200 TW 45 fs laser based on optical parametric chirped pulse amplification

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Abstract: 200 TW peak power has been achieved experimentally using a Cr:forsterite master oscillator at 1250 nm, a stretcher, three optical parametrical amplifiers based on KD*P (DKDP) crystals providing 14.5 J energy in the chirped pulse at 910 nm central wavelength, and a vacuum compressor. The final parametrical amplifier and the compressor are described in detail. Scaling of such architecture to multipetawatt power is discussed.

OCIS codes: (320.7090) Ultrafast lasers, (190.4970) Parametric oscillators and amplifiers, (320.5520) Pulse compression

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1. Introduction

Petawatt-level laser pulses make possible to experimentally investigate highly nonlinear process in atomic, molecular, plasma, and solid-state physics and to access previously unexplored state of matter. The main applications of such lasers are laboratory-based astrophysics, fast ignition fusion, generation of ultrafast coherent X-rays, particles acceleration, radiography etc.

The petawatt laser power was achieved as early as in 1997 [1] based on chirped pulse amplification in Nd:glass. Currently, three laboratories in the world hold petawatt level laser system [2-4]. Many institutes are going to obtain even higher power levels [5-13], but any further increase is limited in principle by the narrow gain width of Nd:glass, small aperture of Ti:sapphire crystals and low damage threshold of diffraction gratings. Using optical parametric amplifier (OPA) instead of an ordinary laser amplifier is one of the most promising ways of overcoming the petawatt power barrier. In such systems first suggested in [14, 15], the conditions of broadband phase-matching are obtained by appropriately selecting a nonlinear crystal, directions of propagation and frequencies of pump and signal waves.

To reach petawatt powers the OPA needs to have, first, kilojoule energy level of pump pulse with duration of about 1 ns. This makes the use of a Nd:glass laser most promising for this purpose. Second, nonlinear crystals with an aperture of 30 cm and more are needed. Due to this restriction, the only appropriate candidates are KDP and KD*P (DKDP) crystals.

In the most papers (see for example [5, 16-21]) devoted to the multiterawatt and petawatt lasers based on OPAs only KDP crystals were concidered for the final amplification cascades. The maximum gain bandwidth in KDP is obtained under pumping by second harmonic of a Nd:glass laser (pump wavelength is 527 nm) close to degenerated interaction (signal wavelength ~1054 nm).

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In [22, 23] we suggested using non-degenerate parametric amplification in a KD*P crystal, which, in contrast to the KDP crystal, is transparent approximately up to 1.4 μm. In addition, studies [23-25] showed that ultra-broadband phase matching at the central wavelength of signal radiation of 910 nm can be achieved in the KD*P crystal due to the peculiar properties of KD*P Sellmeier equation. It makes possible to amplify 10-15 fs pulses which is shorter than KDP by factor of 2.5. The femtosecond master oscillator can be lasers operating at a signal wavelength of 910 nm (Ti:sapphire) or at an idler wavelength of 1250 nm (Cr:forsterite). Good prospects of the second option were demonstrated in [25]. Later on a laser with 0.44 TW power was created based on two OPAs [24, 26]. Adding one more OPA provided a laser power of 100 TW [13].

This paper is devoted to 200 TW laser based on the scalable architecture described in the previous paragraph. The experimental setup is presented in Section 2. The key element of the laser is the final OPA, as described in Section 3. Finally, the pulse compression and output radiation characteristics are discussed in the Section 4.

2. Experimental setup

The schematic diagram of the 200 TW laser comprising a front-end system and a power system is shown in Fig. 1. The front-end system was based on two OPAs and operated at a repetition rate of 2 Hz. The femtosecond master oscillator was a Cr:forsterite laser generating 40 fs pulses with 2 nJ energy at the central wavelength of 1250 nm.

The first two OPAs (OPA I and OPA II) were pumped by the second harmonic of a single-mode single-frequency Nd:YLF laser with a wavelength of 527 nm, up to 1 J energy in a 1.5 ns pulse [27]. The pump intensity at the input of the OPAs had almost uniform cross-sectional distribution and was about 1 GW/cm^2. A two-stage synchronization scheme [28] provided the simultaneous (to within ~50 ps) passage of the pump and amplified radiation pulses through the nonlinear OPA crystals.

