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Table-top KrF amplifier delivering 270 fs output pulses with over 9 W average power at 300 Hz

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ABSTRACT Applying the combination of a solid-state Ti:Sa laser system and a newly developed wide-aperture, discharge-pumped KrF amplifier, output pulses with over 9 W average power at 300 Hz have been achieved in a single output beam. The frequency-tripled seed pulses of the Ti:Sa system – delivering approximately 10 μJ energy at 248 nm – were amplified to over 30 mJ using a 3-pass off-axis amplification scheme. The optical set-up has been fitted to the amplifier's parameters, and stored-energy measurements were carried out with different parameters in order to optimize the operational conditions of the device for the highest average power.

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1 Introduction

Over the last few years, an enormous development of high-power laser sources has been realized. By developing large-scale laser systems, intensities in the range 10^{20}–10^{21} W/cm^2 have been reached [1]. Two alternatives for such powerful laser sources are solid-state lasers, in the IR or VIS, and excimers operating in the near-UV region [2–4]. Broadband solid-state media (Ti:Sa, etc.) facilitate the generation of ultrashort pulses (10–20 fs), with unavoidable wavefront distortion, however, in the stretcher/compressor part of the power amplifiers. By contrast, the low-density gaseous amplifying media of excimer devices ensure a much smaller phase distortion, thus giving better beam focusability. The maximum focused intensity scales inversely with the square of the wavelength, thus favoring UV sources. However, there is no effective way to generate ultrashort pulses in the UV region; therefore it is necessary to amplify frequency-converted pulses in a UV excimer module. Recently the group of S. Watanabe reported on a solid-state Ti:Sa excimer system delivering 50 W output power at 200 Hz with 248-nm femtosecond UV pulses [5]. The significant increase in the output power was achieved by splitting the seed pulse into four parts and than amplifying them, resulting in four output beams with 12.5 W power output beams each, delayed by 2.5 ns. Without recombination of the pulses – which is practically impossible – the applicability of such an arrangement with a 4-beam pulse train is restricted to specialized experiments. (A multiple-pulse structure cannot be tolerated in experiments like, for example, the formation of a plasma channel for multi-kilovolt X-ray generation [6] or the study of hot electron production [7], etc.) Moreover, a rather complex, homemade front-end was used in [5], thus strongly limiting the applicability of such an arrangement in an industrial environment, for example for material processing.

In this paper, we report on the development of a table-top, compact UV femtosecond system based on the combination of a Ti:Sa laser system and an excimer amplifier. Frequency-tripled seed pulses of the Ti:Sa system were amplified in an excimer module using a 3-pass off-axis scheme. The device was specially modified and carefully optimized for short-pulse amplification. Measurements of the dependence of the stored energy on the pressure, repetition rate and peaking capacitance were carried out. At optimized operational conditions, the laser system delivered 270-fs pulses at 248 nm with an average power of more than 9 W at 300 Hz in a single output. The compactness and reliability of the system would, in principle, allow industrial application of the apparatus.

2 System set-up

The system presented in this paper consisted of three main parts (Fig. 1). The first was a commercially available Ti:sapphire solid-state laser system (Spectra-Physics Lasers, Inc., CA), generating around 130-fs pulses at 745 nm with a repetition rate up to 1000 Hz. The output pulse energy was around 400 μJ. These pulses were frequency converted in the second part, which was a frequency-tripling unit built in a linear arrangement. As non-linear media, we used polished BBO crystals with 0.8-mm and 0.24-mm thickness for the doubling and tripling, respectively. To compensate for the group velocity delay after frequency doubling, a 1.1-mm-thick polished MgF_2 wave plate was used. By rotating the normal of the crystal surface relative to the incoming beams, the optical path length and the refractive indices for the different beams were changed, so that the required group delay could be adjusted. To reach parallel polarization between the fundamental and the second harmonic, we used a 2-mm-thick MgF_2 retardation plate with an antireflective coating (dual

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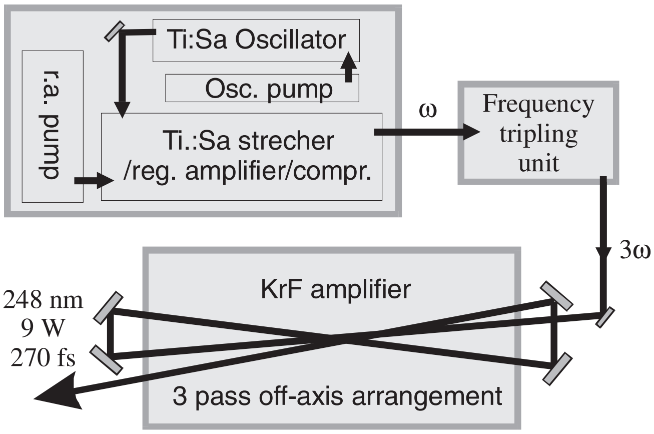

