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Generation of megawatt peak power picosecond pulses from a divided-pulse fiber amplifier

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Abstract

Control of nonlinearity is a challenge in fiber amplifiers designed to generate pulses of a few picoseconds duration, and as a result, picosecond fiber amplifiers have failed to reach peak power of 1 megawatt. Divided-pulse amplification, combined with the use of circular polarization, allows the generation of 2.2-ps pulses with energy as high as 2.5 μ J and peak power of 1 MW.

High-energy picosecond pulses are needed for a variety of applications, such as micromachining. In some cases the pulses should be close to the transform limit. For example, for frequency-doubling the spectrum should be narrower than the phase-matching bandwidth of the nonlinear crystal. In the design of high peak power picosecond fiber amplifiers, it is crucial to avoid excessive nonlinear phase shift, which leads to spectral broadening and eventually to distortion of the temporal profile. The spectrum will broaden when the pulse propagates a distance longer than the nonlinear length. Ideally, the nonlinear length should exceed the length of the amplifier. To this end, one can decrease the peak power, and/or use gain fibers with large mode area (LMA).

Chirped-pulse amplification is an effective way of decreasing pulse peak power during amplification. However, it is not well-suited to the amplification of picosecond pulses owing to their narrow bandwidth; impractically-large dispersion is typically needed to stretch and compress pulses longer than ~ 1 ps. As a result, direct amplification is commonly employed in picosecond systems. A peak power of 200 kW for 10-ps pulses was reached by amplification in an LMA photonic crystal fiber (PCF) [1]. However, significant spectral broadening occurred. Spectral compression [2] was employed to reach a time-bandwidth product of 1.42, which is about 3 times the transform limit. In addition, the degree of polarization of the output degraded to $\sim 50\%$. By the use of a LMA photonic-crystal rod, Zaouter *et al.* reached 940-kW peak power with 10-ps pulses [3]. To our knowledge, this is the highest peak power reported for pulses in the 1–10 ps range from a fiber amplifier. Spectral compression was again employed, to reach a time-bandwidth product of 1.1. Impression of the needed chirp on the pulse to induce spectral compression adds complexity to these systems, which still end up with at least a factor of 2 excess bandwidth.

Divided-pulse amplification (DPA) was proposed as a way to reduce nonlinear effects in picosecond-pulse amplification [4]. In this technique, the input pulse is divided into many copies to decrease the individual pulse peak power before amplification. The individual

amplified pulses are recombined after the amplifier to create a pulse with high peak power. The division and recombination process can be realized with birefringent crystals [4], a Sagnac interferometer [5], or polarization cubes [6]. In the initial report of DPA [4], amplification to nanojoule energies was demonstrated as a proof of the concept.

Scaling of DPA to higher energy should be feasible with larger divisors and LMA fibers. However, the limits of faithful division and recombination have not been explored. In particular, nonlinear phase shifts accumulated by high-energy pulses may be expected to adversely affect the recombination process. In this letter we report DPA at the microjoule level, which is 3 orders of magnitude increase over the initial demonstration [4]. We describe a DPA system that generates 2.2-picosecond pulses with linear polarization, pulse energy of up to 2.5 μJ , and peak power up to 1 MW. As far as we know, this is the highest peak power to date from a picosecond fiber amplifier.

The seed pulse comes from a soliton fiber oscillator, and a bandpass filter suppresses the Kelly sidebands. Three stages of amplification are used to reach an overall gain of about 40 dB. The stages employ single-mode fiber with a 6- μm core, double-clad fiber with a 10- μm core, and a double-clad PCF with a 40- μm core, respectively. The fibers are Yb-doped. All three amplification stages employ DPA, but that is not essential; it was a convenient way to produce 10-nJ seed pulses for the main amplifier, which is our focus here. After the first preamplifier, an acousto-optic modulator (AOM) reduces the repetition rate from 44 MHz to 880 kHz. The extinction ratio of the AOM for pulses adjacent to the selected pulse is 20 dB, so we reduced the repetition rate by only a factor of 50, to avoid excess energy in secondary pulses. The experimental schematic of the main amplifier is shown in Fig. 1. Without DPA, nonlinearity begins to distort the spectrum at the 100-nJ level.

The DPA concept is described in detail in Ref. 4. Briefly, the shortest crystal length is chosen to split the input pulse into copies separated by more than the pulse duration. Each successive crystal is chosen to be roughly a factor of 2 longer than the previous one, to produce a sequence of 2^N pulses with N crystals, and ideally reduce the peak power by the same factor. The factor 2 is to get equally-separated pulses, but may not be necessary. The amplified pulses are recombined by the reverse process. In the main amplifier, division by 32 is implemented with a set of five *a*-cut YVO₄ crystals. The polarization-mode delay is ~ 0.8 ps/mm at 1040 nm. For amplification of 2-ps pulses, the shortest crystal should be at least 2.5 mm long. In contrast to the initial report of DPA [4], the crystals are placed in order of decreasing length (57.6 mm, 28.8 mm, 14.4 mm, 7.2 mm and 3.6 mm) for the division process (Fig. 2). In this way, the divided pulses have linear polarizations that alternate between horizontal and vertical, instead of the polarization changing only once, after the first 16 pulses. Figure 2 shows the polarization states of the individual divided pulses when the input pulse goes through the first three crystals. The alternating polarizations reduce interference between the tails of the pulses, which can distort the recombined pulse [7].

