# Effectively Single-Mode Chirally-Coupled Core Fiber

**Chi-Hung Liu, Guoqing Chang, Natasha Litchinitser, and Almantas Galvanauskas**

*EECS Department, University of Michigan, 1301 Beal Avenue, Ann Arbor, MI 48109-2122*

*Phone: (734)615-7166; fax: (734)763-4876; e-mail: liuch@umich.edu*

**Doug Guertin, Nick Jabobson, Kanishka Tankala**

*NUFERN, 7 Airport Park Road, East Granby, CT 06026*

**Abstract:** We demonstrate Chirally-Coupled-Core (CCC) fiber with 35-µm diameter and 0.07 NA core which is effectively single-mode. This is a new type of fibers whose modal properties are defined both by their longitudinal and transverse structure.



**OCIS codes:** (060.2280) Fiber design and fabrication; (140.3510) Lasers, fiber

Rapid advance in fiber laser technology has led to multi-kW average[1] and multi-MW peak[2,] powers in diffraction-limited output beams. Technologically this advance is based on increasing fiber core size, which is typically 20-µm to 30-µm diameter for kW fiber lasers and >65-µm for multi-MW peak power generation. Such core sizes are well beyond single-mode limit in conventional index-guiding fibers, and achieving fundamental-mode output from a multimode core requires careful mode-management in these large-mode-area (LMA) fibers. This offsets many traditional technological advantages of conventional single-mode low-power fiber laser technology. It would be highly beneficial to replace LMA fibers with such index-guiding fibers, which could be managed just as telecom-type single-mode fibers (splicing, fiber pigtailing, fiber packaging, etc.), but which would allow large core sizes well beyond single-mode limit.

Here we report the first demonstration of such a fiber structure. Chirally-coupled-core (CCC) fiber structure with 35-µm and 0.07 NA core has been designed and fabricated, which permits low-loss (~0.1-dB/m) propagation for the fundamental mode and which effectively suppresses higher-order mode (HOM) propagation by more than 130-dB/m. Quantitatively, in terms of single-mode preservation this fiber performs indistinguishably from a true single-mode fiber of this core size, permitting splicing with <0.1-dB splice loss, and being completely impervious to external perturbations and modal mismatched excitation.

The geometry of CCC fiber, as shown in Fig.1, contains a straight center core and at least one helical satellite core, wrapped around the central core and in the optical proximity of it. The central core guides modes propagating along *z*-direction, while the helix-coiled side core (or cores) supports modes, which are propagating in a helical path around the central core. This composite structure enables to accomplish two main functions: (1) provide efficient and highly selective coupling between higher-order modes in the central straight core and the side-helix modes; and (2) provide high loss for modes propagating in the helix cores, thus imparting high loss onto all coupled higher-order modes of the central core. Conventionally, mode coupling between two waveguides requires achieving exact phase-velocity matching between these coupled modes (propagation constants $\beta^{(1)} = \beta^{(2)}$). The essentially novel part of the concept is that coupling between central-core modes and helix side can be made sensitive to the modal symmetry. Indeed, since the central-core modes have general form $E(r,\varphi) = E(r)\sin(l\varphi)$, where integer $l$ represents an azimuth order of each mode, helix side rotating around fiber axis $z$ along the fiber with a period $\Lambda$ after each period will see an additional phase difference $2\pi l$ between the central-core and side-core modes. The phase matching condition between these modes becomes $\beta^{(1)} = \beta^{(2)} + \beta^{(1)}\left(\sqrt{(2\pi R/\Lambda)^2 + 1} - 1\right) \pm 2\pi l/\Lambda$, where the middle term includes effect of side-mode slow-down due to helical path. For central-core $LP_{01}$ mode the last, quasi-phase matching term vanishes, shifting its resonance condition away from the HOM resonance. By proper choice of $\Lambda$ helix-side can be made high loss (due to the fiber coil) for any mode coupled into it from the central core.

