

## Air-clad chirally-coupled-core Yb-fiber femtosecond oscillator with >10 W average power

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**Abstract.** We demonstrate high-power (> 10 W), 300-fs mode-locked oscillators at 83-MHz repetition rate using air-clad Chirally-Coupled-Core Yb-fiber with 37-  $\mu\text{m}$  central-core diameter, corresponding to a 30-  $\mu\text{m}$  mode-field-diameter.

### Introduction

Progress in developing high power/energy femtosecond Yb-fiber oscillators has rapidly advanced in recent years, primarily due to the use of large-mode-area (LMA) Yb-fibers to reduce the intracavity nonlinear phase. Using LMA (mode-field diameter of 75  $\mu\text{m}$ ) photonic crystal Yb-fiber, 0.8- J ultrashort pulses at 60 W have been achieved [1]. However, such photonic crystal Yb-fibers are sensitive to bending, and cannot be tightly coiled, which contrasts sharply with the key advantages (e.g. robustness, monolithicity, compactness, etc.) offered by conventional single-mode fiber technology.

Recently, chirally-coupled core (CCC) fibers have emerged as a new technological platform for the next generation fiber lasers. CCC fibers consist of two cores placed in optical proximity. The core in the center is straight along the fiber axis for the signal transmission. The second core (i.e., side core), is chirally wound around the center core. Much smaller in diameter, the side core exerts substantial propagation loss on the higher-order modes inside the center core so that only the fundamental mode propagates in the center core with minimal loss. Providing robust single-mode core-size scaling without the need of external mode-filtering or mode-matching methods, CCC fibers can be spliced together and coiled for compact packaging. Therefore they are well suited for fabricating standardized CCC-fiber pigtailed components with single-mode throughput [2, 3].

Using the first-generation CCC Yb-fibers with 21-  $\mu\text{m}$  mode-field-diameter (MFD), two groups have demonstrated femtosecond mode-locked oscillators operating in the stretched-pulse regime (25-nJ pulse energy) [4] or all-normal dispersion regime (40-nJ pulse energy) [5]. Further energy/power scaling necessitates CCC Yb-fibers with much larger MFD. Recently, air-clad CCC Yb-fibers with 30-  $\mu\text{m}$  MFD were fabricated, leading to a demonstration of a 511 W fiber MOPA system featuring single-frequency and single-transverse mode [6]. Use of air-clad structure facilitates high pump-absorption (i.e., 8-dB/m), making this CCC Yb-fiber especially suitable for constructing high

repetition-rate (e.g.,  $\sim 100$  MHz) and high-power oscillators employing short fiber length. In this paper, we demonstrate a femtosecond, all-normal-dispersion oscillator operating at 83-MHz repetition rate with pulse energy  $> 140$  nJ (average power  $> 10$  W).

## Experimental setup and results

As Fig. 1 shows, the oscillator consists of 1.7-m air-clad CCC fiber with an Yb-doped central core of 37- $\mu\text{m}$  diameter (30- $\mu\text{m}$  MFD, 0.07-NA), a 260- $\mu\text{m}$  0.6-NA inner cladding, and a 443- $\mu\text{m}$  outer cladding. The 976-nm pump with 75-W maximum power is delivered by a 400- $\mu\text{m}$  core-diameter fiber with NA=0.22. The dichroic mirror transmits the pump and reflects the lasing pulse that circulates counter-clockwise inside the ring-cavity. A combination of waveplates (i.e. QWP1, HWP, and QWP2 in Fig. 1) and a polarization beam splitter (i.e. PBS in Fig. 1) initiates the mode-locking via nonlinear polarization evolution (NPE) that significantly reshapes the intra-cavity pulse. Rotation of these three waveplates leads to different mode-locking states. Mode-locking is further stabilized by a bandpass filter with 4-nm full-width-half-maximum (FWHM). The optical isolator ensures the intracavity pulse circulating uni-directionally. The output pulse ejected from PBS exhibits a positive chirp with picosecond duration depending on the modelocking states. The output pulse is then compressed by a pair of gratings (600 line/mm line density) configured at double pass with  $\sim 50\%$  transmission efficiency.

