Improvement of the temporal and spatial contrast of high-brightness laser beams

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Abstract

A novel method is suggested for temporal and spatial cleaning of high-brightness laser pulses, which seems more energy-scalable than that based on crossed polarizers and offers better contrast improvement compared to the plasma mirror technique. The suggested arrangement utilizes nonlinear modulation of the beam in the Fourier-plane leading both to directional and to temporal modulation. By the use of a 'conjugate' aperture arrangement before and after the nonlinear spatial selector, intensity dependent transmission is obtained; simultaneous temporal and spatial filtering can be realized both for amplitude and phase modulation. In the case of phase modulation introduced by plasma generation in noble gases the experimental observations are in good agreement with the theory; demonstrating $>10^3$ improvement in the temporal contrast, ~40% throughput, associated with effective spatial filtering. Due to the broad spectral and power durability of the optical arrangement used here, the method is widely applicable for energetic beams even of UV wavelengths, where most of the former techniques have limited throughput.

(Some figures may appear in colour only in the online journal)

1. Introduction

Most of the applications of high-intensity laser systems require pulses of high temporal and spatial quality. Prepulses are detrimental for high intensity laser-material interactions, as the longer prepulse may generate a preplasma. In such cases, the main laser pulse interacts not with the solid target but with a preformed plasma. It was recently shown [1, 2] that prepulses of 10^7–10^8 W cm^{-2} intensities can change laser-matter interactions considerably. The achieved and the planned intensities are already in the 10^{22}–10^{25} W cm^{-2} range, which sets the necessary temporal contrast beyond 10^{14}–10^{18}.

Short-wavelength lasers have in principle better capability for temporal and spatial compression of the energy carried by the main pulse, however, can only be utilized, if the optimum beam quality is maintained [3]. In short-pulse excimer laser systems the generation and the final amplification of the pulse is performed at two different wavelengths necessitating frequency doubling [4] or tripling [5] before UV amplification. Using a novel method for frequency doubling—referred to as active spatial filtering [6]—not only does the inherent temporal cleaning of the intensity dependent nonlinearity occur, but also efficient spatial filtering can be achieved. In this way the temporal and spatial contrast are reset to the 'middle' of the system, resulting in output pulses of excellent spatial and temporal quality for medium output power. However, for larger output energies, the rapidly growing amplified spontaneous emission (ASE) in the UV amplifiers deteriorates the temporal contrast below 10^{10}.

Recent development of Ti:sapphire lasers combined with optical parametric amplifiers (OPA) and fiber-based pulse compression permit the generation of powerful few-cycle pulses [7] to enter the attosecond regime [8] and to give the highest peak powers [9–11]. In these systems the pulse cleaning technique based on nonlinear frequency conversion cannot be used. Due to the long wavelength, it is not only the

ASE, but—in the temporal vicinity of the pulse—mainly the temporal background associated with the chirped pulse amplification (CPA) scheme which is responsible for the limited temporal contrast. There are several methods to reduce the ASE content of such systems, including the use of more powerful oscillators [12] of saturable absorbers [13] and the utilization of the OPCPA technique [10]. The most effective way is the realization of a laser system with two CPA stages, separated by an intermediate pulse recompression where nonlinear interactions decrease the unwanted temporal background (double CPA, DCPA) [14, 15]. As a nonlinear method, nonlinear Sagnac interferometer [16], nonlinear ellipse rotation [14, 17] and—as the most promising method—cross-polarized wave generation XPW [18, 19] are suggested and experimentally verified. Because of the increased nonlinear absorption and the poor contrast (extinction coefficient) of the presently available polarizers in the UV regime, methods based on polarization rotation cannot be used effectively for short-pulse excimer laser systems.

Beyond the limited throughput and power acceptance of these methods, the inherent problem of CPA schemes—the relatively high temporal background in the ~100 ps vicinity of the main pulse—still remains [14, 15, 18], which is proven to be critically dependent on the spectral distortions of the amplifier chain [20]. The spatial quality is also limited by the limited optical quality of the solid-state material and by associated dynamic distortions. For these reasons intense ultrashort laser pulses generally suffer from prepulses which may originate either from the ASE of the IR or UV amplifier chain or from the pedestals due to the imperfect pulse compression.

