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LETTERS

Compression after compressor: threefold shortening of 200-TW laser pulses

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Abstract. **Compression of a 12-J laser pulse from 63 to 21 fs is experimentally demonstrated for a beam 18 cm in diameter. The compression is implemented for a pulse freely propagating in glass under conditions of self-phase modulation and subsequent compensation for dispersion under reflection from dispersion mirrors. This simple and inexpensive technique for increasing multiply the pulse power is characterised by almost 100% energy efficiency and can be used at the output of any ultra-high-power laser, without any changes in its optical scheme.**

Keywords: *self-phase modulation, compression of femtosecond pulses, multiterawatt laser system.*

1. Introduction

Literally several years after the development of the first laser in 1960, the laser radiation intensity was raised to 10^{14} W cm^{-2}, but it remained practically at the same level during the next 20 years. The development of the chirped-pulse amplification (CPA) method in 1985 [1] led to a sharp increase in the laser power; the record intensity value (10^{22} W cm^{-2}) was obtained in 2004 [2]. However, no new records have been made since that time. The reason is that limitation on power is now imposed by the compressor rather than the CPA amplifier: the laser intensity is determined by specifically the breakdown threshold of the compressor diffraction grating (see, e.g., [3]). Thus, the CPA compressor is now the weakest unit in the stretcher–amplifier–compressor chain. There are three possible ways to increase laser power. The first is to use mosaic (combined) gratings in the compressor, and the second way is to form phase-matched parallel CPA channels, each of which has an intrinsic compressor at the output. These two approaches have a number of significant drawbacks: multiple increase in the pulse energy, difficulties in practical realisation, large sizes, and high cost. These drawbacks are absent in the third approach, where an increase in power is provided by not increasing the pulse energy but decreasing the pulse duration: the pulse is compressed after the compressor. This technique is referred to as the compression-after-compressor approach (CafCA) [4]. To implement this procedure (see Fig. 1), the spectrum of a pulse propagating in a medium with Kerr nonlinearity is expanded due to the self-phase modulation (SPM), after which it is compressed by dispersion mirrors.

The concept of using cubic nonlinearity for SPM was proposed by R. Fisher et al. in 1969 [5]. A several-fold compression of a 20-ps pulse under SPM conditions in a cell filled with CS_2 was also demonstrated in 1969 [6]. Later on, SPM was implemented (in the femtosecond range) in a fibre [7], in gas-filled hollow waveguides [8], and in a volume limited in the transverse direction [9]. However, compression was obtained for only pulses with energies of few millijoules, because the beam diameter was less than 1 mm in all these experiments. The energy scaling limitation is related to the spatial beam inhomogeneity, which is insignificant for the waveguide propagation but is of fundamental importance in the case of free-space propagation. The CafCA method has been developed for much higher power lasers, with beams characterised by a quasi-homogeneous intensity distribution. In 2011, multiple spectral broadening of a second-harmonic pulse with an energy of 4.7 mJ and a beam diameter of 3 mm was experimentally observed in [10]. A number of experiments have been performed in the last few years [11–15], where the CafCA method was successfully implemented for beams with energies ranging from 20 mJ to 5.5 J. These studies were motivated to a great extent by the proposed and experimentally confirmed technique for suppressing the small-scale self-focusing [16], which makes it possible to increase significantly the compression multiplicity, as well as the concept [17] of using polymer materials (plastic) as a nonlinear medium. The current record result was obtained using specifically a plastic: a 5.5-J pulse with a width of 57 fs was compressed to 22 fs [13].

In this study, we report the next step in the direction of CafCA scaling: a threefold compression of a 12-J pulse on the total (18 cm) beam aperture of a 200-TW laser is experimentally demonstrated.

2. Experimental results

A schematic of the experiment is presented in Fig. 1. The PEARL laser beam (centre wavelength 920 nm, diameter 18 cm) with a pulse energy of 10–15 J and width of 50–70 fs, after the reflection from the last diffraction grating of the compressor, propagated at a distance of 2.5 m in free space for self-filtration [16]. Then it was successively transmitted

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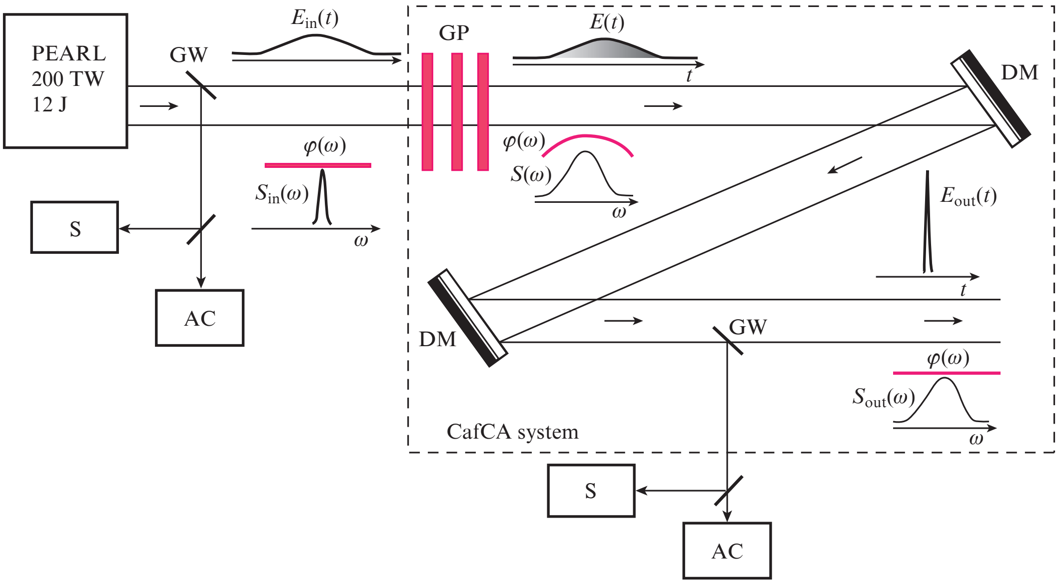