The nonlinear KD*P elements in the OPA I and II were 70 mm in length, and the deuteration level was 88.7%. OPA I was a double-pass amplifier. During the first pass, the OPA I performed broadband conversion of chirped pulses at 1250 nm into pulses of signal radiation at 910 nm. During the second pass, the 910 nm radiation was amplified. So we called the injected radiation at 1250 nm as idler and the radiation at 910 nm as signal one. After OPA II, pulse energy reached a few tens of millijoules. The adjustment procedure and spectral, angular and energy characteristics of the first two OPAs are described in detail in [24].

The requirements to the stretcher dispersion characteristic change significantly if the signal is excited by the idler wave. During the three-wave interaction the chirp inversion is occurred. In this case, the quadratic dispersion of the stretcher-compressor system is zero if the second order dispersions of the stretcher and compressor are identical. As for the cubic dispersion of the system, it can turn to zero only if the third derivatives of the phase incursions in the stretcher and compressor are opposite in sign. We used an original stretcher which incorporates a prism pair between the diffraction gratings [24, 26]. For a certain choice of parameters this stretcher allows efficient pulse compression at a wavelength of 910 nm after OPA using an ordinary grating compressor [29]. The stretcher having a transmission band of 1000 см$^{-1}$ expanded the pulse duration up to 600ps.

OPA III was pumped by second harmonic of a five-stage Nd:glass amplifier [27, 30]. The amplifier was seeded by part of the fundamental harmonic radiation of the Nd:YLF laser. The amplifier worked with a period of one shot in 30 minutes and ensured output pulse energy of 130 J at the fundamental wavelength at pulse duration of 1.2-1.5ns. The second harmonic pulse energy reached 75 J. The near field distribution of the 8 cm pump beam was smooth enough for providing the good quality of the signal beam (see the Section 3). The pump beam divergence was three diffraction limits. This satisfies the requirement imposed on pump

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radiation of the OPA III. A detailed description of the pump system for the all parametric amplifiers can be found in [27].

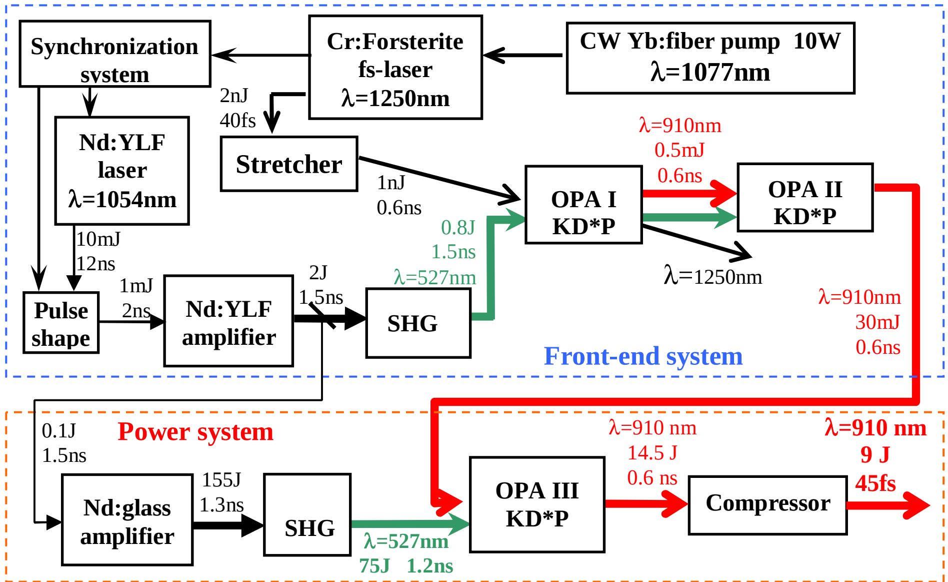

Fig. 1. Scheme of 200TW laser system based on OPAs.

After OPA II the signal radiation passed through a spatial filter, delay line and expanding telescope and was directed to OPA III. The nonlinear element was non-coated KD*P crystals with the length 80 mm and clear aperture of 100 mm. Although we have investigated the main physical characteristics of the broadband optical parametric amplification in the KD*P crystal based on the front-end system [24, 26] , while the third amplifier did only energy scaling of the system, the single-shot operation regime of the pump laser required a special procedure to adjust the OPA III. This procedure and characteristics of OPA III are described in the following section.

