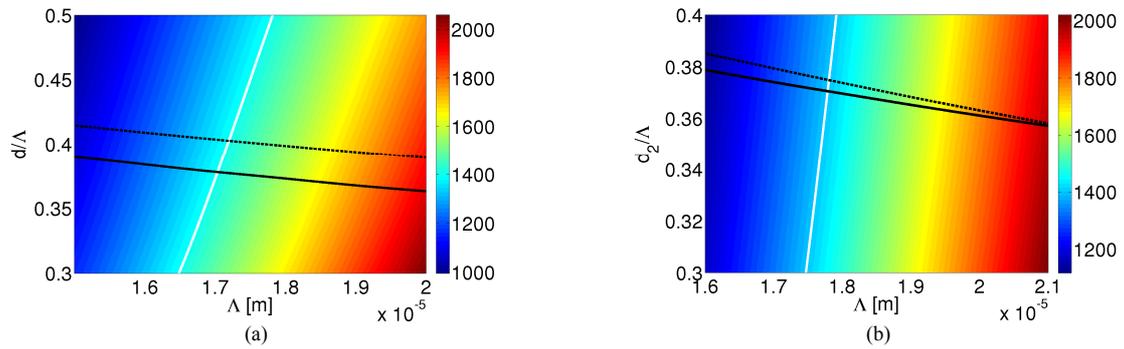


Fig. 2. Effective FM area at 1064 nm as a function of (a) Λ and d/Λ for LCF9o and (b) Λ and d_2/Λ for LCF9o-2, setting $d_1/\Lambda = 0.7$.

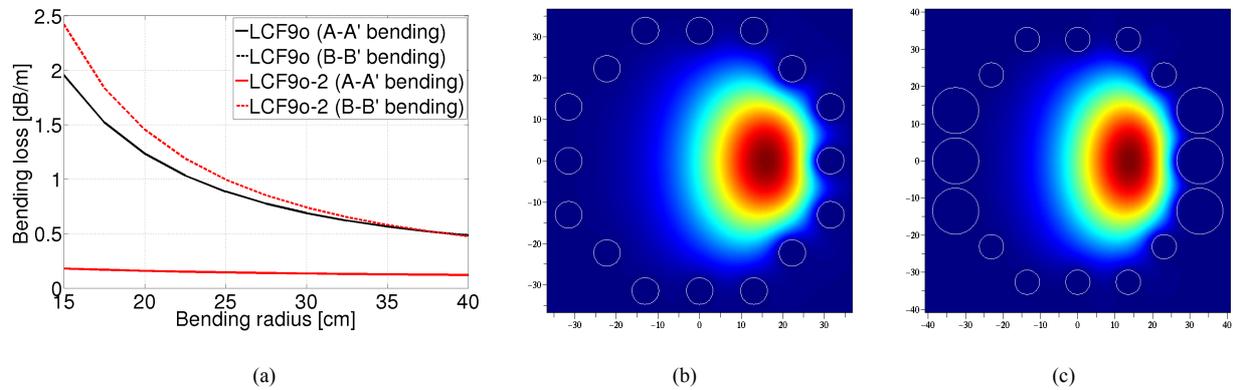


Fig. 3. (a) Bending loss in dB/m as a function of the bending radius in cm at 1064 nm, and optical field distribution of FM in the bent (b) LCF9o and (c) LCF9o-2 fibers at 1064 nm, for a 15-cm bending radius.

3. Conclusion

A novel type of polygonal effectively-single-mode LCFs with $1400 \mu\text{m}^2$ effective area has been investigated. An octagonal LCF with a nine-cell solid core and a single ring of air-holes can achieve a large core diameter around $50 \mu\text{m}$ and bending loss below 0.2 dB/m at 1064 nm up to a 15 cm bending radius.

4. Acknowledgment

The authors would like to acknowledge the Strategic International Cooperative Program of Japan Science and Technology Agency (JST) for supporting this work.

5. References

- [1] J.M. Fini, *J. Opt. Soc. Am. B* **24**, 1669–1676 (2007).
- [2] P. Wang, L.J. Cooper, J.K. Sahu, and W.A. Clarkson, *Opt. Lett.* **31**, 226–228 (2006).
- [3] Y. Jeong, J.K. Sahu, D.N. Payne, and J. Nilsson, *Electron. Lett.* **40**, 470–472 (2004).
- [4] A. Galvanauskas, *IEEE J. Sel. Top. Quantum Electron.* **7**, 504–517 (2001).
- [5] M.D. Nielsen, J.R. Folkenberg, and N.A. Mortensen, *Electron. Lett.* **39**, 1802–1803 (2003).
- [6] X. Peng and L. Dong, *Opt. Lett.* **32**, 358–360 (2007).
- [7] L. Dong, J. Li, and X. Peng, *Opt. Express* **14**, 11512–11519 (2006).
- [8] W.S. Wong, X. Peng, J.M. McLaughlin, and L. Dong, *Opt. Lett.* **30**, 2855–2857 (2005).
- [9] L. Dong, X. Peng, and J. Li, *J. Opt. Soc. Am. B* **24**, 1689–1697 (2007).
- [10] L. Dong, J. Li, H. McKay, A. Marcinkevicius, B. Thomas, M. Moore, L. Fu, and M.E. Fermann, CPDB6, Conference on Lasers and Electro-Optics and Quantum Electronics and Laser Science Conference 2008 (CLEO/QELS 2008), San Jose, Calif., May 2008.
- [11] K. Saitoh, Y. Tsuchida, and M. Koshiba, *IEICE Electronics Express* **6**, 412–417 (2009).
- [12] L. Rosa, K. Saitoh, Y. Tsuchida, S.K. Varshney, M. Koshiba, F. Poli, D. Passaro, A. Cucinotta, S. Selleri, and L. Vincetti, IWB3, Integrated Photonics and Nanophotonics Research and Applications (IPNRA 2008), Boston, Mass., July 2008.
- [13] K. Saitoh and M. Koshiba, *IEEE J. Quantum Electron.* **38**, 927–933 (2002).
- [14] K. Kakihara, N. Kono, K. Saitoh, and M. Koshiba, *Opt. Express* **14**, 11128–11141 (2006).