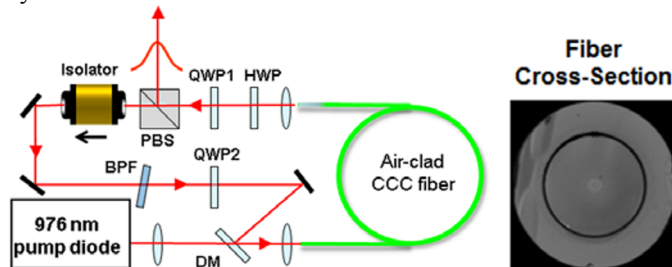


Fig. 1 Schematic setup of the oscillator (left) and the fiber cross-section (right). DM: dichroic mirror; QWP: quarter-wave plate; HWP: half-wave plate; BPF: bandpass filter; PBS: polarization beam splitter.

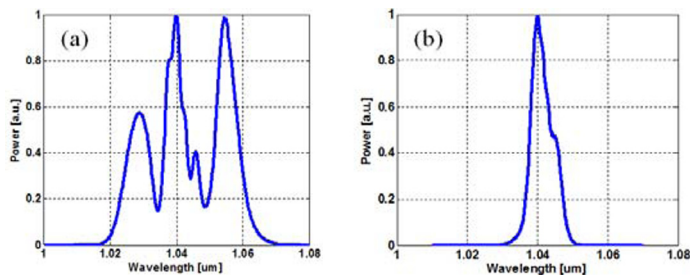
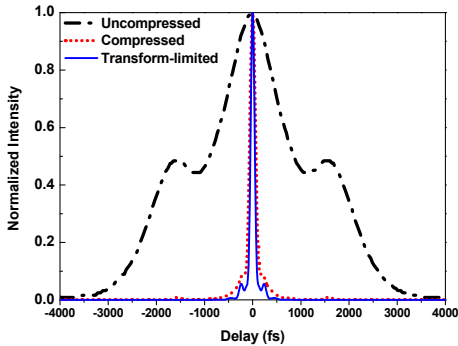


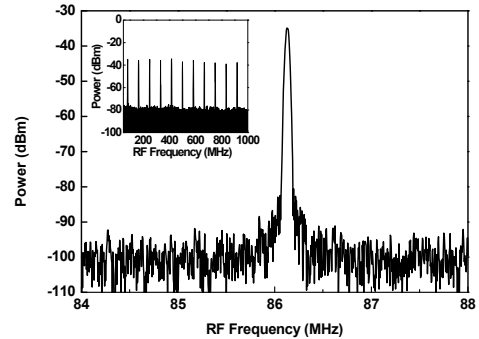
Fig. 2 Optical spectra measured at NPE output of the oscillator operating at an output power of (a) 5W and (b) 12W.

Adjusting the waveplates varies the output coupling ratio, and leads to various self-starting modelocking states. The broadest output spectrum shown in Fig. 2(a) has a 32-nm FWHM bandwidth and 5-W average power before the compressor. The spectral modulation indicates that the pulse experiences strong self-phase modulation when propagating inside the CCC fiber. We use an autocorrelator with 150-ps scanning range together with optical/RF spectral measurements to confirm single-pulse operation. The autocorrelation traces for the output pulse (black dash-dot curve) and the compressed pulse (red short-dot curve) are shown in Fig. 3; also plotted in the same figure is the calculated transform-limited pulse (blue solid curve) from the spectrum in Fig. 2(a). The autocorrelation durations of the uncompressed and compressed pulses are 4 ps and 140 fs, respectively. The corresponding RF spectrum (inset in Fig. 4) and the RF measurement of the

repetition-rate are shown in Fig. 4. The signal-to-background ratio is larger than 40dB. By adjusting the waveplates, we increased the output coupling ratio and consequently increased the output power to 12 W. In this modelocking state, the output spectrum, shown in Fig. 2(b), has only 6-nm FWHM bandwidth as a result of reduced intracavity power. This narrow spectrum exhibits only slight modulation implying that the pulse experiences reduced self-phase modulation from propagating in the CCC fiber due to the higher output coupling ratio. The autocorrelation duration of the compressed pulses is 420 fs.



)LJ□ Autocorrelation traces of the pulses.



)LJ□ Fundamental and broadband RF spectrum.

## Conclusion

In conclusion, we have demonstrated a high-energy femtosecond oscillator that incorporates an air-clad CCC Yb-fiber to ensure single-mode operation. Stable mode-locking is achieved using NPE together with a bandpass filter. The 300-fs mode-locked oscillator emits output power as high as 12W with 83-MHz repetition rate, corresponding to  $\sim 144$ -nJ pulse energy.

## Acknowledgment

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