3. Study of final OPA

At non-collinear geometry of three-wave interaction, two phase-matching angles should be tuned for broad-band amplification. These are an angle θ_3 between the pump wave vector and the optical axis of the KD*P crystal and an angle φ_{13} between wave vectors of pump and signal radiation (see Fig. 2).

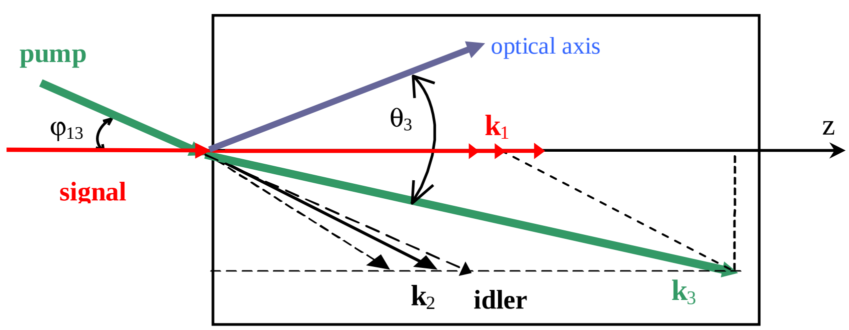

Fig. 2. Schematic diagram of non-collinear three-wave interaction in a nonlinear crystal at optical parametric amplification of broadband signal radiation.

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The angle θ_3 was tuned based on observation of the far field distribution of parametric super luminescence (CCD-camera placed in the focal plane of 200mm lens, see Fig. 3). At each frequency the wave vectors of parametric super luminescence form cone around pump's wave vector. So if angle θ_3 is tuned right for broadband amplification of collimated signal then we should observe a contrast arc in the far field distribution of luminescence radiation, because lots of spectral components propagate in the same direction [24]. For preliminary adjustment of the OPA III we pumped it by frequency-doubled radiation from the first active element of the Nd:glass amplifier with 10mm diameter, see Fig. 3. On the one hand it allowed us to make shots once in five minutes. On the other hand, this pump beam was intense enough for us to observe parametric super luminescence. This beam was superposed in direction with the main pump beam in the focal plane of a 3m lens. This lens also served for control of the directions of pump and signal beams before shots. Fig. 4 demonstrates a contrast arc of parametric super luminescence in the focal plane of a 200 mm lens.

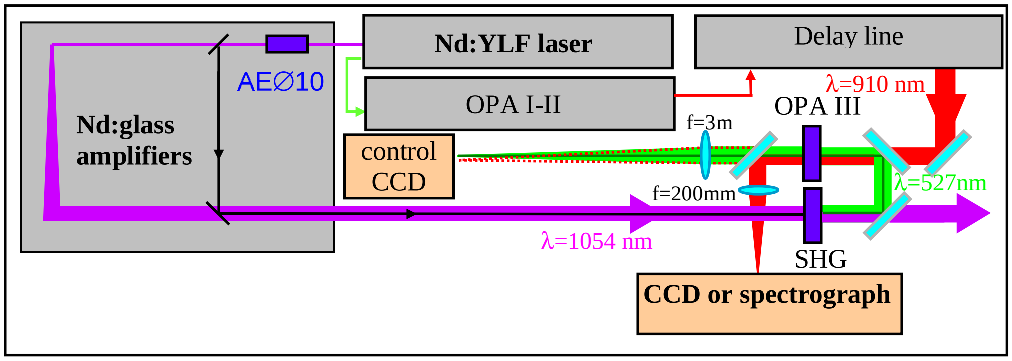

Fig. 3. Schematic diagram of experimental setup for OPAIII adjustment.

For a more precise adjustment of the angle θ_3 we focused parametric super luminescence radiation on a spectrograph consisted of an entrance slit, two concave mirrors, which transform the image from the slit to a CCD camera, and a diffraction grating placed in the mirror focal plane. The spectrograph allows to observe the spectral-angular diagram [24, 25], see Fig.5. The horizontal axis on this diagram corresponds to wavelength and the vertical axis corresponds to propagation direction in the vertical plane (the critical plane of parametric interaction). The proper adjustment of the angle θ_3 corresponds to the horizontal line on the spectral-angular diagram, see Fig. 5(b), i.e., all frequencies propagate in the same direction.

