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Giant-chirp oscillators for short-pulse fiber amplifiers

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Abstract

A new regime of pulse parameters in a normal-dispersion fiber laser is identified. Dissipative solitons exist with remarkably large pulse duration and chirp, along with large pulse energy. A low-repetition-rate oscillator that generates pulses with large and linear chirp can replace the standard oscillator, stretcher, pulse-picker, and pre-amplifier in a chirped-pulse fiber amplifier. The theoretical properties of such a giant-chirp oscillator are presented. A fiber laser designed to operate in the new regime generates ~ 150 -ps pulses at 3-MHz repetition rate. Amplification of these pulses to 1- μ J energy with pulse duration as short as 670 fs demonstrates the promise of this new approach.

The generation of femtosecond pulses with energies above 1 μ J from a practical fiber source requires one or more stages of amplification. To avoid excessive nonlinear phase accumulation in the amplifiers, large-mode-area fibers are employed along with chirped-pulse amplification (CPA) [1]. A typical fiber CPA system (small blocks in Fig. 1) consists of an oscillator, a stretcher, one or more preamplifiers, a large-mode amplifier, and a pulse-picker to optimize the use of the available power and to lower the repetition rate to that appropriate for a given application. Much progress has been made in fiber CPA systems, but to date they have barely begun to supplant solid-state instruments in applications despite their major potential advantages. There is clear motivation to simplify the systems to better exploit the benefits of fiber, particularly greater integration and lower cost.

Here we report the properties of fiber lasers that operate in a new regime, characterized by the generation of pulses with chirp one to two orders of magnitude larger than can be achieved with existing mode-locked lasers. The pulses, which are dissipative solitons, can be dechirped to near the transform limit. The behavior and performance of these giant-chirp oscillators (GCOs) is predicted by analytic theory as well as by realistic numerical simulations. Stable chirped pulses with large energies can be generated at low repetition rates. A GCO may therefore eliminate the stretcher, pulse-picker, and one or more pre-amplifier stages from a fiber CPA system, as illustrated in Fig. 1. We experimentally demonstrate such a system at 3-MHz repetition rate, with initial results that reach microjoule pulse energies and sub-picosecond pulse durations. Extensions of these performance parameters will be discussed.

Recently, fiber lasers with only normal-dispersion components have been successfully mode-locked by the inclusion of a spectral filter [2, 3]. The pulses are dissipative solitary waves of the cubic-quintic Ginzburg-Landau equation (CQGLE) that governs pulse propagation in the cavity [4]. This analytical formalism (Ref. [4]) can be extended to the GCO mode-locking regime. The non-dimensionalized CQGLE,

$$U_z = gU + (1 - i\frac{D\Omega}{2})U + (\frac{\alpha}{\gamma} + i)|U|^2U + \frac{\delta}{\gamma^2}|U|^4U, \quad (1)$$

where D is the GVD, g is the net gain and loss, Ω is the filter bandwidth squared, α is a cubic saturable absorber term, δ is a quintic saturable absorber term, γ refers to the cubic refractive nonlinearity of the medium, U is the product of the electric field envelope and $\sqrt{\gamma}$, z is the propagation coordinate and t is the product of the local time and $\sqrt{\Omega}$, admits the following exact solution:

$$U = \sqrt{\frac{A}{\cosh(\frac{t}{\tau}) + B}} e^{-i\frac{\theta}{2} \ln(\cosh(\frac{t}{\tau}) + B) + i\theta z}. \quad (2)$$

The variation of Eq. 2 with GVD (Fig. 2) illustrates the features that are most important here. $\frac{\alpha}{\gamma}$ and g are constrained for the exact solution to satisfy Eq. 1. As the cavity dispersion increases, the pulse duration and the chirp (which is positive) increase along with the pulse energy. The bandwidth (dechirped pulse duration) decreases (increases) slowly, and the dechirped pulse duration begins to deviate from the transform-limited value. These trends show that the GCO operation is a natural extension of the pulse evolution in Refs. [2–5]. The GCO produces pulses with large quantitative differences from previous oscillators as a result of the intricate balance of the nonlinear and linear processes in the system, given by the CQGLE, an intuitive explanation of which will be the subject of future investigation. An interesting feature of dissipative solitons is that the chirp (e.g. see Fig. 2) can be larger than the GVD of the cavity, meaning that the spectral phase is partially created by the nonlinearity of the system.