FIGURE 1 Femtosecond laser system consisting of a Ti:Sa solid-state front end, a frequency-tripling stage and an excimer amplifier in a three-pass off-axis arrangement

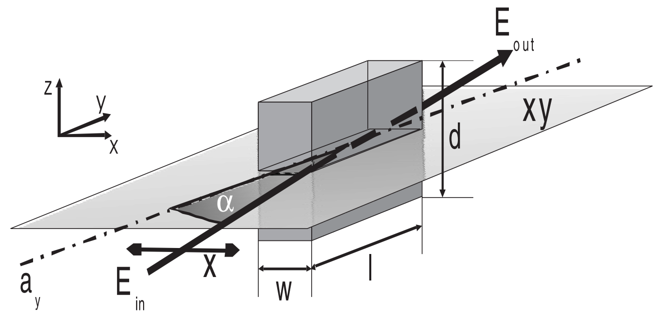

FIGURE 2 Set-up for the stored-energy measurements. In the picture, the discharge volume is visible, where w is the width, l is the length and d is the height of the discharge (electrode separation). E_{in} and E_{out} represent the measured input and output energies, a_{y} is the longitudinal axis of the amplifier, $\alpha = 1.5°$ is the angle enclosed by the beam and a_{y}, and x is the direction of the scan in the xy-plane

	Laser param.	$\ln(E_{\text{out}}/E_{\text{in}})$	w' (mm)	E_{st} (mJ)
Repetition rate	25 Hz	5.701	21.6	61.6
	100 Hz	5.531	22.0	60.8
	250 Hz	5.559	23.2	64.5
	300 Hz	5.647	21.9	61.8
Pressure	1.9 bar	4.813	23.5	56.6
	2.3 bar	5.109	23.4	59.8
	2.8 bar	4.877	24.1	58.8
	3.3 bar	5.647	21.9	61.8

TABLE 1 Measurement of the dependence of the stored energy on the repetition rate and gas pressure. $\ln(E_{\text{out}}/E_{\text{in}})$ and w' are measured values, E_{st} is the calculated momentarily stored energy (see [10])

wave plate with AR/AR coating for 400 and 800 nm from Alphalas GmbH, Göttingen). The crystals, together with the wave and retardation plates, were placed into a sealed box filled with Ar gas to protect the crystals against humidity, thereby prolonging the lifetime of these components. The maximal efficiency for the tripling was around 8%. Although this is not the highest possible conversion efficiency, the linear arrangement provides absolutely hands-off, "no-tweak" operation of the tripling unit. In order to improve the homogeneity of the spatial beam profile, we placed a 2-m-focal-length focusing lens before the tripling box (thus propagating and focusing the fundamental beam in air). After frequency tripling, a telescope was used to adjust the proper divergence for subsequent amplification. After the telescope, the 248-nm pulse was directed into a specially modified wide-aperture discharge-pumped excimer module based on a LP NovaLine laser. The length of the discharge was 970 mm, with an electrode separation of 25 mm. The excimer module was used in a 3-pass off-axis arrangement in order to reach the optimal conditions for the amplification of femtosecond pulses [8, 9]. The divergence was adjusted so that the beam filled the amplifier aperture at the end of the 3rd pass (25 mm × 25 mm). The chosen off-axis angles were 1°, 1.5° and about 2° for the three passes, respectively.

