Anomalous Bend Loss in Large-Mode Area Leakage Channel Fibers

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Abstract: Large-mode-area leakage channel fibers, designed to suppress higher-order modes, demonstrate dramatic power loss at certain critical radii of curvature. Using C^2 imaging, we experimentally characterize this anomaly, attributing it to resonant mode-coupling.
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Introduction: Resonantly enhanced leakage-channel fibers (LCF's) with large mode areas are designed to provide high-power propagation of diffraction-limited beams in high-power fiber lasers [1]. The microstructure of these fibers is tailored to enhance the loss of higher-order modes (HOM's), while maintaining tolerable loss of the fundamental mode (FM), resulting in single-mode operation with large field diameters.

Coiled fibers experience additional power loss. Several studies [2-4] have primarily focused on bend loss of the guided modes directly coupled to the cladding modes, concluding that the loss is significantly higher for HOM's than for the FM, similar to the results of earlier work [5]. Another mechanism of power loss is based upon bend-induced coupling between guided modes [6,7]. The coupling increases dramatically when the effective indices of two modes approach one another as a function of the fiber curvature. The avoided crossing occurs at the critical radius, which can be estimated as $R_c \propto \Lambda^3/\lambda^2$ in the short-wavelength limit, where λ is the wavelength of light, and Λ is the characteristic core size [6,7]. For the currently tested LCF's with the core size $\Lambda \sim 50\ \mu m$, the mode coupling is expected at $R_c \sim 10\ cm$ at the wavelength $\lambda \sim 1\ \mu m$.

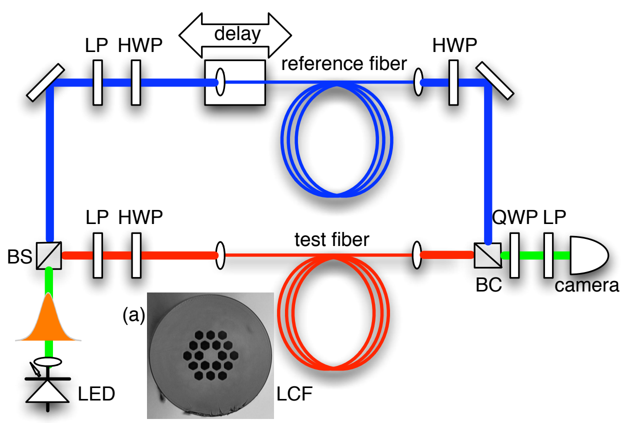

Fig. 1: C^2-imaging setup: LED – light-emitting diode, LP-linear polarizer, HWP – half-wave plate, QWP – quarter-wave plate, BS – beam-splitter, BC – beam combiner. *Inset:* Cross-section of the LCF

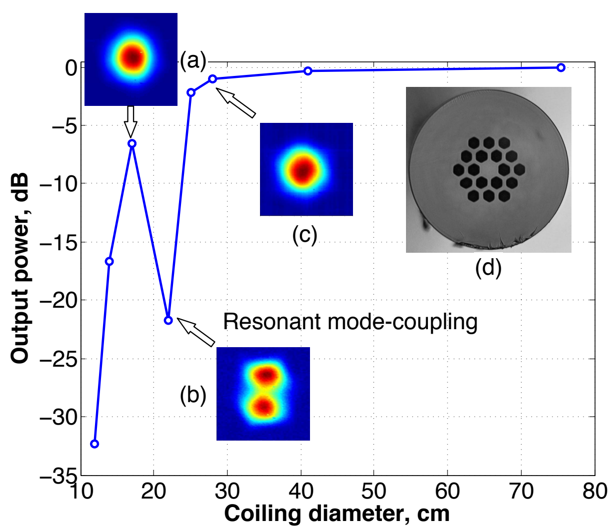

Fig. 2: Output power as a function of coiling diameter. *Insets* (a-c): Output mode profiles at different coiling diameters; (d) Cross-section of the LCF sample

Our work: In this work, we explore the effect of resonant mode coupling on the bend loss in a large-mode area LCF and observe an enhanced power loss at a certain coiling diameter. The fiber of 285 cm length has the core diameter of 50 μm and cladding diameter of 400 μm. The two rings of low index (F-doped) silica regions shown in Fig. 1(a) provide the leakage channel. The core made of silica is index matched to the outer silica glass. A high-index regular acrylate coating applied to the cladding ensures stripping out of the cladding modes. The LCF has been designed to have negligible HOM content at lengths greater than 3 m and coiling diameters over 30 cm. The input end of the fiber was spliced to a single-mode fiber to provide same in-coupling conditions throughout the experiments.

