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Fiber Laser Replacement for Short Pulse Ti:Sapphire Oscillators – Scalable Mode Locking to Record Pulse Energies

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FY05 LDRD Final Report

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LDRD Project Tracking Code: 05-LW-062

Jay Dawson, Principal Investigator

Abstract

We have investigated fiber-based lasers that mode-lock via three nonlinear mechanisms: pulse evolution, bend loss, and tunneling.

Experiments with nonlinear pulse evolution proved especially promising; we report here a fiber laser that produces 25 nJ, sub-200 fs pulses, an energy that is 60% higher than previous reports. Experiments with nonlinear bend loss were inconclusive; though bend-loss data show that the effect exists, we were not able to use the phenomenon to lock a laser. New models suggest that nonlinear tunneling could provide an alternate path.

Introduction/Background

Ultrafast lasers are critical tools for many of the physics experiments and applications of interest to NNSA, DOE and LLNL. Currently the most common ultrafast laser is the Ti: Sapphire laser. Commercial versions of these typically have pulse widths of 100 fs, repetition rates of 80 MHz, pulse energies of 15 nJ, and average powers of about 1 W [1]. They are useful laboratory tools, but tend to be expensive (approximately \$200k, including the pump laser and facilities in the laboratory) and require considerable skill to maintain and operate.

Mode-locked fiber lasers are reliable, inexpensive alternatives to Ti: Sapphire lasers. Until recently, their pulse energies were limited to a few nanojoules, but reports now show that they can generate 15 nJ pulses [2]. These lasers rely on nonlinear pulse evolution (NPE), the same mechanism that had previously been limited to 2 nJ due to multi-pulsing. The higher energies are attributed to the fortuitous creation of self-similar pulses, which can propagate without splitting [3].

Alternatives to NPE include nonlinear bend loss, the effect originally proposed for this work, and nonlinear tunneling, an effect that we first discuss here.

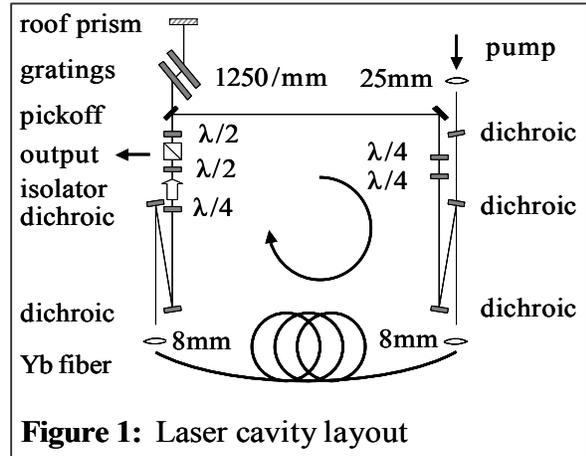
Nonlinear Pulse Evolution

NPE is the most common mode-locking mechanism employed in fiber-based lasers. Pulse energies have generally been limited to 2 nJ, but recent work demonstrates that self-similar pulses can achieve energies as large as 15 nJ.

We report here on experiments with an NPE-based mode-locked fiber oscillator. They were intended as a baseline assessment of pulse energy, though we found that we could achieve energies as large as 25 nJ with this technique – 60% higher than previous reports – making it competitive with Ti: Sapphire lasers.

1. Laser Cavity

Figure 1 depicts the layout of the laser. A 980 nm diode-laser pumps the cladding of an 8 m section of double-clad Yb-doped fiber (core and cladding diameters of 12 and 400 μm); for the experiments reported here, the pump power ranged as high as 7.5W. Five dichroic filters, which transmit light from the pump but reflect light having wavelengths longer than 1045 nm, ensure that only the amplified emission from the Yb ions can propagate through the cavity. An isolator forces unidirectional lasing.



A pair of fused silica transmission gratings (Ibsen Photonics), having groove densities of 1250 lines/mm, controls the net chromatic dispersion of the cavity. After a first pass through the pair, a roof prism shifts the beam vertically and reflects it back through the gratings, where it is then re-routed by a pickoff mirror. The grating separation can be adjusted to achieve net-zero dispersion in the cavity.

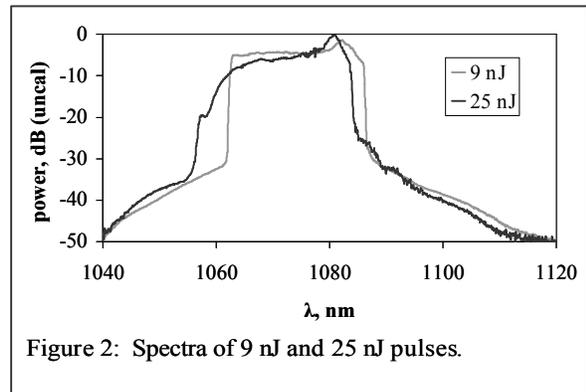
The cavity contains two half-wave plates and three quarter-wave plates. One of the half-wave plates controls the fraction of power that is coupled through a polarizing beamsplitter, and the other optimizes the throughput of the grating pair. Two of the quarter-wave plates control the polarization state of the beam as it enters the fiber, and the remaining one controls the state through the polarization-dependent isolator.