To verify and refine the analytical results, numerical simulations of the oscillator are also performed. The simulations include the appropriate terms of the CQ-GLE with saturating gain, $g = g_o/(1 + E_{pulse}/E_{sat})$, where g_o corresponds to 30 dB of small-signal gain,

$E_{pulse} = \int_{-T_R/2}^{T_R/2} |A|^2 dt$, where A is the electric field envelope, T_R is the cavity round trip time and $E_{sat} = 10$ nJ. A 62-m segment of SMF precedes 40 cm of Yb-doped gain fiber, and a 50-cm segment follows it, with $\beta_2 = 230$ fs²/cm and $\gamma = 0.0047$ (W m)⁻¹. The fiber is followed by a monotonic saturable absorber given by $T = 1 - l_o/[1 + P(\tau)/P_{sat}]$ where $l_o=0.7$ is the unsaturated loss, $P(\tau)$ is the instantaneous pulse power and $P_{sat} = 0.5$ kW is the saturation power. The gain is assumed to have a gaussian spectral profile with a 60 nm bandwidth, the output coupling is 88%, and a gaussian filter with 10 nm bandwidth is placed after the saturable absorber. The 30-nJ output pulse is 70 ps long (Fig. 3), and it can be dechirped to 800 fs with 10 ps² of anomalous GVD. The numerical results confirm a feature that will be important for applications: with increasing chirp, the dechirped pulse duration deviates from the transform limited value. For chirp values relevant to microjoule-energy CPA, the deviation is a factor of 2–3. A residual quartic spectral phase underlies the deviation.

We constructed a laser with all-normal-dispersion elements as in Refs. [2–5], but with a much longer segment of SMF, as in the simulation of Fig. 3, to obtain a net GVD of 1.4 ps². A birefringent filter with 10-nm bandwidth was chosen for the experiments presented here. The 3.2-MHz repetition rate would be difficult to achieve with a soliton laser designed to generate sub-picosecond pulses, owing to the resonant instability that limits the cavity length to several times the soliton period [6]. Different operating states of the laser are accessed *via* adjustments to the wave plates and the pump power, corresponding to adjustments of γ , α ,

and g in Eq. 1. Here we will focus on two specific modes, which highlight the capabilities and flexibility of the laser even with fixed fiber and filter parameters. The first mode illustrates the typical parameters that are possible, and the other demonstrates larger effective chirp on a narrower-bandwidth pulse.

To assess the utility of the laser for seeding amplifiers, we employed a setup with an SMF preamplifier pumped in-core by a single-mode diode, a large-mode-area ($\sim 1000 \mu\text{m}^2$) photonic crystal fiber (PCF) main amplifier pumped with as much as 25 W, and a grating compressor (as in Fig. 1). In CPA it is generally desirable to stretch the pulse to the longest duration that can be recompressed, and fiber versions commonly stretch the seed pulse to hundreds of picoseconds. The longest pulses generated by this GCO are shown in Fig. 4. The steep-sided spectrum (Fig. 4a) is characteristic of the normal-dispersion pulse solutions (*e.g.*, see Refs. [2, 3] and solutions with $B < 1$ in Ref. [4]). The spectrum implies a transform-limited pulse duration of ~ 500 fs, so the 140-ps duration (Fig. 4b) is ~ 300 times the transform limit. The transform-limited pulse would require the dispersion of ~ 500 m of fiber ($\sim 10 \text{ ps}^2$) to reach the measured duration. The oscillator is pumped with only 190 mW, and the output power is 50 mW, for a pulse energy of 15 nJ. For the given amplifier fiber, the pulse is long enough to avoid nonlinear distortion for pulse energies up to $\sim 10 \mu\text{J}$. The pulse is amplified to 67 nJ in the preamplifier, and to $1.3 \mu\text{J}$ in the amplifier (4.3-W average power, limited by the available pump power). The spectrum is unchanged by the amplification (Fig. 4c), except for some asymmetry that seems likely to result from seeding the amplifier at wavelengths below the peak of the gain. The amplified pulses can be dechirped to 880-fs duration (Fig. 4d) by gratings that supply 11 ps^2 of anomalous GVD. The amplified pulse duration is thus within a factor of 2 of the transform limit. Dechirped pulse durations as short as 670 fs are also observed with this setup.