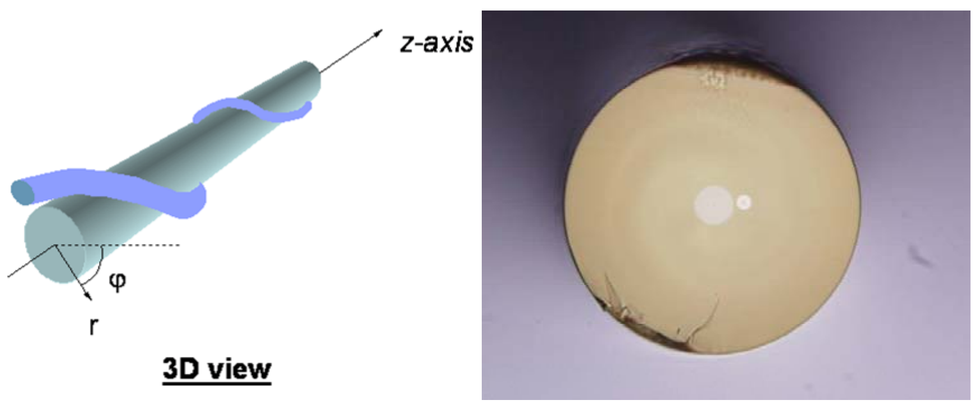


Fig. 1 Structure of CCC fiber

Fig. 2 shows the calculated modal loss for the fabricated CCC fiber structure. Fiber parameters are: center core diameter 35-µm and 0.07NA, satellite core diameter 12µm and 0.09NA, pitch period 6.2mm, edge-to-edge core separation 2 µm. According to Fig. 2, for $\lambda$ > 1550-nm all higher order modes have high loss (from >130dB/m to >300dB/m), while the predicted $LP_{01}$ mode loss is ~0.3dB/m, i.e. expected fiber performance is effectively single-mode. Between ~1100-nm and ~1500-nm range fiber is effectively dual-mode. Experimental results confirmed these numerical predictions. At 1550-nm fiber output was purely single mode even for fiber pieces as short as 25-cm, irrespective of excitation conditions. Modal pattern was not affected by fiber perturbation, bending, etc. Fig. 3 shows beam profile and $M^2$ value measurement, with the measured $M^2 = 1.03$. Measured fundamental-mode loss is 0.095dB/m. Cutback measurements indicated modal degradation occurring only for fiber lengths shorter than 20-cm, consistent with the calculated HOM loss level. CCC fiber pieces could be spliced together with no modal-quality degradation and with only <0.1dB splice loss. Furthermore, 33-m long CCC fiber spool showed 34-dB polarization extinction, indicating compatibility of the fiber design with polarization-preservation.

In conclusion we have demonstrated a new design of index-guiding CCC fiber that effectively supports only a fundamental mode for the core diameter of 35-µm (corresponding MFD at 1550-nm is

29.5-μm). Such fibers should enable highly practical monolithic high-power and high intensity fiber laser designs. Our analysis and simulations indicate that such CCC fibers can be made with significantly larger cores, possibly even larger than 100-μm in diameter. Initial experimental results indicate that CCC fibers are compatible with polarization preservation. It is also important to emphasize that CCC fiber represent a new class of fibers, in which guiding properties are defined not only by the transverse but also by the longitudinal fiber structure. This permits to control other fiber properties such as dispersion, transmission spectrum, etc. This work has been supported by US Army Research Office grant W911NF0510572.

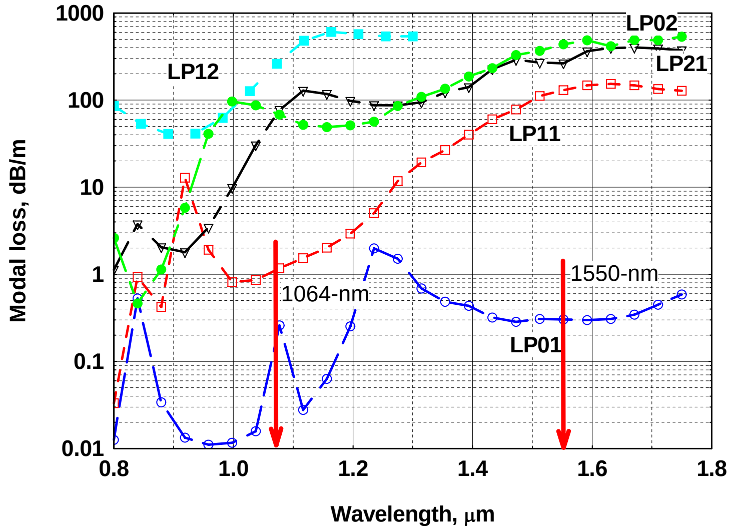


Fig. 2 Simulated modal loss using Beam Propagation Method

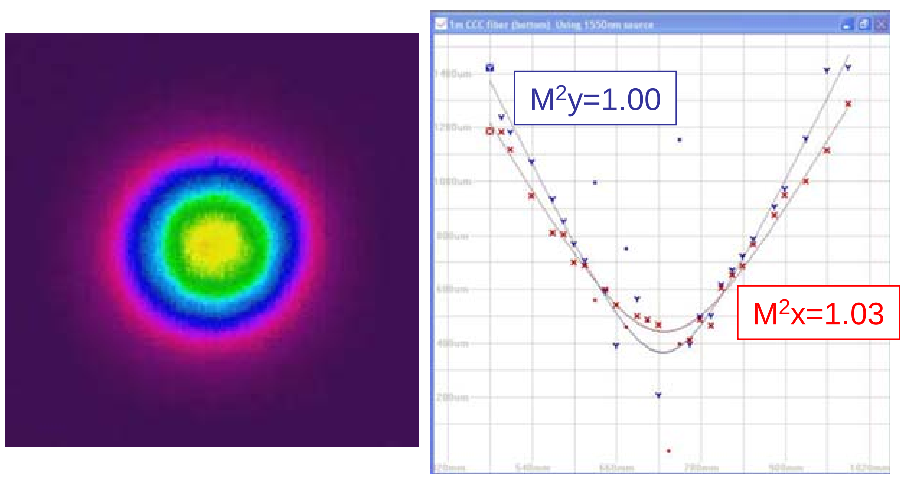


Fig. 3 Output beam profile and measured $M^2$

## References


[1] V. Gapontsev, D. Gapontsev, N. Platonov,O. Shkurikhin, V. Fomin, A. Mashkin, M. Abramov, S. Ferin, "2 kW CW ytterbium fiber laser with record diffraction-limited brightness," Proc. Conference on Lasers and Electro-Optics/Europe, Munich, Germany, June 12-17, 2005, Page(s) 508

[2] Kai-Chung Hou, Ming-Yuan Cheng, and Almantas Galvanauskas, Doruk Engin, Rupak Changkakoti, and Pri Mamidipudi, "Multi-MW Peak Power Scaling of Single-Transverse Mode Pulses using 80-μm Core Yb-doped LMA Fibers," Advanced Solid State Photonics, Tahoe, USA, January 29 – February 1, 2006, postdeadline paper MF5