Published in final edited form as:

Opt Lett. 2013 January 1; 38(1): 43–45.

High energy similariton fiber laser using chirally-coupled-core fiber

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Abstract

We present a high energy amplifier similariton laser based on chirally-coupled core fiber. Chirped pulse energies up to 61 nJ at 3.3 W average power are obtained with effectively singlemode output. The pulses can be compressed with a simple grating compressor to durations below 90 fs. We demonstrate for the first time a fused pump-signal combiner to confirm the integration potential of chirally-coupled core fibers.

Fiber lasers have recently emerged as reliable sources of high energy ultrashort pulses. Thanks to recent advances in the understanding of ultrashort pulse evolution and of large mode area (LMA) fiber technology, fiber sources matching and exceeding solid-state laser performance have been demonstrated [1-3]. This opens the way for robust turnkey sources powered by low cost diode pumps, expanding the reach of ultrafast science and its applications.

A major challenge for achieving high energy in ultrafast fiber lasers is to manage large nonlinear phase accumulations to avoid wave-breaking. This is most effectively done using normal-dispersion chirped-pulse evolutions, which reduce the average peak power and linearize large nonlinear phase shifts. With a spectral filter in an all-normal dispersion cavity, dissipative solitons that are stable at large energies are formed [1]. To scale to very short pulses, a chirped-pulse evolution with large spectral breathing is desired. This is possible in a similariton amplifier, in which pulses asymptotically evolve to a self-similar parabolic profile [4]. Similaritons can be formed in the gain segment of fiber lasers through self-consistent seeding conditions such as a dual soliton-similariton design [5], or by introducing a narrow spectral filter [6, 7]. Pulses from amplifier similariton lasers can be dechirped to below 60 fs with a standard grating compressor [6], and close to 40 fs using adaptive pulse shaping [8].

The energy from a given pulse evolution can be scaled up using LMA fiber technology. So far, the most successful way of achieving this is using photonic crystal fibers (PCF). Indeed, oscillators that deliver peak powers above 1 MW have been demonstrated [2, 3]. However, the integration potential of LMA PCF is limited; fusion splicing is challenging due to

potential collapse of the guiding micro-structure. For applications where robust integration is key, solid glass LMA fiber designs are preferable. However, large fiber cores tend to guide multiple modes. A laser using multimode step-index fiber was briefly reported [9], but systematic investigation suggests that higher-order mode (HOM) content destabilizes mode-locking and limits single-pulse performance [10]. Integrated and robust mode-filtering mechanisms are thus necessary to reach the full potential of LMA fiber lasers. Examples of solid-glass selective HOM filtering include leakage-channel fibers [11] and Bragg fibers [12]. A mode-filtering mechanism of particular interest is chirally-coupled core (3C) fiber, where a secondary core is helically wrapped around a large central core to selectively couple out higher-order modes [13]. Mode-locked fiber lasers based on 3C fiber can achieve effectively single-mode operation without external mode filtering or mode matching [14,15].

In this letter, we report a fiber laser that combines the similariton evolution with 3C fiber. We demonstrate for the first time a fused pump-signal combiner for doubleclad pumping of 3C fiber, which enables integrated high-energy short pulse oscillators. Chirped pulse energies above 60 nJ are obtained at more than 3 W average power and with dechirped pulse durations below 90 fs. Numerical simulations confirm that a linearly-chirped parabolic pulse evolves self-similarly inside the cavity. Peak powers of 0.5 MW can be obtained, which to our knowledge is the highest delivered from a fiber laser with integrated pump coupling.

The laser cavity design is shown in Figure 1. The gain fiber is 3 m of Yb-doped 3C fiber with a core diameter of 33 μm , a numerical aperture (NA) of 0.06 and a mode effective area of $\sim 350 \mu\text{m}^2$. Up to two 976 nm fiber-coupled multimode diodes are spliced to the ports of a custom 2+1:1 pump-signal combiner with about 50 cm of matched passive 3C fiber. All fibers are spliced together using a standard fusion splicer. A filter with 2.2 nm bandwidth is created by placing a 600 lines/mm grating about 10 cm from the coupling lens of the signal port of the combiner. A half-wave plate in front of the grating maximizes efficiency. A polarization-sensitive isolator ensures unidirectional ring propagation. An iris blocks residual cladding light. Nonlinear polarization evolution (NPE) is turned into effective saturable absorption with 3 waveplates and a polarizer. The NPE port is used as a variable output coupler. The zero-order grating reflection is used to monitor the intra-cavity pulse. A dichroic mirror is placed after the output port to separate the signal from the residual pump, and a grating pair compressor is used to dechirp the pulses.

To verify that similariton pulses are formed in the cavity, we performed split-step Fourier simulations of the non-linear Schrodinger equation as in [16]. The group velocity dispersion $\beta_2 = 20 \text{ ps}^2/\text{km}$ and the non-linear coefficient $\gamma = 0.40 (\text{W km})^{-1}$. The small signal gain is $g_0 = 30 \text{ dB}$ and the saturation energy $E_{\text{sat}} = 60 \text{ nJ}$ is chosen to match the experimental output energy below. The saturable absorber has a modulation depth $I_0 = 1.0$ and saturation power $P_{\text{sat}} = 5 \text{ kW}$. The gaussian spectral filter has a 2.2 nm full-width at half-maximum (FWHM) bandwidth, the output coupling is 0.70, and a lumped linear loss of 0.70 accounts for fiber coupling and grating efficiency. The gain filter has a 40 nm bandwidth. The results are shown in Figure 2. The pulse duration and bandwidth grow continuously in the gain fiber, as expected in self-similar evolution. The saturable absorber has limited effect on the steady-state pulse. The spectral filter shapes the pulse back to a narrowband, nearly transform-limited pulse that seeds the next cycle of self-similar evolution. As is typical of similariton lasers, spectral breathing by a factor of 15 is observed. The output pulse taken after the saturable absorber is a linearly-chirped parabola with 60 nJ energy, 33 nm bandwidth and dechirped duration of 80 fs.