One of the most efficient (and energy-scalable) methods to remove prepulses is based on the self-induced plasma shuttering or plasma mirror technique [21, 22], which was also successfully demonstrated for short-pulse KrF laser systems [23]. The achievable contrast improvement with the use of plasma mirrors is constrained by the limited ratio of their high and low intensity reflection, therefore significant contrast improvement can only be achieved by subsequent use of more plasma mirrors, which limits the overall throughput of the system. Another disadvantage of the present use of plasma mirrors is that it is normally positioned into a beam of finite size, where the optical quality of the plasma front influences the phase front of the beam. Furthermore a fresh target area is needed for each shot, therefore the repetition rate and the obtainable number of shots is limited. At this time there is no practical method suitable for temporal and spatial contrast improvement of short-pulse UV systems.

For these reasons a novel pulse-cleaning technique is introduced, which is generally applicable, and does not suffer from the shortcomings of the standard plasma mirror method.

2. Experimental setup

In the newly suggested arrangement, the nonlinear component is situated in the centre of a confocal telescope surrounded by a conjugated filter pair consisting of an input beam-block and an output diaphragm. As long as no amplitude (and/or phase) modulation occurs in the focal plane, the output diaphragm
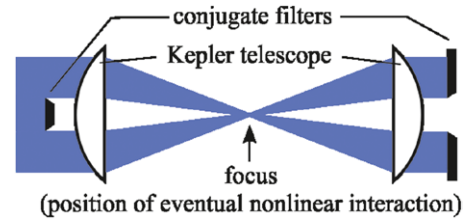

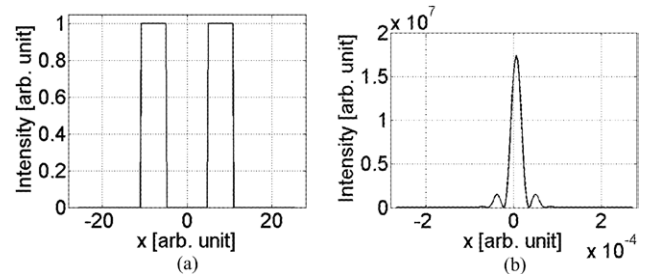**Figure 1.** Schematic of the nonlinear filter.

**Figure 2.** Cross-section of an annular beam (a) and its distribution in the focal plane (b).

totally screens the light, allowing full exclusion of eventual prepulses of low intensity. Figure 1 shows the scheme for a collimated beam. In general case the position of the conjugate filters is of importance; the output diaphragm must be positioned at the image plane of the input beam-block (see later).

The basic idea behind the suggested method is similar to that of the active spatial filtering [6]: an intensity dependent modulation—introduced in the Fourier-plane—leads to directional modulation, therefore temporal modulation in a given solid angle. For such purpose an annular input beam (figure 2(a))—formed by the input beam-block of figure 1 from the KrF beam of flat-topped distribution—seems ideal having an 'Airy-like' intensity distribution in the Fourier-plane (see figure 2(b)), It has already proven that a nonlinear modulation can generate a 'Gaussian-like' output beam [6]. Thus, for the intense main pulse; which undergoes intensity dependent modulation in the focal plane; finite transmission and pronounced contrast improvement are expected to occur.

Numerical simulations were carried out based on 2D fast fourier transformation (FFT) to study the effect of different types of nonlinear modulation in the Fourier-plane for an annular beam. Figure 3(a) shows the calculated output distribution when the intensity of the diffraction pattern (corresponding to figure 2(b)) is suppressed by a factor of 25 with the exception of the central lobe. This calculation approximates the case, when a plasma mirror is placed at the focal plane.

It is conspicuous that some fraction of the energy of the beam is diffracted to the central part (to the hole of the output diaphragm) resulting in finite transmission, and significant improvement of the contrast. On the other hand, considering the diffraction losses and the limited plasma reflectivity [21], the overall transmission is expected to be less than 10%.

