Chirally Coupled Core Fibers at 1550-nm and 1064-nm for Effectively Single-Mode Core Size Scaling

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Abstract: Novel index-guiding-core single-mode fibers with V >> 2.405 are demonstrated at 1550-nm and 1064-nm wavelengths. This fiber design is based on chirally-coupled core concept, which enables a new type of index-guiding and photonic-crystal fiber structures.

OCIS codes: (060.2280) Fiber design and fabrication; (060.2320) Fiber optics amplifiers and oscillators

1. Introduction.

Recent advance of fiber laser technology into multi-kW average[1] and multi-MW peak[2,] power generation in diffraction-limited output beams have been critically based on adopting so called Large-Mode Area (LMA) fibers, in which multimode fibers with large cores (typically 20-µm to 30-µm diameter, with 65-µm to 80-µm state of the art demonstrations[2]) are used with careful mode-management[3, 4] for achieving single-mode operation. This offsets many traditional technological advantages of conventional single-mode low-power fiber laser technology, hindering development of all-monolithic large-core fiber systems.

In this paper we report concept, fabrication, experimental demonstrations, and theoretical study of scalability of chirally-coupled core (CCC) fiber structures which permit effectively single-mode core sizes well beyond conventional V = 2.405 limit. Such fibers provide with robust single-mode output in a manner identical to conventional single-mode fibers, i.e. such fibers do not require any external mode management and can be spliced into complex systems or used for development of a variety of fiber-optic devices using standard fiber splicing and processing techniques. We demonstrate that single-mode CCC fibers can be produced with core sizes well exceeding standard 30-µm core LMA fibers (in fact exceeding 50-µm), for operation in 1550-nm and 1064-nm spectral regions, compatible with Er, Er/Yb and Yb doped gain fibers.

2. Chirally-Coupled Core (CCC) fiber concept.

The geometry of CCC fiber, as shown in Fig.1, contains a straight central 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 fiber axis, while the helix-coiled side core (or cores) supports modes, which are propagating in a helical path around the central core. This composite structure can be designed to control the following interactions: (1) provide phase-velocity matched coupling between LP_{01} mode of the central straight core and helix-side core by selecting suitable side-helix parameters such that $\beta^{(side\,mode)} + \Delta\beta_{helix} = \beta^{(central\,mode)}$, where $\Delta\beta_{helix} = 2\pi n/\lambda\left[\sqrt{(2\pi R/\Lambda)^2+1}-1\right]$ is the phase-

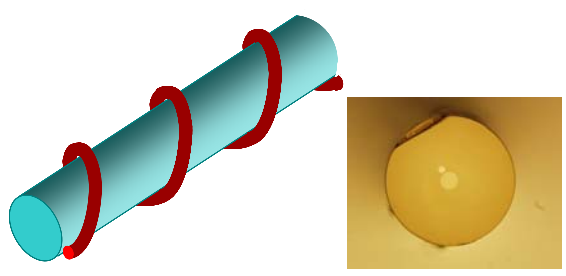

Figure 1: Chirally-Coupled Core fiber structure (left) and cross section of a fabricated CCC fiber (insert).

velocity of the side core component that can be controlled by helix period Λ and radius R; (2) provide efficient modal-symmetry selective coupling between higher-order modes (HOM) in the central straight core and the side-helix modes through quasi-phase matching of phase velocities $\Delta\beta_{QPM} = \Delta\beta_{helix} \pm (2\pi/\Lambda)l$ (l – is the HOM azimuthal number); and

(3) by selecting suitable side-core parameters and period to provide high loss for selected helix-side modes. This permits large variety of functionalities of such a fiber structure. For example, CCC fiber can be made effectively single-mode by using (2) and (3), i.e. by coupling all HOM of the central core into high-loss helix side modes and thus allowing only LP_{01} mode in the central core to propagate. As another example, by inducing partial coupling between the central-core LP_{01} mode and a non-lossy side mode through the use of (1), the phase velocity and dispersion of the LP_{01} mode can be controlled. Indeed, both positive and negative dispersion values can be achieve in arbitrary-large fiber cores with magnitudes >>10xtimes larger than dispersion of fused silica.