3 System characterization

After modifications to the discharge frame, the windows and the window holders, stored-energy measurements were carried out to characterize the module and to fit the operational conditions to the requirements of short-pulse amplification. In such a measurement, a femtosecond probe pulse was sent through the spatial maximum of the gain (in our case enclosing an angle of 1.5° with the longitudinal axis a_{y} of the amplifier) and the gain-length product, $\ln(E_{\text{out}}/E_{\text{in}})$ was measured scanning through the effective width of the discharge (w') in a lateral direction (Fig. 2). The input signal was attenuated in order to avoid saturation of the amplification during the whole measurement. From the measured values, the stored energy could be calculated, as described in [10]. The dependence of the stored energy on the repetition rate and gas pressure is displayed in Table 1. The measurements on the repetition rate dependence were carried out at 3.3 bar pressure with 43 nF peaking capacitance. The results show that our amplifier's stored energy was practically independent of the repetition rate in the measured region. At high repetition rates, the stored energy can strongly depend on the pressure because of insufficient circulation of the gas in the discharge volume. The measured dependence of E_{st} on the pressure is also shown in Table 1 (measured at 300 Hz with 43-nF peaking capacitance). It is seen that E_{st} is optimal at the highest pressure allowed in the chamber (3.3 bar), although the dependence is not linear and a smaller local maximum around 2.3 bar is also visible. This dependence is easier seen in a simpler measurement where the beam is not scanned through the active medium, but the small-signal amplification is measured only in the middle position of the discharge at a 1.5° off-axis angle. The results of such a measurement are displayed in Fig. 3, where $E_{\text{out}}/E_{\text{in}}$ is plotted for the short-pulse seed beam at 300 Hz repetition rate as a function of the gas pressure. In further measurements, we applied 3.3 bar pressure in the amplifier and measured the dependence of the stored energy on the capacitance. By optimizing the number of peaking capacitors, it was possible to reach an increase of about 14% in the stored energy compared to the original value. This best case was achieved by decreasing the number of capacitors by about 34% (Table 2). The values in these measurements were recorded at 300 Hz repetition rate at a total pressure of 3.3 bar. For the further experiments, we set the number of capacitors to the measured optimal value and built up the 3-pass off-axis arrangement, which can be described as follows. The frequency-tripled beam from the telescope (with a given di-

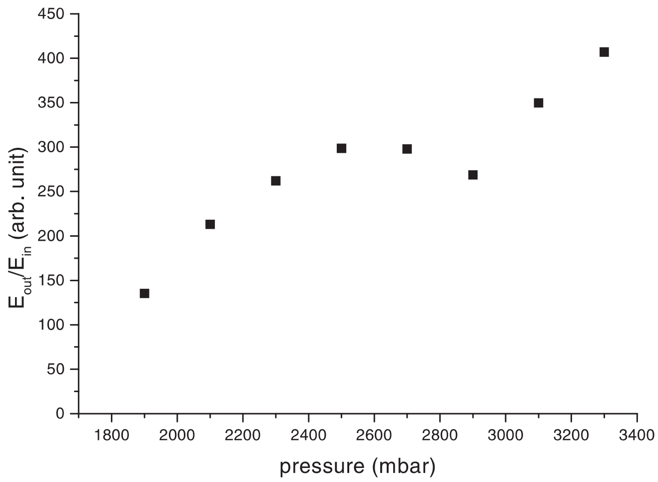

FIGURE 3 Small-signal gain (E_{out}/E_{in}) of the amplifier as a function of gas pressure, measured at 300 Hz

Peaking capacitance (nF)	$\ln(E_{out}/E_{in})$	w' (mm)	E_{st} (mJ)
43	5.647	21.9	61.8
35	5.732	23.2	66.5
28.5	5.779	24.3	70.2
20.5	5.686	23.1	65.7

TABLE 2 Measurement of the dependence of the stored energy on the peaking capacitance

vergence) propagated through the amplifier three times. After each pass, a delay line was applied because of the approximately 2–3-ns recovery time of the amplifying medium. In the 1st pass, the energy was boosted up to the mJ region. In the second pass the energy reached the 10–15 mJ region. The energy density was around 2–2.3-times the saturation energy density (E_{sat}) of KrF in a beam about 17 mm × 17 mm. In the last pass, the beam reached the 25 mm × 25 mm-size (which is the maximum allowed by the electrode separation), with a pulse energy of around 30 mJ at an off-axis angle of 2° (the highest allowed by the windows and the off-axis frame we used). This resulted in an output energy density of around 2.4-times E_{sat}, which is in the optimal region for a power amplifier [8, 11]. The measured ASE content was around 15% in the case of maximal gain but by reducing the gain to 80% of its original value, it was possible to reduce the ASE level to below 4%–5%. These values represent an upper limit, since they were calculated as the ratio of the output power without and with a seed pulse. However, the real ASE content was smaller because the gain was depleted by the femtosecond pulse, preventing ASE generation in the presence of the short pulse [5]. The dependence of the output power on the repetition rate has been measured. The results show a linear dependence through the measured region with a gradient of 1, which means that the output pulse energy was practically independent of the repetition rate (as has already been found by measuring the stored energy). The measured values can be seen in Fig. 4. The 3D graph of the output beam profile shown in Fig. 5 was recorded by a CCD camera and then processed with a home-built beam profiler system. A relatively