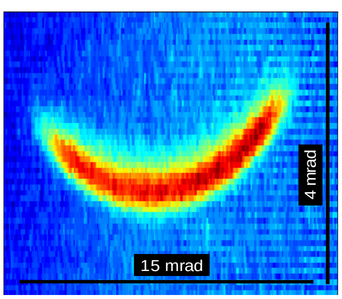

Fig. 4. Contrast arc in far field of parametric superluminescence.

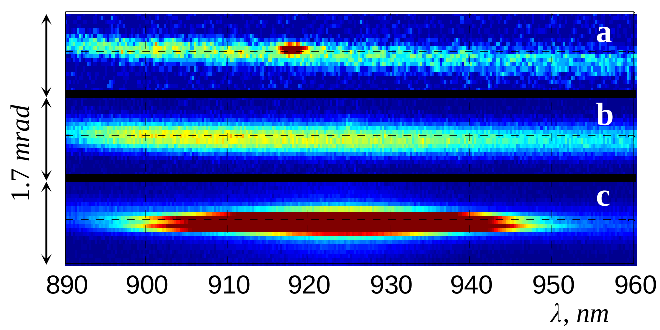

Fig. 5. Spectral-angular diagram of parametric superluminescence at wrong (a) and proper (b) alignment of θ_3 and as well as of an amplified signal from OPA I (c).

Once the angle θ_3 was tuned, we needed only to superpose the signal direction with the direction of superluminescence radiation to adjust the angle φ_{13}. We did it using only the front-end system with 2Hz repetition rate. Finally we checked angle φ_{13} by observation in single shot the spectral-angular diagram of super luminescence in OPA III and a signal from front-end system amplified in OPA III (Fig. 5(c)). The pump of OPA II was blocked to equalize signal and super luminescence. The suggested adjustment procedure of the parametric amplifier allowed for independent tuning of the phase-matching angles and typically required only two shots of the pump laser, which was very fruitful in practice.

To study the characteristics of OPA III, part of signal radiation (~1%) was branched off by means of a coated glass wedge to a diagnostic system. It allows us to measure the pulse energy, the signal beam distribution in the far and near fields, and the spectral-angular diagram at a single shot.

Output energy and efficiency of the OPA III are shown in Fig. 6. The small signal gain was 1600 at pump energy 65 J. At an input signal of 10…30mJ this provided deep saturation of parametric amplification. Maximal efficiency of the OPA III was 25% with respect to energy. Due to the saturation and good quality of the pump beam, the chirped pulse energy at the compressor input was up to 14.5 J. Pretty good quality of this beam is demonstrated in Fig. 7. The far field distribution was measured in the focal plane of the lens with a focal length of 5m.

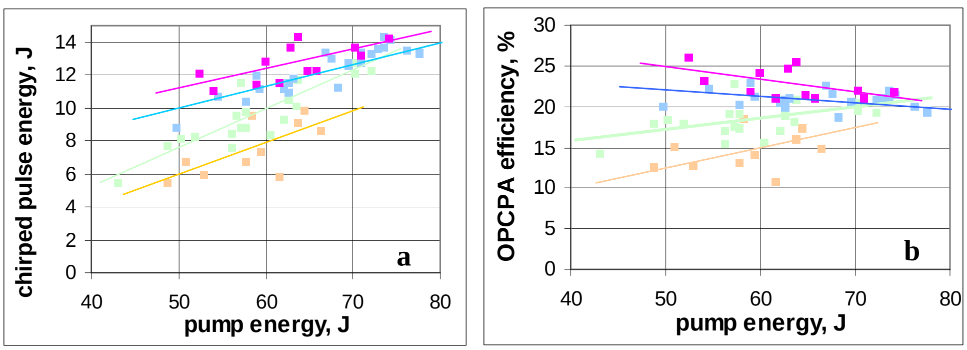

Fig. 6. Pulse energy at the compressor input (a) and OPA III energy efficiency (b) vs. pump pulse energy at input OPA III signal pulse energy 3-7.5mJ (brown), 7.5-15mJ (green), 15-20mJ (blue), and 20-27mJ (pink).

