Ultrafast Technology

Compressing Femtosecond Laser Pulses Non-Iteratively

Matthew E. Anderson, Josh Thornes
and Phillip Poon

Recent progress in femtosecond laser optoelectronics has allowed pulse shaping and pulse measurement to move into the mainstream. Shaping and measurement devices can be found in femtosecond laser laboratories throughout the world, and the combination of the two has proven an attractive means of dispersion control and optimization. Often, the most desirable pulse for femtosecond applications is simply the shortest possible pulse, i.e., a transform-limited pulse. Until recently, attempts to compress complex pulses relied on either a well-characterized reference pulse or an iterative search algorithm.[1] In July 2004, we reported a method of correcting arbitrary spectral phase aberrations in a single step without use of a reference pulse.[2] The technique uses spectral phase interferometry for direct electric-field reconstruction (SPIDER)[3] to measure the spectral phase of an ultrashort pulse, then sends a corrective signal to a liquid crystal spatial light modulator (LC-SLM).[4] Since both SPIDER and the LC-SLM operate on the spectral phase, they are ideally suited for one another.

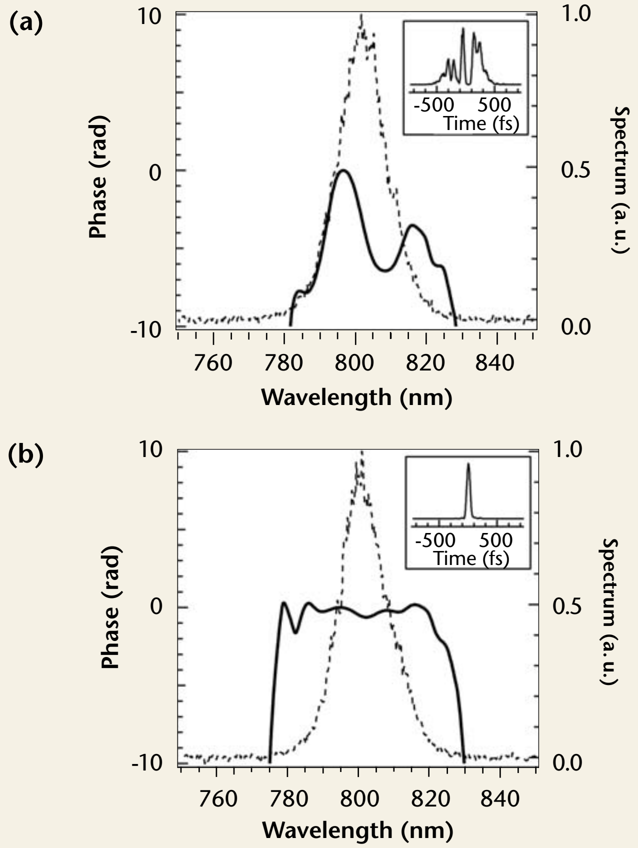

Figure 1. Spectral phase (*solid line*) and spectrum (*dashed line*) of our laser pulse passing through cellophane (a) before correction and (b) after correction. The inset shows the corresponding temporal intensity.

For the experiment, we used a Ti:sapphire oscillator operating at 80 MHz with a center wavelength of 800 nm, a pulse duration of 70 fs and average power of 20 mW. The pulse travels first to the pulse shaper, which consists of a 4*f* zero dispersion pulse compressor and an LC-SLM. The pulse then travels to our SPIDER apparatus,[5] where it produces a spectral interferogram, or "Spidergram." The Spidergram contains the spectral phase information, which is recovered through a series of numerical Fourier transforms and filters. This process is direct and non-iterative, and requires no knowledge of the input pulse. Combining this spectral phase with the spectrum of the pulse, the complete pulse information is therefore known, and the pulse can be represented in either the frequency or the time domain. Once the computer has recovered the spectral phase, it instructs the LC-SLM to add the inverse of the spectral phase to the pulse, thereby flattening the overall spectral phase.