Figure 1. Schematic of the experiment: (GP) glass plates; (DM) dispersion mirrors; (GW) small-aperture glass wedges; (AC) autocorrelators; (S) spectrometers.

through three glass plates (each 1 mm thick), spaced at a distance of about 1 cm. The use of three plates instead of one (3 mm thick) made it possible to reduce the small-scale self-focusing. Then, after the free propagation at a distance of 4 m, the beam was reflected from two dispersion mirrors 20 cm in diameter (UltraFast Innovations GmbH); the dispersion of each mirror was -100 fs^{-2}, and the reflectance exceeded 99%. To measure the parameters of input and output pulses, two glass wedges with an aperture of 1×2 cm and a matte rear surface were introduced into the beam. One was installed before the glass plates, and the other was placed behind the dispersion mirrors. The beams reflected from the wedges were directed to two spectrometers and two autocorrelators. Since the cross-sectional homogeneity of the PEARL laser beam was sufficiently high, the spectra and widths of the input and output pulses coincided accurate to 10% in the absence of glass plates. Thus, we implemented the possibility of measuring the radiation characteristics for one shot.

The measured spectra and the intensity autocorrelation functions (ACFs) for both pulses are presented in Fig. 2 (solid lines); the pulse energy is 12 J, the intensity is ~1.1 TW cm^{-2}, and the B integral stored in three plates is ~6. Based on the measured spectra, we chose the pulse shapes whose ACFs were closest to the measured ACFs. Their shapes and ACFs are shown by dotted lines in Fig. 2. The output-pulse parameters were calculated (Fig. 2, dashed lines) for the chosen shape of input pulse.

It can be seen in Fig. 2a that the output pulse spectrum is significantly broadened and contains narrow peaks, characteristic of the spectra of non-transform-limited pulses subjected to SPM (see [18] for details). There is a qualitative coincidence between the calculated and experimental spectra, although the widths and amplitudes of the peaks differ.

The FWHM values for the experimental ACFs at the input (93 fs) and output (31 fs) of the CafCA system differ by a factor of 3 (Fig. 2b), whereas the ACF of the theoretically

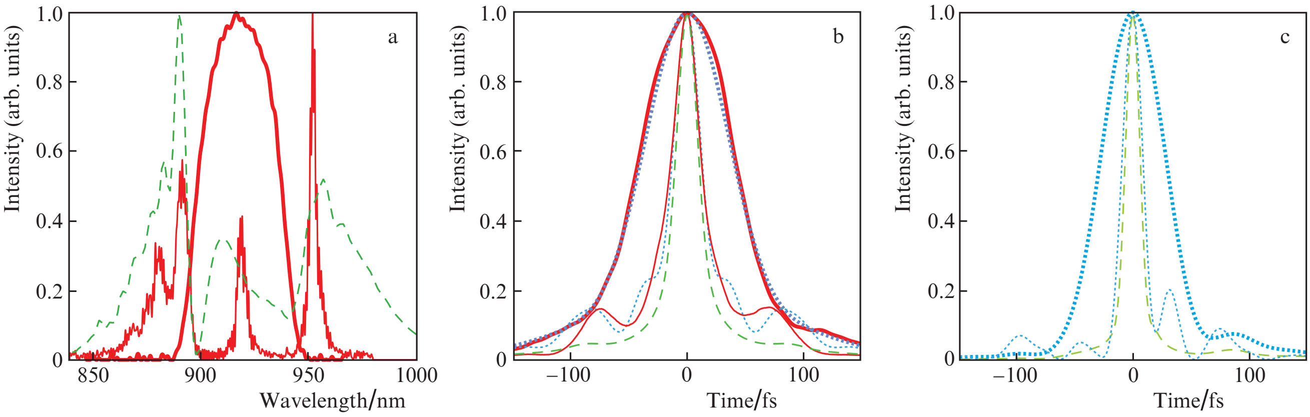

Figure 2. (a) Spectra, (b) ACFs, and (c) shapes of pulses at the input (bold lines) and output (thin lines) of the CafCA system: (solid lines) experimental, (dashed lines) theoretical, and (dotted lines) chosen (see text) data.

calculated pulse is shortened by a factor of 4. Apparently, the reason is that the experimental spectrum of the output pulse is narrower than the theoretical one. The pulse FWHM also decreases by a factor of 3: from 63 ± 3 to 20.5 ± 2.5 fs, although the calculation predicts fourfold shortening (Fig. 2c). One of possible causes of the discrepancy between the experiment and theory is the spectral narrowing in the measuring channel of our system because of the large loss of radiation with wavelengths above 955 nm in the transport optics. A detailed comparison of the theoretical and experimental data will be given in a separate publication.

Thus, the results presented above demonstrate a possibility of threefold narrowing of a 200-TW pulse by nonlinear compression. The CafCA method has three undoubted advantages. Primarily, it is simple and inexpensive: one needs only a plane-parallel plate and one or several dispersion mirrors, whose fabrication technology is well developed. The second advantage of this method is the possibility of applying it to practically all existing super-power lasers without any modification of the latter. Finally, CafCA is highly efficient: the energy losses (with allowance for the possibility of orienting the plate at the Brewster angle and using dispersion mirrors with a reflectance higher than 99.6%) do not exceed 1%.

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