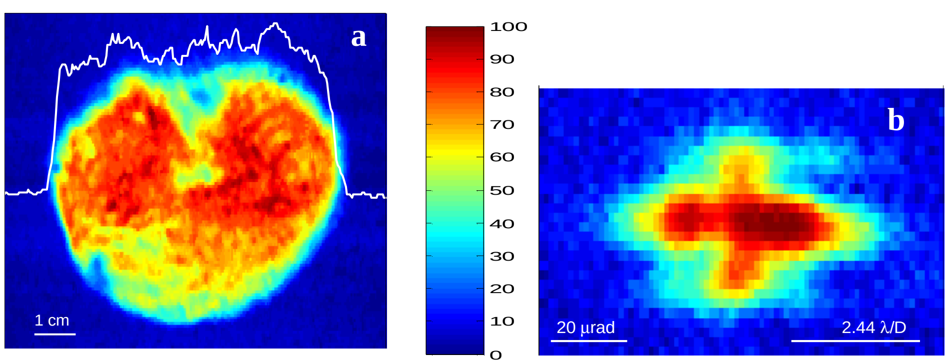

Fig. 7. Quality of signal beam after OPA III in near field (a) and far field (b).

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4. Compression of amplified radiation

For pulse compression we used a compressor with a clear aperture of 110 mm consisted of two diffraction gratings and a roof reflector. The gratings (38x24cm aperture, 1200 l/mm) were coated by 400 nm gold layer [31] and separated by 134 cm. Reflectivity of the grating at 910 nm wavelength was 90…92% within the incident angle 33±10 degree (33.1 degree is Littrow angle). The measured energy transmission coefficient of the compressor was 66%. The compressor bandwidth was $1200 cm^{-1}$.

To prevent undesirable non-linear effects in the air the compressor was placed into a vacuum chamber. All optical elements of the compressor including auxiliary optics are moved remotely by step-motors with an accuracy of 5 angular seconds and 5 microns. For preliminary adjustment we used the CW diode laser operated at 910 nm. Precise alignment was made using wideband signal at 2 Hz repetition rate (OPA III was not pumped) and auxiliary optics temporally moved into the beam path. It took us about 10 minutes to align the compressor or to check the alignment.

The diagnostic system of compressed radiation was situated outside the vacuum chamber and consisted of an energy meter, a single-pulse autocorrelator, a spectrograph measuring the spectral-angular diagram [24, 25], and CCD cameras that measured beam distributions in the far- and near-fields. Mutual compensation of the stretcher's and the compressor's dispersions was adjusted by minimizing the autocorrelation function width without pump of OPA III (2 Hz repetition rate). We did not observed any spectrum narrowing or residual angular chirp at the output of the compressor. To measure radiation parameters when OPA III was pumped, a part of compressed radiation (~0.1%) was branched off and directed to the compressor output by means of remotely controlled movable wedges.

Maximum energy of compressed pulses was 9 J. The autocorrelation function is shown in Fig. 8. It corresponds to a 45 fs Gaussian pulse at FWHM. The same duration is given by the measurement spectra if a Fourier transform limited pulse is assumed. Thus, peak power at the output of the femtosecond laser based on optical parametric chirped-pulse amplification was 200 TW. This value 12 times exceeds the record level achieved earlier [19] in the lasers based on optical parametrical chirp pulsed amplification. Note, that 45fs pulse duration is shorter than in other high power OPCPA setups: 120fs in [19], 80fs in [20], 72fs in [13].