2. Pulse Characterization

We monitor the pulse train with several diagnostics, including an analog oscilloscope coupled to a 0.5 GHz photodetector, a long-range autocorrelator covering a temporal range of 0.6 ns, an RF spectrum analyzer coupled to a 3 GHz photodetector, an optical spectrum analyzer having resolution of 0.1 nm, and a commercial FROG (frequency resolved optical gating) spectrometer.

3. Method and Results

Passive mode-locking results from nonlinear evolution of the polarization state inside the cavity [4]. We find the mode-locking condition by first adjusting the output-coupling half-wave plate for 50% output power, and then systematically adjust the three quarter-wave plates. In principal, only two plates are required to achieve mode locking – a half- and a quarter-wave plate. However, we find that splitting the half-wave plate into a pair of plates provides refined control of the oscillation conditions.



We varied the pulse energy from 5 nJ to 25 nJ by adjusting the net chromatic dispersion in the cavity from approximately 0.01 ps² to 0.08 ps², while fine-tuning the waveplates to keep oscillation. Beyond 25 nJ we found that the oscillator entered a Q-switch mode and became unstable. The autocorrelator substantiated that only a single train of pulses circulated in the cavity, and the RF analyzer showed better than 70 dB signal-to-noise ratio about the fundamental harmonic at 16.6 MHz.

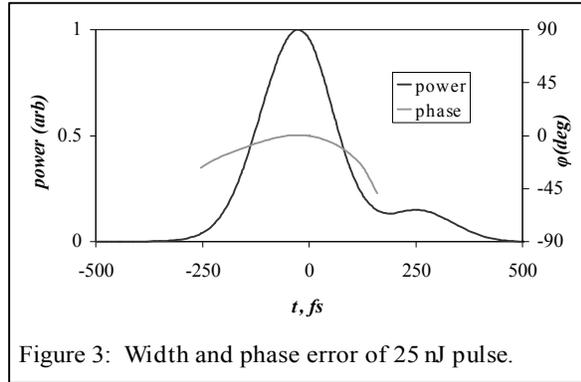


Figure 3: Width and phase error of 25 nJ pulse.

Figure 2 shows the spectra obtained from the 9 nJ and 25 nJ pulses. The spectral shape distorts as the net dispersion is increased, but the 25 nJ pulse still retains the sharp-sided features indicative of good mode locking. Figure 3 shows the temporal and phase characteristics of the 25 nJ pulse, obtained from the commercial FROG instrument. The compressed pulse width is less than 200 fs with a time/bandwidth product of 0.6, and the phase error changes by less than 10° over the FWHM of the pulse.

4. Summary

We report 25 nJ pulses from a fiber-based laser, a result that exceeds previous reports by 60% and implies that fiber-based oscillators can achieve energies similar to those obtained with mode-locked Ti:sapphire lasers.

The high pulse energy is very encouraging, but our estimate of the residual dispersion in the laser – up to 0.08 ps² – exceeds the value reported for 15 nJ by roughly an order of magnitude [2]. Our early modeling results, which follow an analysis similar to [5, 6], imply that part of dispersion imbalance may be contributed by the waveplates in the cavity. The modeling also shows that the waveplates narrow and shape the recirculating spectrum, and may thus encourage the formation of quasi-parabolic or self-similar pulses.

Nonlinear Bend Loss

The nonlinear bend loss technique that we have advocated is conceptually simple – the numerical aperture of a fiber is chosen so that low-energy pulses will not be poorly guided when the fiber is bent, while high-energy pulses, which would see a slightly large numerical aperture, will remain guided.

In our earliest experiments, we tested the concept as a pulse discriminator. Figure 4 shows the differential attenuation experienced by a stream of 600 fs pulses