To test the procedure on a complicated phase profile, we inserted a phase plate—in this case, a wrinkled piece of cellophane—just before the LC-SLM. The cellophane did little to disturb the spectrum of the pulse but had a strong effect on the spectral phase [see Fig. 1(a)]. The inset of Fig. 1(a) shows the temporal intensity, which has multiple peaks over a time window of nearly one picosecond. This pulse had reasonable agreement with an independent autocorrelation trace. When the correction procedure was applied, the corrected pulse had considerably flatter spectral phase over the corrected spectral window [see Fig. 1(b)] and the temporal profile was again restored to that of a fairly clean 70 fs pulse.

Non-iterative correction is ideal for a number of applications, such as extremely high-energy lasers, in which repetition rates can approach one shot per hour or slower, and laser amplifiers, in which thermal drift is a problem. With single-shot SPIDER and fast spatial light modulators, in principle there is no obstacle to applying this technique at kilohertz update rates in the near future.

This work was performed at San Diego State University, San Diego, Calif. Matthew E. Anderson (matt@sciences.sdsu.edu) is with the Department of Physics. Josh Thornes is currently with Raytheon in El Segundo, Calif. Phillip Poon is currently an officer in the U.S. Army.

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Dispersion-Managed Breathing Mode-Locking: Generation of High-Power 185 fs Pulses From a Semiconductor Laser

Bojan Resan, Luis Archundia
and Peter J. Delfyett

Compact sources of ultrashort high-power pulses are highly desirable in many applications such as biomedical imaging and treatment, material processing and telecommunications, to name a few. Mode-locked semiconductor lasers could be commercially important because of their small size and cost, and their excellent electrical efficiency. Limited output pulse power and attainable pulse durations of no shorter than approximately 0.5 ps due to strong self-phase modulation are still obstacles to wider industrial applications. The novel dispersion-managed breathing-mode semiconductor mode-locked laser scheme which has been developed addresses both disadvantages.[1]

Chirped-pulse amplification concepts are implemented inside a semiconductor ring laser cavity. The pulses are stretched prior to entering the gain medium, and compressed before encountering the saturable absorber (SA), as shown in the figure. The lower peak power of the stretched pulses minimizes the amount of self phase-modulation generated in the semiconductor gain media. The "breathing-mode" designation derives from the fact that the intracavity pulses are alternately stretched and compressed as they circulate around the ring resonator, changing the pulse width more than 50 times. The stretching and compression of the intracavity pulses and the external cavity pulses are implemented by dual-pass grating stretchers/compressors with internal telescopes,[2] but other types of dispersion compensators can also be used. Pulse stretching could be achieved by impressing normal dispersion to the pulse prior to the gain media (up chirping) or anomalous dispersion (down chirping). Depending on the temporal and spectral dynamics of the semiconductor gain media with respect to the saturable absorber, up or down chirping allows broader mode-locked spectra and the generation of shorter pulses.[3] In our case, down chirping is preferable for semiconductor gain media that is red-shifted with respect to the excitonic absorption band of the semiconductor saturable absorber. The red part of the pulse is more strongly amplified due to the red shifted gain peak, but the blue part is initially passed through the semiconductor optical amplifier (SOA) in temporal domain and experiences greater gain before the SOA gain depletes. Therefore, the amplification in the spectral and temporal domains is balanced, and broader mode-locked spectra are attainable. The resulting linearly chirped laser output pulses are externally amplified with higher efficiency and compressed to pulse duration as short as 185 fs [Figure 1(b)]. The second-harmonic generation frequency-resolved optical gating (SHG-FROG)[4] method is employed in characterizing the femtosecond pulses from the semiconductor mode-locked laser. The average output power is 14 mW at 323 MHz, implying a peak power of ~230 W and a focused intensity of ~4.6 GW/cm^2 in a 5 x 1 μm^2 spot. The mode-locking build-up in the laser cavity is numerically simulated and the close agreement between the simulated and the measured results verifies our ability to control the physical mechanisms involved in pulse formation and shaping within the ring cavity.[1] We believe that our approach shows the great potential of semiconductor lasers to produce even shorter pulses. The results achieved confirm that the dispersion-managed breathing-mode scheme is advantageous compared to conventional nondispersion-managed linear or ring cavities for generating ultrashort pulses from a semiconductor mode-locked laser.

