100-TW Femtosecond Laser Based on Parametric Amplification


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In experiments on the parametrical amplification of femtosecond pulses in wide-aperture DKDP crystals, a power of more than 100 TW has been reached, which is much higher than the record level achieved in such lasers. The energy efficiency obtained for the parametric amplifier is equal to 27%. The energy of a 72-fs pulse is equal to 10 J. © 2005 Pleiades Publishing, Inc.

Petawatt power was reached for laser radiation already in 1997 [1] using the amplification of chirped pulses in neodymium glass. To date, this level has been achieved only in three laboratories in the world [1–3]. A further increase in the power is fundamentally limited by the narrow gain band of neodymium glass and the low optical stability of diffraction gratings. The use of parametric amplifiers instead of standard laser amplifiers is one of the most promising ways for overcoming the petawatt power barrier. In such systems, which were first proposed in [4, 5], by choosing a nonlinear crystal, propagation directions, and frequencies of the pump and signal waves, the conditions of broadband phase matching are realized and, in addition, the principle of sequential extension (chirping), multicascade amplification, and, in addition, the compression of amplified pulses, which is traditional for the generation of superstrong fields is used.

The amplification of femtosecond pulses to petawatt powers in parametric amplifiers requires, first, the kilojoule energy of a pump pulse with a duration of about 1 ns, which makes neodymium glass lasers most promising, second, nonlinear crystals with an aperture of 30 cm or larger, which restricts the choice to only two candidates: the KDP and DKDP crystals.

The problem of creating parametric amplifiers of femtosecond pulses to multiterawatt and petawatt levels was discussed and experimentally studied in [6–10]. In those works, KDP crystals were considered as nonlinear elements in the last cascades of parametric amplifiers. In these crystals, upon pumping by the radiation of the second harmonic of a neodymium-glass laser (pump wavelength of 527 nm), the maximum width of the gain band is reached close to degenerate interaction (signal wavelength of about 1054 nm). In [11, 12], we proposed to use nondegenerate parametric amplification in the DKDP crystal, which, in contrast to the KDP crystal, is transparent to about 1.4 μm [13]. Moreover, as was shown in [12, 14], for the central wavelength of 910-nm signal radiation, the ultrabroadband phase matching is realized in the DKDP crystal, which makes it possible to amplify pulses with a duration of 10–15 fs. As driven femtosecond generators, lasers operating at the wavelength of 910-nm signal radiation (sapphire with titanium) or 1250-nm idler radiation (forsterite with chromium) can be used. As was shown in [15], the latter variant is promising. More recently, a 0.44-TW laser was created [14, 16]. This laser is a start system for a 100-TW laser complex described in this paper.

Figure 1 shows the scheme of the 100-TW laser complex with a Cr: forsterite laser emitting 45-fs pulses with an energy of 3 nJ (central wavelength of 1250 nm) as a master oscillator. We used an original stretcher (passband of 1000 cm⁻¹), which contained two prisms in addition to ordinary diffraction gratings, which made it possible to efficiently compress a 600-ps pulse with a wavelength of 910 nm by means of a usual compressor [14, 16].

The second harmonic of a single-mode single-frequency Nd:YLF laser with a wavelength of 527 nm, energy up to 1 J in a 1.5-ns pulse, and a pulse repetition frequency of 2 Hz is used as the pumping of the first two parametric amplifiers. A fraction of the radiation of
the fundamental harmonic of this laser is directed through a multistep spatial filter [16, 17] to the input of a five-cascade amplifier based on phosphate neodymium glass. The amplifier worked with a period of one pulse per 30 min and ensured the output energy of 70 J of a second-harmonic pulse with a duration of 1.2–1.5 ns for a beam diameter of 10 cm. The divergence of the output radiation was equal to three diffraction limits, which satisfies the requirement imposed on the pump radiation of the third parametric amplifier. The pumping system of all parametric amplifiers was described in detail in [18] and its synchronization with the femtosecond driving generator was discussed in [19].

The first parametric amplifier was two-pass. It performed the wide-band transformation of 1250-nm chirped pulses into 910-nm signal pulses at the first pass and amplified the 910-nm radiation at the second pass. After the second amplifier, the pulse energy reached several tens of millijoules. The adjustment procedure, as well as spectral, angular, and energy characteristics of the first two parametric amplifiers (terawatt power), was described in detail in [14].

The third parametric amplifier (a noncoated DKDP crystal 65 mm in length with a clear aperture of 100 mm) had a weak-signal amplification factor of 1500 for a pumping energy of 50 J. For an input signal of several tens of millijoules, these parameters ensured the deep saturation of the parametric amplification. The energy of 16 J of the chirped pulse at the input of the compressor was reached due to saturation and the high quality of the pump beam, see Fig. 2. The maximum physical energy efficiency of the parametric amplifier was equal to 27%. The radiation spectrum was not narrowed.

To compress the pulse, we used a vacuum compressor based on two diffraction gratings and one angular reflector with a pure aperture of 110 mm. The transmission coefficient of the compressor was equal to 65%. The remote adjustment system ensured the adjustment of all the optical elements of the compressor with an accuracy of five angular second. Neither narrowing of the spectrum nor angular chirp is observed in the output radiation. The maximum energy of the compressed pulses was equal to 10 J. Figure 3 shows the autocorrelation function. It corresponds to a Lorentz pulse with an FWHM of 72 fs. Thus, the peak power at the output of the femtosecond laser complex based on the parametric amplification of chirped pulses was equal to 130 TW, which is eight times higher than the record