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Divided-Pulse Lasers

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Abstract

We demonstrate the use of coherent division and recombination of the pulse within an ultrafast laser cavity to manage the nonlinear phase accumulation and scale the output pulse energy. We implement the divided-pulse technique in an ytterbium-doped fiber laser and achieve 16-times scaling of the pulse energy, to generate 6 nJ and 1.4 ps solitons in single mode fiber. Potential extensions of this concept are discussed.

Nonlinear phase accumulation limits the pulse energy from many ultrafast lasers. In particular, this limitation can be severe in fiber lasers. Numerous approaches have been taken to address this issue, including lowering peak power through dispersion management [1], utilizing the linearization of nonlinear phase in self-similar pulse evolutions [2–4], and modelocking dissipative solitons in the all-normal dispersion regime [5], which can tolerate larger nonlinear phase accumulation. The above approaches can be combined with scaling of the core size of the fiber to reduce nonlinear effects [6].

In amplifiers, divided-pulse amplification (DPA) has been demonstrated to reduce peak power and scale pulses to higher energy by temporally dividing the pulse before amplification [7]. For picosecond fiber amplifiers, pulse division has enabled the scaling of peak powers into the megawatt regime [8]. In conjunction with chirped-pulse amplification (CPA), DPA has been used to achieve gigawatt peak powers with 300 fs pulses [9] from a fiber source. In an extension of the DPA technique, pulse division has been used before a nonlinear compression stage to achieve recombined compressed pulses at higher energies than are possible without pulse division [10]. Other recent work has addressed limitations to passive DPA systems, including gain saturation and imperfect division and recombination [11].

Here we propose and demonstrate a divided-pulse laser (DPL), which implements coherent pulse division and recombination within the laser cavity. In analogy to the temporal pulse division in DPA, the pulse is divided before the gain medium, where most of the nonlinear phase is accumulated, and then recombined before the output to scale the pulse energy. The concept is illustrated schematically in Figure 1 using two dividing elements. The technique is demonstrated experimentally in an ytterbium-doped fiber soliton laser, where we achieve 16-times energy scaling utilizing this approach. Other applications of the DPL technique will be discussed. Compared to the combination of a low-energy oscillator and an amplifier

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designed to reach the same pulse energy, we expect that DPLs may offer higher pulse quality, lower noise, and will require fewer pump lasers.

As a specific embodiment of the DPL, we construct the fiber soliton laser shown in Figure 2. The birefringence of yttrium orthovanadate crystals is utilized for the pulse division and recombination, as in [7, 8]. The pulse enters the first dividing crystal from a polarizing beam splitter (PBS I) horizontally polarized. The optical axis of the crystal is oriented 45 degrees to the polarization of the incoming pulse, causing the pulse to split into two copies, one along each axis of the crystal. The two pulses exit the crystal with a time delay induced by the birefringence. Additional dividing crystals are oriented 45 degrees from the preceding crystal so that the splitting process repeats. At the end of N crystals, there will be 2^N copies of the initial pulse. The shortest crystal is selected so that its time delay is greater than the pulse duration. In this experiment, the crystals were arranged from longest to shortest, so the pulse copies have alternating horizontal and vertical polarization at the end of the crystal stack.

The quarter-wave plate (QWP) before the gain fiber converts the polarization of each pulse to circular, which effectively reduces the nonlinear coefficient of the single-mode fiber (SMF) [12], independent of the pulse division. The divided pulses are then amplified in a double-pass through 70 cm of single mode Yb gain fiber (CorActive Yb501), with a Faraday rotator and mirror serving as the retroreflector. The Faraday rotator acts to flip the polarization state of the divided pulses, which is necessary for them to recombine through the same crystal stack. This causes the recombined pulse to be vertically polarized, so it is now reflected by PBS I. The half-wave plate (HWP) and PBS II serve as a variable output coupler. The pulse reflected by PBS II is reflected from a mirror and PBS III to pass through a QWP, a polarization-insensitive grating pair (LightSmyth Technologies LSFSG-1000-3212-HP) to provide the anomalous dispersion necessary for soliton formation, and a semiconductor saturable absorber mirror (SESAM; BATOP optoelectronics SAM 332-IVb.18). After the second pass through the grating pair, the QWP converts the polarization to horizontal, so the pulse passes through PBS III and the isolator to begin the next round trip. The net dispersion is approximately -0.5 ps^2 . The repetition rate of the cavity is 34 MHz. The fiber section of the cavity is around 2.2 m (single-pass), and the rest of the cavity is comprised of free space components.

Without any pulse division (but with circularly polarized pulses in the fiber), the cavity produces soliton pulses with 0.35 nJ of energy and 1.4 ps duration, as shown in Figure 3(a) and (b). Efforts to increase the pulse energy further result in multiple-pulsing.

To demonstrate the DPL concept, the longest dividing crystal of length 57.6 mm is added to the cavity. The results are summarized in Fig. 3(c-e). By increasing the pump power, the single pulse energy of the output pulse can reach 0.7 nJ with the same 1.4 ps duration, which corresponds to each divided pulse having the same 0.35 nJ pulse energy in fiber. Fig. 3(d) shows the intensity autocorrelation of the recombined output pulse, and Fig. 3(e) shows the intensity autocorrelation of the divided pulses, obtained from leakage from a cavity mirror. The autocorrelation of the divided pulse clearly corresponds to that of two pulses of equal intensity, and the 50 ps spacing corresponds to the delay induced by the birefringent crystal.