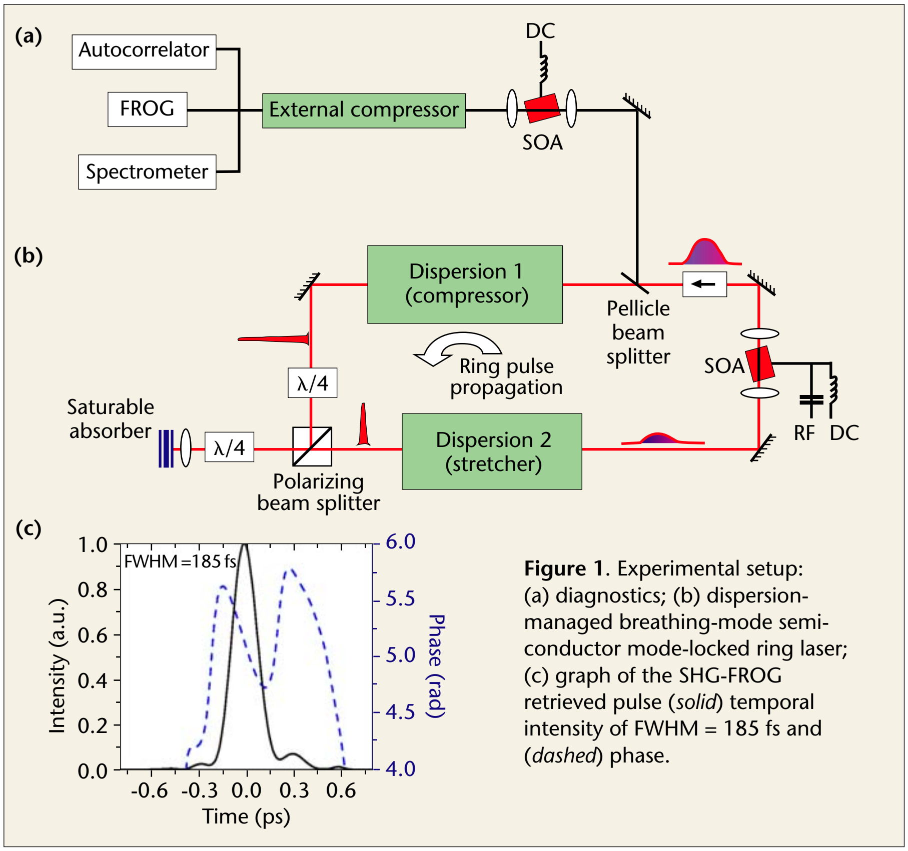

Figure 1. Experimental setup: (a) diagnostics; (b) dispersion-managed breathing-mode semiconductor mode-locked ring laser; (c) graph of the SHG-FROG retrieved pulse (*solid*) temporal intensity of FWHM = 185 fs and (*dashed*) phase.

Bojan Resan (bresan@mail.ucf.edu), Luis Archundia and Peter J. Delfyett (delfyett@creol.ucf.edu) are with the College of Optics and Photonics/CREOL & FPCE, University of Central Florida, Orlando, Fla.

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Similariton Lasers Generate High-Energy Femtosecond Pulses

Frank Wise

Femtosecond fiber lasers have enormous potential for applications owing to their stability and compactness, but realization of this potential has been slowed by the limited pulse energies that mode-locked fiber lasers could produce. Stretched-pulse fiber lasers deliver pulse energies of up to ~2-nJ and average powers of up to 100 mW, which are much less than those delivered by solid-state lasers such as Ti:sapphire.

The most fundamental limitation to pulse energy arises from wave-breaking. A soliton can tolerate only a small nonlinear phase shift before instabilities occur. Pulses that propagate at normal group-velocity dispersion avoid wave-breaking under some conditions, despite strong nonlinearity. Theoretically, wave-breaking is suppressed if a pulse develops a monotonic frequency chirp as it propagates. Such a pulse evolves self-similarly; i.e., the pulse is always a scaled version of itself. These *similariton* pulses tend toward a parabolic shape and accumulate a linear chirp. Self-similar propagation of pulses in a fiber amplifier was reported a few years ago.[1]