Much better results are obtained and simultaneous temporal and spatial filtering occurs, when phase modulation is introduced in the focal plane instead of amplitude modulation. Figure 3(b) shows the results of the corresponding calculation when the phase of the central lobe of the diffraction pattern
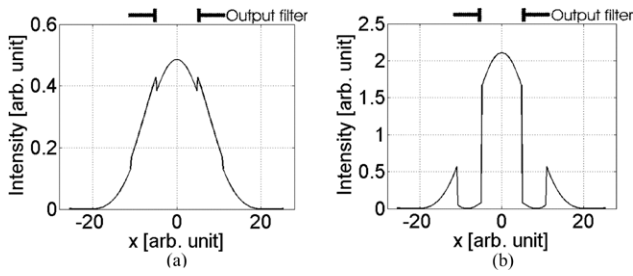
Figure 3. Output of the confocal telescope when the relative amplitude (a) and the phase (b) of the central lobe of the diffraction pattern are modulated (for details see text).
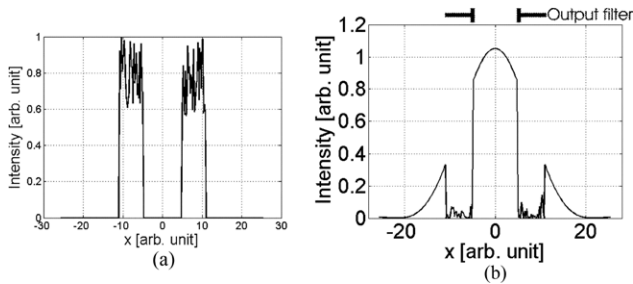
Figure 4. Output beam distribution (b) for a noisy (input) annular beam (a).

(corresponding to figure 2(b)) is shifted by $\lambda/2$. Practically the 'inverse' of the annular input beam emerges at the output; as high as 55% of the energy of the input beam is diffracted to the central hole of the output aperture, resulting in similar throughput for a practical system having no amplitude modulation but on intensity dependent phase shift. The output distribution and the efficiency have slight change if continuous phase shift is assumed. The assumption of a 'step-like' phase shift is reasonable based on the good agreement of the experimental results with this theory as it is explained by the self-channeling mechanism later. Here the loss caused by the input beam-block was not considered, since such an annular beam can easily be formed practically without losses by axicon lenses. Another advantage of this method—beyond the expected high contrast improvement and high overall throughput—is that even spatial filtering occurs in the central (transmitted) part of the beam.

According to numerical calculations and experimental observations, eventual modulation of the high spatial frequencies (noise) of the input beam (as in figure 4(a)) is only present in the low intensity, ring-shaped part of the output, which is blocked by the output diaphragm (see figure 4(b)).

If a gas jet is situated in the focal plane—by proper setting of the intensity of the central lobe, the length and density of the gas—~$\lambda/2$ phase shift can be introduced without practical absorption. Experimental realization of the system is shown in figure 5. Using a pulsed gas jet and a noble gas as a nonlinear phase shifter, after passing the nonlinear medium of well-defined length (and of no absorption) constructive interference of the different orders leads to a beam of different directional properties which allows minimization of the losses, and the suppression of the unwanted spatial and temporal components at the same time. The method is 'self-aligning'; no

interferometric alignment procedure is needed to match the central lobe to an eventual aperture.

In our experimental realization a Kepler telescope formed by two lenses of $f_1 = f_2 = 730$ mm focal length was used in a $2f$ arrangement for the Fourier forward- and back-transformation. A pulsed gas jet of 1 mm diameter formed the nonlinear interaction medium. Argon was selected as the active noble gas. For an input pulse of 500 fs duration and of ~3 mJ energy at 248 nm the focused intensity was ~10^{15} W cm^{-2}. By changing the backing pressure and the opening time of the gas jet an optimal phase shift was found. The best output distribution was observed when the focus was ~0.5 mm far from the nozzle, the backing pressure was ~4 bar and the opening time was typically 1 ms. Considering the Rayleigh-length of the beam, the intensity was approximately constant within the gas jet. The estimated plasma density was ~10^{19} cm^{-3} based on [24]. The system was normally running with 1–10 Hz repetition rate, but the operation of the nonlinear filter was demonstrated up to 100 Hz, using a simple fore vacuum pump of 16.5 m^3 h^{-1} pumping speed.

3. Experimental results and discussion

The phase shift introduced by the above experimental arrangement led to an 'inverted' output distribution, as seen in figures 6(a) and (b). The internal energy efficiency was ~40% which approaches the theoretical 55% limit. Despite the fact that the experimental result in figure 6 is regarded as a proof of principle, some investigations were carried out to determine the intensity dependence of the process. It was found experimentally that around the threshold the phase shift introduced by the plasma generation has a 'switching'-feature; only a slight decrease of the optimal intensity of the input main pulse diminishes the optimized 'high-intensity' operation of the nonlinear filter (corresponding to figures 5(b) and 6(b)) and switches to the 'low-intensity' state (figure 6(a)).