With the autocorrelation showing the recombined pulse at the output, this confirms that the pulse division is operating as expected. The autocorrelation of the recombined pulse shows that any residual energy in the divided-pulse has been suppressed to below the dynamic range of the autocorrelator, which is around 25 dB.

The achievable single-pulse energy of the recombined pulse doubles with each additional crystal. The data for 2, 3, and 4 dividing crystals are presented in Figure 4. With 4 dividing crystals in the cavity, we have achieved around 16 times scaling of the pulse energy, reaching over 6 nJ of pulse energy (over 200 mW of average power) from the soliton laser, as shown in Fig. 4(e). The spectrum in Fig. 4(e) starts to exhibit fringes from imperfect recombination of the divided pulses, but the autocorrelation in Fig. 4(h) shows that the corresponding secondary pulses have less than 1 % of the energy of the main pulse. The output pulses are chirped to about twice the transform limit, and can be dechirped to the transform limit. The radio-frequency spectrum near the fundamental repetition rate exhibits an instrument-limited contrast of over 70 dB (data not shown). Additionally, the mode is self-starting and stable over the course of a day, which is the longest time period tested. Although it is not the main point of this work, an attractive feature of this implementation is that operation is impervious to thermal and mechanical perturbations of the fiber owing to the Faraday rotator.

The results above demonstrate that coherent pulse division and recombination within the laser cavity can be used to avoid excessive nonlinearity and thereby scale the output energy from an ultrafast laser. This demonstration shows the utility of a DPL for scaling the energy of picosecond pulses from fiber lasers, which have typically been limited to sub-nanojoule energies. Thus, this technique may be advantageous for applications, such as coherent Raman imaging, that may require higher energy picosecond pulses. The DPL can also be used to create controllable pulse bursts, which are called for in some applications. The number of pulses is determined by the number of dividing elements, and a burst of equal amplitude pulses can be obtained by taking the output before recombination. More generally, the pulse burst can be tailored by tuning the dividing elements. An example of this with 2 dividing crystals (4 pulses) is shown in Figure 5.

Of course, the use of bulk crystals for pulse division and recombination does sacrifice some of the benefits of fiber construction. Thus, the DPL approach might be most-attractive in fiber-based lasers that already contain bulk components. However, in the current set-up, the free-space alignment could be reduced to a point-to-point alignment through the crystal stack by replacing the other bulk components with their fiber-format equivalents, such as fiber Bragg gratings for the anomalous dispersion, fiber-coupled SESAMs and Faraday rotators, and fiber polarization controllers. As mentioned above, the implementation shown here is naturally compatible with environmental stability of the fiber segment in the laser.

DPLs may offer advantages for other lasers and pulse evolutions, such as in dissipative soliton, self-similar, and dispersion managed soliton lasers. Experimental results on divided-pulse nonlinear compression [10] indicate that the pulse division and recombination works in the presence of spectral breathing, which will occur with these pulse evolutions. The DPL technique is compatible with other energy-scaling techniques such as the use of large-core

fiber. The technique should be applicable to other gain media. Control of the pulse evolution is generally limited in solid-state systems, so divided-pulse lasers may be particularly interesting, although polarization sensitivity of the gain media will have to be addressed.

In conclusion, we have proposed and demonstrated the use of coherent pulse division and recombination within a laser cavity. The DPL concept has enabled 16 times scaling of the pulse energy from a fiber soliton laser. This technique should be applicable to other laser systems and may enable record-breaking oscillator performance.

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Fig. 1.

(Color online) Schematic representation of DPL illustrated using two dividing elements.

SAM: saturable absorber mirror; DD: dispersive delay. The dispersive delay line may or may not be included.

Fig. 2.
(Color online) Divided-pulse soliton fiber laser. M: mirror; F.R.: Faraday rotator; col.: collimator; WDM: wavelength division multiplexer; QWP: quarter-wave plate; HWP: half-wave plate; PBS: polarizaing beam splitter; ISO: isolator; SESAM: semiconductor saturable absorber mirror.

Fig. 3.

(Color online) Experimental results with no pulse division: (a) spectrum; (b) autocorrelation of output pulse; and experimental results with 1 dividing element in the laser cavity: (c) spectrum; (d) autocorrelation of recombined output pulse; and (e) autocorrelation of divided pulse.

Fig. 4.

(Color online) Experimental results: with 2 dividing crystals (a) spectrum; (b) autocorrelation of recombined pulse; with 3 dividing crystals (c) spectrum; (d) autocorrelation of recombined pulse; with 4 dividing crystals (e) spectrum; (f) autocorrelation of recombined pulse. The autocorrelation is multiplied by a factor of 20 and displaced vertically (blue traces) to highlight the slight imperfections in the recombination.

Fig. 5.
Autocorrelation of a pulse burst with two dividing crystals in the cavity.