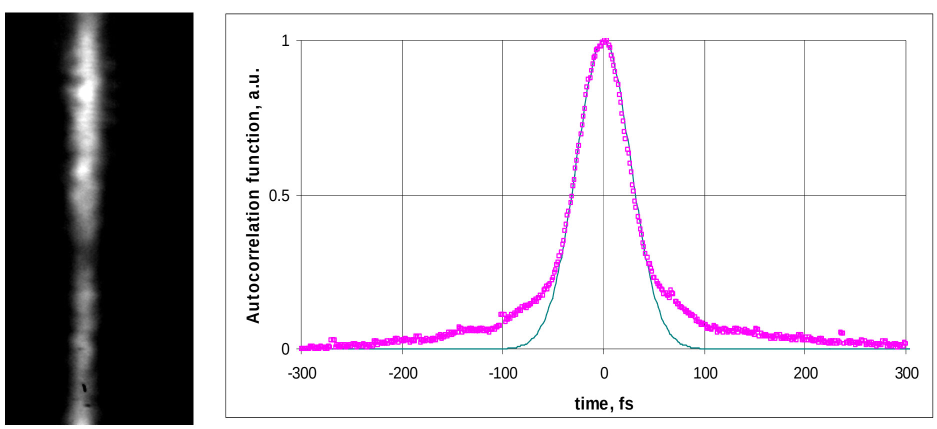

Fig. 8. Autocorrelation function of compressed pulse (photo and ping squares) and autocorrelation function for 45 fs Gausian pulse at FWHM (black solid line).

As shown in Fig. 8 the compressed pulse still has wings due to not perfect dispersion compensation. FWHM pulse duration was limited by the spectrum of our master oscillator which is much narrow than KD*P crystal amplification bandwidth [23-25].

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In the 1ns time window the intensity contrast ratio of the output pulse was better than $2.5x10^{-8}$ (limited by the measurements sensitivity). As for few nanoseconds gate the contrast ratio is infinity due to just single pulse from the pulse train is converted from 1250nm to 910nm wavelength and due to super luminescence is generated during pump pulse duration only. Energy and pulse duration shot-to-shot rms fluctuations were less than 10% rms.

We observed no grating damage after several shots at the 200 TW power level. On the other hand, a small damage appears after about 25 shots in the area where the beam reflected the fourth time. So, taking into account a 6.5 cm beam diameter (see Fig. 7, 9) the damage threshold was more than 500 mJ/cm^2 for a 0.6 ns pulse, and is about 300 mJ/cm^2 for a 50 fs pulse. The grating damage threshold 1 J/cm^2 measured in [31] for a 1.5ns pulse coincides well with our data.

The beam quality at the output of the compressor is shown in Fig. 9. The far-field distribution (Fig. 9(b)) was very stable from pulse to pulse, i.e. it may be improved to the diffraction-limited one by adaptive optics as done in [32]. The difference between the far field patterns before and after compressor is explained by not perfect wide aperture optics in the compressor (we observed the similar behavior of the far field pattern of the auxiliary monochromatic laser).

5. Conclusion

The 200 TW peak power level has been achieved experimentally using the architecture of high-power femtosecond lasers that we suggested earlier. Calculations show that one more optical parametric amplifier with an aperture of 20…25 cm and pump pulse energy of 1…2 kJ at 527 nm is needed to reach the multipetawatt power. Currently work is being done to create a multipetawatt laser source. The KD*P crystal for this amplifier has been already grown at Institute of Applied Physics, and the pump laser is available at Russian Federal Nuclear Center (Sarov) as one of the channels of the high-power Nd:phosphate-glass system "Luch"[33]. A four-grating compressor with clear aperture 22 cm is designed. Such an aperture will allow us to reach 2.3 PW power at the same grating damage threshold and pulse duration. Assuming a 48 cm compressor aperture, 800 mJ/cm^2 damage grating threshold, and 25 fs pulse duration we conclude that peak power limit is 35 PW.

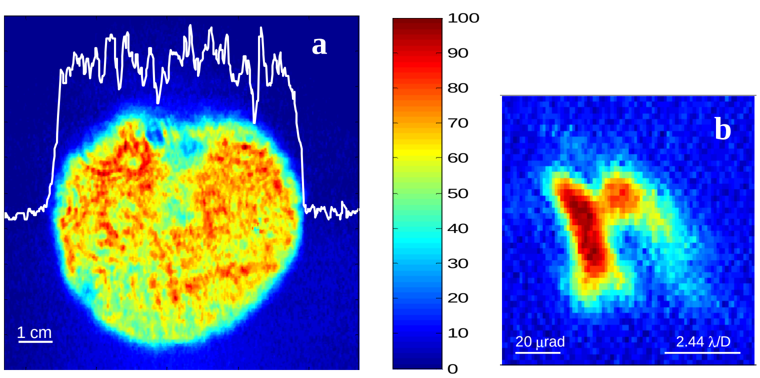

Fig. 9. Quality of signal beam after compressor in near field (a) and far field (b).

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