Experimentally, the wave-plates are adjusted until mode-locking is observed. A stable self-starting pulse train is obtained at 55 MHz repetition rate. Single-pulsing is checked with a sampling oscilloscope and a fast photodiode with a combined bandwidth of about 20 GHz,

as well as an autocorrelator with up to 60 ps delay. Figure 3 shows mode-locked spectra obtained for absorbed pump powers from 10 to 20 W. This corresponds to average output powers of 0.44 to 3.3 W. The intracavity bandwidth increases monotonically with pulse energy from 11 nm to 37 nm, as expected for similaritons. Some rapid oscillation is visible on top of the NPE output spectrum in Figure 3, probably corresponding to spectral interference with a small amount of secondary modes. We suspect that this is generated in the combiner, where residual stress may induce mode-mixing and scatter some light in the cladding. The fringe amplitude corresponds to about 0.1% of the total power in the secondary modes, which confirms the strong mode filtering of the 3C fiber. The RF spectrum (not shown) shows an instrument-limited 80 dB contrast above the noise floor, with a few narrowband features 50-70 dB below the fundamental harmonic at the highest powers. This probably indicates the onset of thermal instabilities. Indeed, although transient mode-locking was observed up to 5.5 W average power, beyond 3.3 W slow thermal instabilities push the laser into Q-switched states that can cause damage to the combiner and fiber end faces.

A self-starting mode-locked state at the maximum stable power is shown in Figure 4. The chirped pulse energy is 61 nJ for an average power of 3.3 W. The output spectrum is steep-sided, while the intra-cavity spectrum has a typical similariton laser shape. The output pulse is 2.2 ps long, and can be dechirped to 86 fs using a standard grating-pair compressor. This is close to the transform-limited duration of 70 fs, which confirms the mostly-linear chirp typical of similariton pulses. The deviation can be due to the limited gain bandwidth, as well as resonances between the fundamental mode and side core of the 3C fiber which currently limit its bandwidth to 40-50 nm. From the grating compressor settings, we infer that the chirp of the pulse is 0.05 ps^2 , smaller than the total cavity dispersion of 0.07 ps^2 . This is typical of similaritons, as the dispersion is accumulated over a single roundtrip [6]. In contrast, dissipative solitons have output dispersions equal or greater than the cavity since the chirp is accumulated over many roundtrips [16]. Effectively single-mode propagation is verified at 3.3 W output power by the gaussian output beam with $M^2 = 1.2$ and the absence of secondary pulses above the 30 dB sensitivity of a background-free autocorrelator.

These results represent a ten-fold increase in energy over a similariton laser with similar parameters and single-mode fiber [6], consistent with the scaling of the fiber core size. Given a 70% efficient grating compressor, peak power of 0.5 MW could be obtained. This is twice the peak power of a similariton laser with 10 μm diameter single-mode fiber and adaptive pulse shaping [8]. As indicated above, mode-locked states with pulse energies up to 100 nJ and bandwidths supporting transform-limited durations approaching 50 fs were observed on a transient basis, until damage occurred. Further engineering of the combiner and other fiber components to minimize fiber stress and increase thermal handling capabilities should enable such high-energy states to be sustained and improve the overall stability of the laser. This should allow megawatt peak powers to be approached by an integrated and spliceable fiber laser. 3C fiber designs with more broadly-spaced fundamental mode resonances will also be necessary to generate shorter pulses.

In conclusion, we have demonstrated a high energy amplifier similariton laser based on step-index chirally-coupled core fiber. A fused pump-signal combiner demonstrates the integration potential of 3C fiber. Chirped pulses with energies up to 61 nJ at 3.3 W average power can be dechirped to durations as low as 86 fs, delivering up to 0.5 MW of peak power. Numerical simulations confirm self-similar pulse evolution in the cavity. Further energy scaling should be possible with proper engineering of fused components. To our knowledge, this is the highest peak power delivered from a fiber laser with fiber-integrated pump coupling, demonstrating the potential for 3C fiber to enable robust and high performance fiber lasers.

Acknowledgments

Cornell University acknowledges support by the National Science Foundation (ECCS-0901323) and the National Institutes of Health (EB002019). The University of Michigan acknowledges support from the US Army Research Office (W911NF0510572).

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Fig. 1.
(Color online) Setup for 3C fiber similariton laser. HWP/QWP: half/quarter-waveplate, PBS: polarizing beam-splitter, SA: saturable absorber.

Fig. 2.
(Color online) Simulated (a) pulse evolution, output pulse (b) spectrum, (c) intensity (solid), parabolic fit (light dashed) and instant frequency (dashed).

Fig. 3.
(Color online) Experimental pulse spectrum trends (a) intra-cavity and (b) at the NPE output.

Fig. 4. (Color online) Experimental output of the 3C similariton laser: (a) NPE output (solid) and intracavity (dashed) spectra; (b) chirped autocorrelation and (c) dechirped autocorrelation. (d) M^2 measurement and output beam profile (inset $(0.72 \text{ mm})^2$ field).