CPA becomes more difficult to implement as the pulse duration increases, owing to the increased dispersion needed to stretch narrow-bandwidth pulses. The pulse spectrum shown in Fig. 5 has a transform-limited duration of 0.6 ps. The 115-ps pulse from the GCO (Figs. 5a and 5b) corresponds to impressing 19 ps^2 of GVD on the transform-limited pulse. This value corresponds to the GVD of 1 km of fiber, which is already a challenge to compensate with a grating pair with reasonable spacing. The 2-nJ pulse (90 mW pump) from the GCO is amplified to $1.2 \mu\text{J}$ and dechirped to 1.7-ps duration (Figs. 5c and 5d).

These examples demonstrate good initial performance, and clearly illustrate the practical benefits of the GCO. Systems that reached these performance levels previously required a stretcher, pulse-picker, and additional pre-amplifier. We should emphasize that the experiments presented here are not intended to represent the performance limits of this approach. They were performed with standard, off-the-shelf fibers and components available in our laboratory. It will be possible to extend the GCO regime in several directions, based on the trends of Fig. 2. For example, at lower repetition rates, the pulse duration and chirp can be much larger, and this will be valuable for the highest-energy fiber CPA systems. The longer chirped pulse comes at the expense of a modest sacrifice in the final pulse duration and the deviation from transform limit. A broader range of pulse parameters will be available with GCOs designed with different fiber parameters, which are available for operation at $1.5 \mu\text{m}$, *e.g.*, or with custom fiber.

In summary, we have demonstrated a new operating regime of dissipative soliton lasers, which features long and highly-chirped pulses. In addition to their scientific importance as solutions of a mode-locked laser, these pulses are attractive for femtosecond and picosecond fiber amplifiers. The combination of long pulse duration, low repetition rate, and relatively high pulse energy is unique, and will allow the removal of the stretcher, pulse-picker, and one or more pre-amplifiers from the standard CPA design. We expect that these lasers will

enable practical fiber amplifiers with performance well beyond the microjoule level attained in initial experiments.

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Fig. 1. Components of fiber CPA systems. The small boxes inside the GCO box represent the components of a standard CPA system that are replaced by the giant-chirp oscillator.

Fig. 2. Variation of exact solution normalized pulse parameters with normalized dispersion.

Fig. 3. Simulation of a GCO with realistic parameters: a) oscillator spectrum; b) dechirped pulse; inset: chirped pulse.

Fig. 4.

Long chirped pulse mode: a) oscillator spectrum; b) oscillator pulse measured by a detector with 50-ps resolution (the additional signal on the right of the pulse is due to capacitive ringing from the cable); c) solid: amplified spectrum; dotted: amplified spontaneous emission spectrum; d) autocorrelation of amplified and dechirped pulse. The pulse duration assuming a deconvolution factor of 1.5 is shown. The trace is asymmetric because the pulse duration is close to the limit of delay in the autocorrelator.

Fig. 5. Narrow-bandwidth mode: a) oscillator spectrum; b) oscillator pulse; c) amplified spectrum; d) intensity autocorrelation of amplified and dechirped pulse, which is too long for interferometric measurement.