The modal content of the LCF was analyzed using C^2–imaging [8] modified to account for elliptical polarization of the output beam. Fig. 1 shows a schematic diagram of the experimental setup based upon the Mach-Zehnder interferometer. We used an LED source centered at about $\lambda = 1050\ nm$ with the spectral width of about $30\ nm$. The output beam of the test fiber focused at the camera interferes with the collimated reference beam. The length of a polarization-maintaining reference fiber is chosen to compensate for the modal dispersion of the test fiber [8]. The cross-correlation signal as a function of the group delay is detected using a computer-controlled delay stage. The polarization state of the test beam is measured selecting different polarization states of the reference beam. In our measurements, at each coiling diameter, the cross-correlation trace has been recorded for three pairs of orthogonal polarization states of the reference beam. We have analyzed polarization properties of every mode and also extracted the correlation trace encoding the total power of the modes, shown in Fig. 3.

Power measurements: The dependence of the output power on the coiling diameter was measured using a power meter. The results are shown in Fig. 2. We observe a dramatic decrease of the output light power at a specific coiling diameter. The observed critical radius $R_{exp} \approx 11\ cm$ is close to the estimate $R_c \sim 10\ cm$, suggesting resonant mode-coupling as the mechanism responsible for the anomalous power loss. Indeed, at the resonance, the output image demonstrates domination of HOM's, while the output images in Fig. 2(b) and (d), recorded at coiling diameters outside the resonance, indicate single-mode operation.

C^2 measurements: C^2-imaging [8] provides insight into the resonant behavior. The envelope of the integrated correlation trace shown in Fig. 3 at the critical coiling diameter demonstrates two modes (LP01 and LP11) propagating with a relative group delay of about $0.2\ ps/m$, with the FM contributing only about 15% of the total power. In contrast, at other coiling diameters, HOM's are suppressed at the power level below $-25\ dB$, as shown in Fig. 4. The strength of the resonance depends on length of the coiled fiber. In a set of similar measurements conducted on the LCF of smaller length of about $180\ cm$, a relatively shallow resonance was found at the same coiling diameter. We expect a significantly deeper resonance for longer fiber lengths.

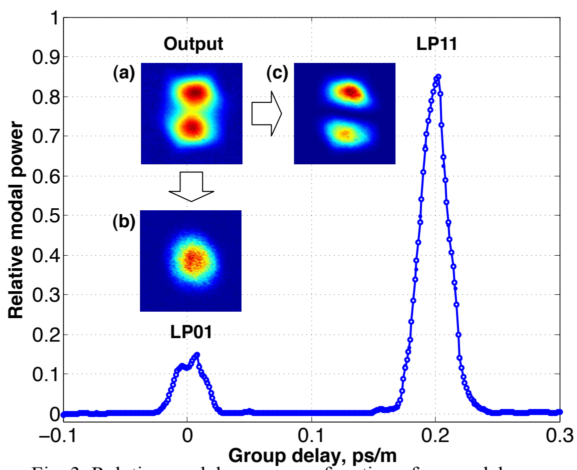

Fig. 3. Relative modal power as a function of group delay at the resonance ($D = 22\ cm$). *Insets:* output image and the images of reconstructed modes

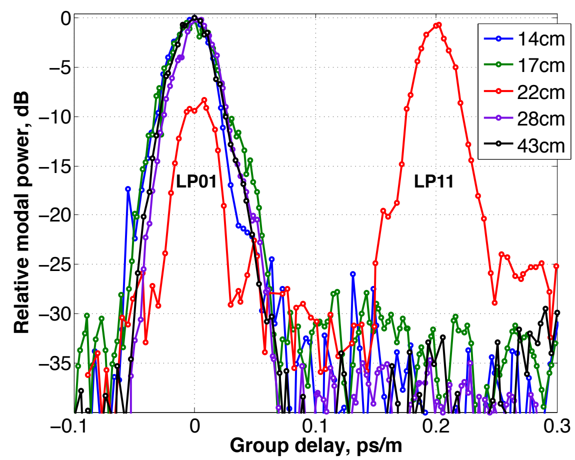

Fig. 4: Relative modal power of LP01 and LP11 (peak values) as a function of the relative group delay, for different coiling diameters

Conclusions: Coiled few-mode fibers experience both power loss and mode coupling. Using C^2-imaging, we explore the interplay of these phenomena in a large-mode-area leakage channel fiber. At a specific coiling diameter, we observe a dramatic decrease of the output power. Outside the resonance, the power recovers to the levels offset by the usual mechanism of bend loss. The anomalous bend loss, attributed to the resonant mode coupling, may have important implications for design of high-power lasers, and also for sensor technology.

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