3. Effectively single-mode CCC fibers.

Several CCC fiber samples with 34-µm core (NA values between 0.065 and 0.07) and a variety of design parameters for operation in 1550-nm and 1064-nm spectral regions have been fabricated and experimentally characterized. CCC fiber geometry can be implemented using commercially available fiber fabrication techniques by spinning fiber preform during fiber draw process. It is critical for achieving effectively single-mode performance that all fiber HOM would be sufficiently suppressed. Approximate criterion is to achieve >100-dB/m loss for HOM in the central core. Fig. 2 shows calculated power transient of a truly SM 30-µm fiber (red line) compared to that of an effectively SM CCC fiber of the same core size with > 100-dB/m HOM loss (blue line). For both cases fiber core is excited with significantly mode-mismatched beam in which only 12.5% of the total power is matching LP_{01} mode. Consequently the remaining power is lost into a cladding within a short 10-20-cm length of each fiber, i.e only the fundamental-mode remains. Results of experimental characterization of one of the fabricated samples are shown in the right-hand side of the figure. A standard SM fiber have been spliced to the CCC sample, ensuring that very poor modal match will be achieved at the excitation port of the CCC fiber, representing situation similar to the calculated results on the left-hand side of the figure. Experimental results clearly show that, despite such deliberately poor coupling and large core size, this CCC fiber acts as a single-mode fiber for fiber lengths as short as 25-cm. Further characterization confirmed that such CCC fibers can be used as a conventional SM fiber: splicing with no modal-content degradation and splice loss of ~0.1, insensitivity to fiber perturbations and coupling conditions, negligible LP_{01} modal loss (<0.1-dB/m), etc. Additionally, this fiber exhibits significant birefringence, which permitted PER of >34-dB after 30-m propagation length. Such CCC fibers represent significant technological breakthrough, permitting mode-size scaling of the conventional telecom-type fiber technology, which should be of critical importance for further practical development of high-power fiber laser technology. Our modeling indicates that effectively SM core sizes of 50 – 100 µm are achievable.

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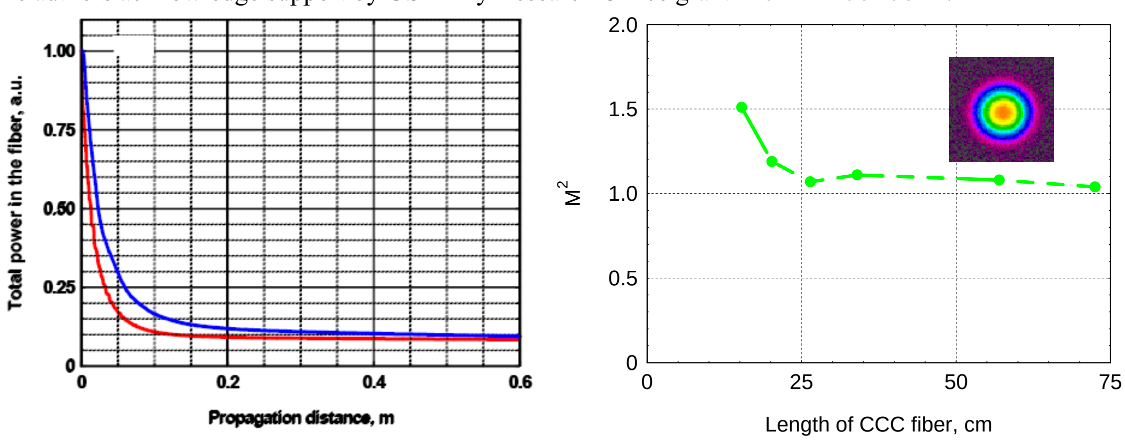

Figure 2: Calculated power transients in SM and effectively SM fiebrs (left-hand side of the figure). Cut-back measurement of the modal quality from a fabricated CCC sample demonstrating effectively-single-mode performance (right-hand side of the figure).

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

[3] M.E.Fermann, “Single-mode excitation of multimode fibers with ultrashort pulses”, Optics Letters, **23**, pp.52-54, 1998.

[4] J.P.Koplow, D.A.V.Kliner, and L.Goldberg, “Single-mode operation of a coiled multimode fiber amplifier”, Optics Letters, **25**, pp.442, 2000.