Ilday and co-workers have now shown that similariton pulses can exist in a laser oscillator.[2] This demonstrates a new regime of operation of mode-locked lasers: the monotonic evolution of the pulse as it traverses the laser is fundamentally distinct from the static evolution in soliton lasers and the breathing solutions of stretched-pulse lasers. The pulse is always positively chirped inside the laser, with the temporal duration varying from ~3 to ~50 times the transform limit. However, it can be dechirped outside the laser to the transform limit. According to numerical simulations, similariton lasers can generate stable pulses with energies two orders of magnitude larger than are possible by other means. The first experimental results[2] are encouraging: a Yb fiber laser designed for self-similar operation generates 100-fs pulses (Fig. 1) with energy of up to 12 nJ. This laser delivers five times the pulse energy and peak power of the best stretched-pulse lasers, which were previously the highest-performing femtosecond fiber lasers. The peak power (100 kW) is already comparable to that available with standard Ti:sapphire lasers.

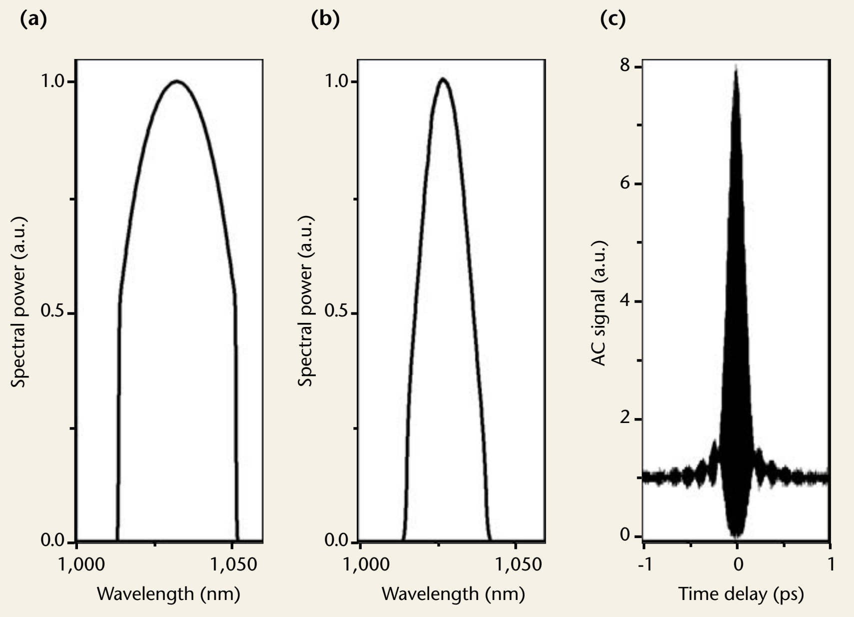

Figure 1. (a) Power spectrum of similariton pulse from numerical simulation. The unusual spectral shape is a signature of self-similar pulse-shaping. (b) Experimental power spectrum produced by Yb fiber laser. (c) Experimental autocorrelation of the dechirped pulse, with duration ~100 fs.

Although self-similar pulse evolution seems to present the greatest benefits for fiber lasers, Ilday et al. have also shown that solid-state lasers such as the Ti:sapphire can benefit from the self-similar regime.[3] Theoretically, ~10-fs pulses with energies as large as 1 microjoule seem possible. Such pulses would have a peak power of 100 MW, which is well above that of any femtosecond laser reported to date. Workers at the Technical University of Vienna recently reported a Ti:sapphire laser operating close to the self-similar regime.[4] The laser produced highly chirped pulses, which could be dechirped to 30 fs with 200-nJ energy. The resulting 5-MW peak power is the highest reported for a femtosecond laser.

Self-similar evolution of an ultrashort pulse in a laser is a new concept that will need further study, but initial experimental results from both fiber and solid-state lasers attest to its potential for the development of practical high-power femtosecond lasers. By offering comparable performance from much smaller, cheaper, and more efficient devices, similariton fiber lasers can be expected to challenge Ti:sapphire lasers in many applications.

Frank Wise (fwise@ccmr.cornell.edu), Department of Applied Physics, Cornell University, Ithaca, N.Y.

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