The advantage of circular over linear polarization in amplifiers due to the different nonlinear refraction coefficients for linearly- and circularly-polarized light has been demonstrated [8]. The nonlinear phase accumulated by circularly-polarized light is 2/3 of that accumulated by linearly-polarized light. To determine the feasibility of exploiting circularly-polarized light in the DPA system, the Jones matrix [9] for the propagation of circularly-polarized light between the division and recombination processes was calculated:

$$\begin{aligned}
T &= T_{QWP,b} T_{Yb,b} T_{FRM} T_{Yb,f} T_{QWP,f} \\
&= \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & i \\ i & 1 \end{bmatrix} g_b \begin{bmatrix} m & -p \\ -n & q \end{bmatrix} \gamma \begin{bmatrix} 0 & -1 \\ -1 & 0 \end{bmatrix} g_f \begin{bmatrix} m & n \\ p & q \end{bmatrix} \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & -i \\ -i & 1 \end{bmatrix} \\
&= g_b \gamma g_f (np - mq) \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}
\end{aligned} \quad (1)$$

where m , n , p , and q are complex values that depend on the birefringence and the polarization-dependent loss in the fiber, and the subscripts f and b stand for forward and backward propagation. If $mq - np = 1$, g_f and g_b become the forward and backward polarization-averaged amplitude gain, respectively, and γ is the transmission coefficient of the Faraday rotator mirror. Equation (1) shows that even with the insertion of wave plates to convert linear to circular polarization, the input polarization to the recombination process is always orthogonal to the output polarization of the division process. This is required when the same set of crystals is used for division and recombination. Thus, amplification of circularly-polarized light is compatible with DPA, and it can be realized by simply inserting a quarter-wave plate into the system.

The full-width-at-half-maximum duration and the 3-dB spectral width of the seed pulse are 1.8 ps and 0.95 nm, respectively, which corresponds to a time-bandwidth product (TBP) of 0.48. The pulse energy is about 10 nJ. Faithful amplification is obtained for average power up to 2.2 W, which is obtained with 11 W pump power (Fig. 3(a)). The output pulse energy is approximately 2.5 μ J. The spectrum of the amplified pulse is just beginning to exhibit some distortion at 2.5 μ J (Fig. 3(b)). The output pulse and spectrum are broadened a bit, to 2.2 ps and 1.1 nm, by the amplification, which corresponds to a TBP of 0.68. The peak power of the output pulse is therefore 1 MW if a Gaussian pulse profile is assumed.

For pulse energies above 2.5 μ J, which corresponds to a nonlinear phase shift of about 0.7π , the spectrum broadens further and develops some structure. Small satellite pulses also begin to appear in the temporal profile (inset of Fig. 3(c)). Numerical calculations identify these as a signature of nonlinear interference in the recombination. We find that the quality of the output beam from the PCF degrades a bit at high pulse energy. As the pulse energy increases from 0.3 to 2.5 μ J, the M^2 value increases from 1.16 to 1.28, and it continues to increase at higher pump power. The inset in Fig. 3(c) shows the near-field beam profile at 2.2 W output power. Nicholson *et al.* found that higher-order mode content may increase with pump power even in PCF [10], and this appears to explain the increase in M^2 that we observe.

Frequency-doubling of the 1040-nm output of the fiber amplifier was carried out using noncritical phase matching in a 15-mm lithium triborate crystal, which has a phase-matching bandwidth of 2 nm. The harmonic power increases less than quadratically with fundamental power, but the efficiency still exceeds 50% with 2.5- μ J pulses. Preliminary simulations with SNLO [11] show a roughly linear dependence of the second-harmonic energy on the fundamental energy, which is consistent with the experimental results. These results reflect the high quality and spectral purity of the amplified pulses.

Extension of the results presented here to higher power should be possible. In principle it is feasible to use more crystals to further decrease the peak power in the amplifier. Limited by the crystal growth technique, YVO₄ crystals longer than 50 mm have reduced quality and become quite expensive. However, we verified that 2 crystals could be abutted to create a longer effective crystal. On the other hand, increasing the divisor by the addition of birefringent crystals with shorter length would require seed pulses of shorter duration to avoid pulse overlap. It may be possible to generate 0.5-ps or 1-ps pulses with higher peak power, *e.g.*

The DPA system has valuable practical features. The output is linearly polarized, as it comes from a polarizing beam splitter. This avoids the degradation of the polarization extinction ratio that is observed at high power in direct amplification with non-polarization-maintaining gain fibers [1]. Furthermore, the use of the Faraday rotator mirror automatically cancels any birefringence perturbations to the gain fiber.

In conclusion, a divided-pulse fiber amplifier that can generate 2.2-picosecond pulses with peak power of 1 MW is demonstrated. We expect that this kind of amplifier will find use in a variety of applications.

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Fig. 1. Schematic of circular polarization DPA with Yb-doped PCF. PBS: polarization beam splitter; QWP: quarter-wave plate; M: mirror; L₁, L₂, L₃: lens; DM: dichroic mirror; FR: Faraday rotator.

Fig. 2. Schematic of polarization evolution of divided pulses when the input pulse goes through 3 crystals. OA: crystal optical axis.

Fig. 3.

(a) Pump power dependence of output power; (b) spectra of the seed and output pulses; (c) autocorrelation trace of the output pulse, insets: expanded view of output pulse, and output far-field beam profile.