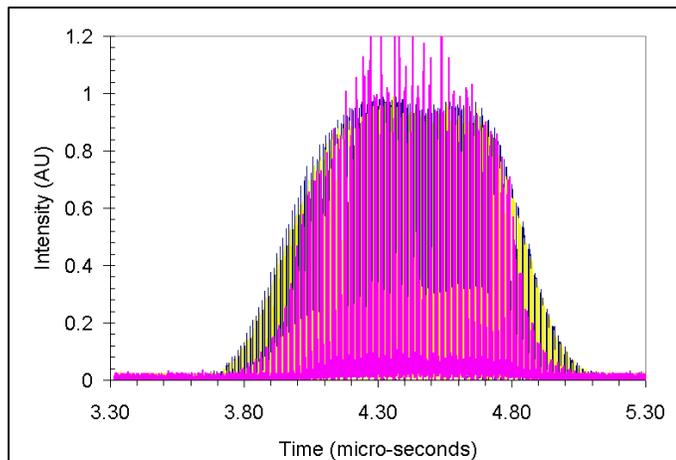


Figure 4 Blue - input pulse stream. Yellow - output with unbent fiber. Pink - output with bent fiber. For the bent fiber, the low energy pulses on the leading/trailing edges of the packet are preferentially attenuated.

propagated through a 0.5 m length of fiber having a mode field diameter of 13 μm and bent to a diameter of 4 cm. Note that the low energy pulses at the leading and trailing edges of the packet are preferentially attenuated by roughly a factor of two. In an oscillator, where pulses circulate through the cavity from tens to hundreds of times, this differential should be sufficient to select only high-energy pulses.

Unfortunately, we were not able to mode lock a fiber laser based on the bend loss principle. The oscillator configuration was essentially the same as shown Figure 1, but with the addition of a 1 m section of fiber bent at various diameters. We bent the fiber to diameters as small as 2.5 cm and as large as 15 cm, but after five days of effort we saw no evidence of mode-locked pulses.

Nonlinear Tunneling

W-profile or depressed-well fibers can be designed so that the fundamental mode does not propagate beyond some finite wavelength. This property is the key to polarizing fibers, whose birefringence allows one polarization state to be guided while the orthogonal state is not [7]; we propose to extend this effect to discriminate low and high energy pulses.

Figure 5 shows an implementation of the concept. With this design, the low energy pulse will tunnel out of the core, since the refractive index profile it sees allows tunneling. A high-energy pulse sees a decidedly different profile, though, due to the power-dependent change in refractive index. In a proper design, the high-energy pulse would be well guided, since its index profile does not allow tunneling.

Figure 6 shows the change in mode size with wavelength. The low-energy mode grows exponentially with wavelength, and so too, do its losses. In contrast, the mode of the high-energy pulse remains well confined in the fiber, making its losses negligible.

The threshold energy needed to thwart tunneling can be quite high; if we assume that the pulse's spectral width extends from 1050 to 1080nm, then our modeling suggests that a pulse's energy must exceed 50 - 100 nJ for it to propagate. Such a high-energy oscillator would exceed the typical limitations of Ti: Sapphire lasers, and should also be more tolerant to stray birefringence than NPE-based oscillators.

Summary

We present a nonlinear pulse evolution-based oscillator whose pulse energy, 25 nJ, exceeds current reports by 60%; this result has been submitted to the CLEO 2006

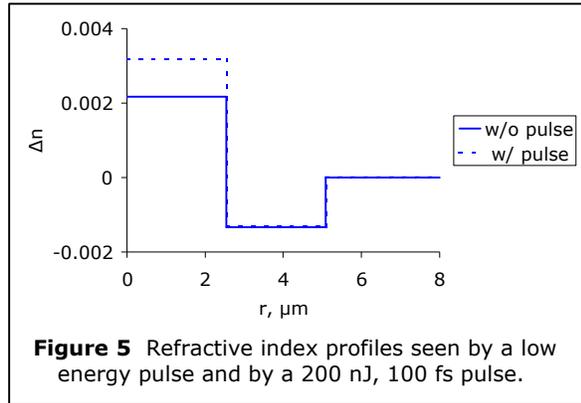


Figure 5 Refractive index profiles seen by a low energy pulse and by a 200 nJ, 100 fs pulse.

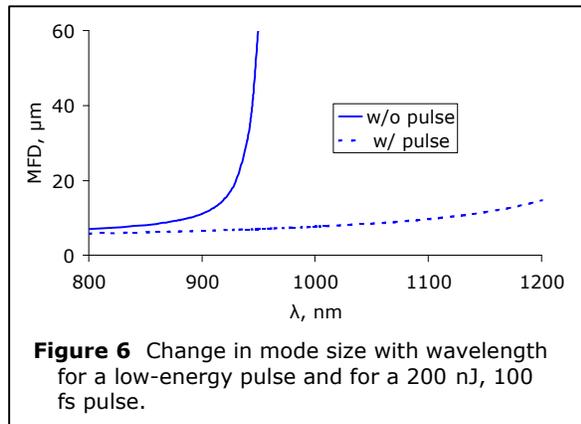


Figure 6 Change in mode size with wavelength for a low-energy pulse and for a 200 nJ, 100 fs pulse.

conference. We also discuss results from a nonlinear bend loss-based oscillator, and present a potential alternative, nonlinear tunneling loss.

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