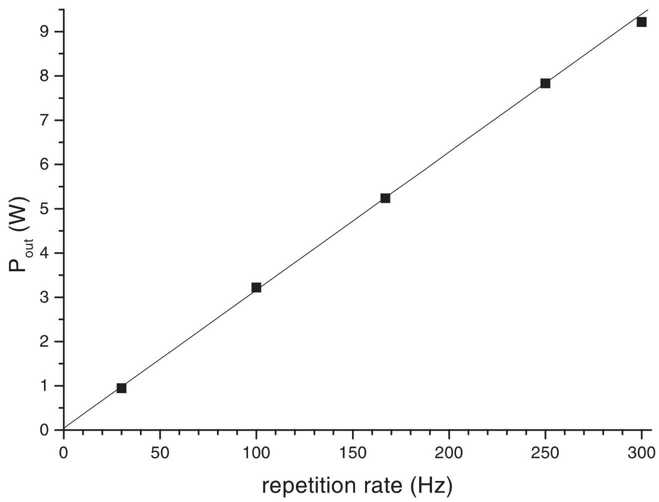

FIGURE 4 Measured output power as a function of the repetition rate

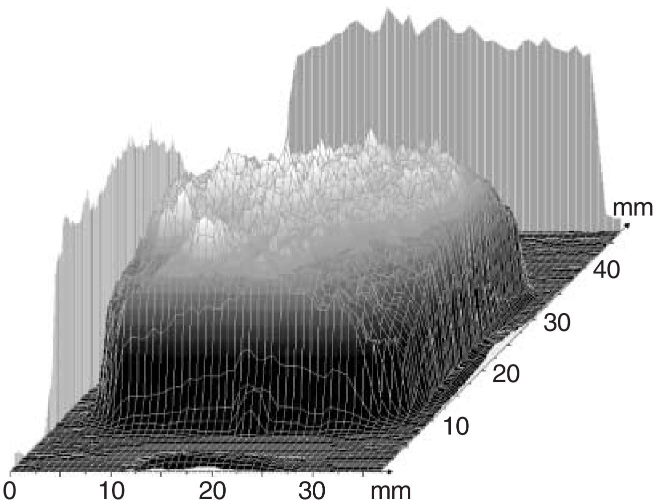

FIGURE 5 Measured 3D near-field beam profile recorded by a CCD camera and processed with a beam profiler system

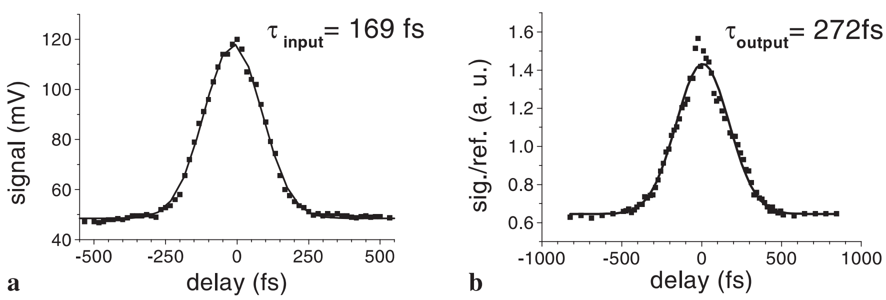

FIGURE 6 Autocorrelation curves and calculated pulse widths of the seed (τ_{input}) (**a**) and the amplified (τ_{output}) (**b**) pulses

flat-top beam profile is visible. We also measured the pulse length of the seed pulse and the amplified pulse using a home-made UV autocorrelator, based on multiphoton ionization in NO [12]. In Fig. 6a and b, autocorrelation measurements of the seed pulse and the amplified output pulse are visible. The autocorrelation widths for the two pulses were found to be 241 and 388 fs for the incoming and the amplified beams, respectively, corresponding to 169 and 272-fs pulse lengths, calculated for Gaussian pulse shapes. The values demonstrate a temporal broadening of 103 fs. Calculations show that the measured temporal broadening is mainly caused by the GVD in the window materials. The total broadening caused by $n_g(\lambda)_{248\ \mathrm{nm}}$ of the window materials (6-mm-thick CaF_2) was calculated (using $\Delta\lambda = 0.65\ \mathrm{nm}$ and $(\mathrm{d}n_g/\mathrm{d}\lambda)_{CaF_2,248\ \mathrm{nm}} = 1.334 \times 10^{-3}\ 1/\mathrm{nm}$) and found to be 104.5 fs, which is in good agreement with our experimental results.

4 Summary

In conclusion, an ultrahigh-average-power, high-repetition-rate short-pulse UV laser system has been developed. Combining the advantages of a solid-state front-end with those of an excimer KrF amplifier, and with optimized operational conditions, it was possible to achieve output pulses of over 30-mJ in a single beam. Stored energy, pulse duration and spectral measurements were carried out. The repetition rate could be increased up to 300 Hz, reaching an average output power of over 9 W in a single 270-fs UV pulse. To our knowledge, at this repetition rate, this system generates the most powerful UV pulses ever obtained.

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