It is favourable feature of our results that the phase shift is stable. This suggests the presence of some self-channelling mechanism in the central lobe (a subsequent or parallel effect of self-focussing and defocusing by plasma generation). Although the plasma generation itself can provide a phase shift, these processes can be affected greatly by self-focusing. This may cause channelling of the beam and stabilization of the phase shift at certain intensities. Historically, self-focusing was shown to occur during the ionization process of gases [25], which can clamp the intensity [26], and may result in very long filaments [27].

In our case—due to the threshold-like appearance of these effects—the nonlinear phase-shift has a minor contribution to the unwanted transmission of the prepulse (ASE in our case). The transmission for the low intensity prepulse—therefore the achievable contrast improvement—are found to be mainly determined by the quality (by the spatial contrast) of conventional imaging. This problem is presently investigated both theoretically and experimentally. In a standard image system >10^3 contrast improvement is demonstrated. The improvement of the temporal contrast was measured by
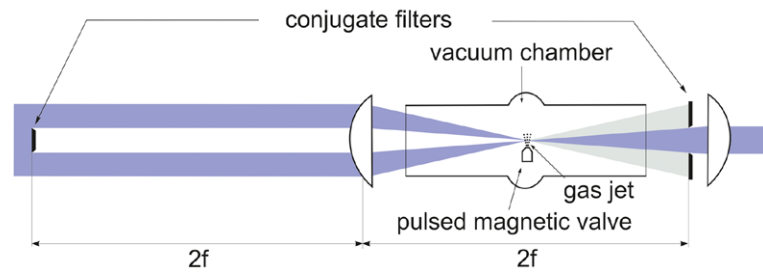
Figure 5. Experimental arrangement for nonlinear filtering with phase modulation (the beam propagation refers to high intensity operation).
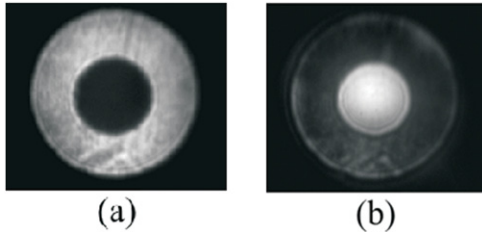
Figure 6. Spatial distribution of the beam measured just before the output filter when the intensity of the input is halved (a) and with optimized parameters (b) (for experimental details see text).

a photodiode, with the assumption that the ASE is the only source of the noise which has uniform distribution both in time and space.

It is important to note that the method based on the phase-shift of the plasma of an ionized noble gas—corresponding to figure 5—is applicable in a broad wavelength range. However, the practical limitation for CPA systems is that the application of the nonlinear temporal filter necessitates the presence of the compressed (minimum) pulse durations, which is normally available at the end of the amplifier chain or—similarly to other temporal cleaning methods reported in CPA solid-state systems—the use of DCPA is needed. Alternatively, in high-intensity excimer systems—due to the direct amplification of pulses—the pulses of short duration are available at any part of the amplifier chain. Therefore the use of the nonlinear filter of high throughput, together with saturated operation of the following amplifier(s) leads to a negligible decrease of the output energy. Additionally, the generally good temporal and spatial quality of excimer lasers (due to the frequency conversion and to the direct amplification scheme) are further improved. Optimization of the experimental parameters together with theoretical considerations and corresponding measurements for the improvement of the contrast are in progress; improved imaging using proper apodization appear to provide spatial contrast beyond 10^{10}.

4. Conclusion

In conclusion high contrast temporal and spatial filtering method is presented, based on an intensity-dependent diffraction of the beam. Due to the broad spectral and power durability of the optical arrangement used here, the method is a challenging extension of the former techniques.

Main features of the nonlinear Fourier filter:

- high improvement of the temporal contrast ($>10^3$), sharpening of the leading edge (temporal filtering),
- beam smoothing (spatial filtering),
- self-adjusting (no need for precise alignment),
- very high overall transmission (up to 40% obtained experimentally),
- applicable in a broad wavelength range (directly applicable in excimer systems, however, pulse compression and eventual stretching is needed in CPA schemes).

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