Laser and Particle Beams (2013), *31*, 17–21.

doi:10.1017/S0263034612000870

Multi-terawatt femtosecond laser system of visible range based on a photochemical XeF(C-A) amplifier

S.V. ALEKSEEV,[1] A.I. ARISTOV,[2] N.G. IVANOV,[1] B.M. KOVALCHUK,[1] V.F. LOSEV,[1,3]
G.A. MESYATS,[2] L.D. MIKHEEV,[2] YU.N. PANCHENKO,[2] AND N.A. RATAKHIN[1,3]

[1]Institute of High Current Electronics SB RAS, Tomsk, Russia
[2]Lebedev Physical Institute RAS, Moscow, Russia
[3]Tomsk Polytechnic University, Tomsk, Russia

(RECEIVED 20 March 2012; ACCEPTED 20 September 2012)

Abstract

This paper reports on the creation of a THL-100 multi-terawatt hybrid laser system based on a Start-480M titanium-sapphire starting complex and photochemical XeF(C-A) amplifier with a 25-cm aperture. The complex produces 50-fs radiation pulses of energy up to 5 mJ at a second harmonic wavelength of 475 nm. The active medium of the amplifier is created in a XeF_2/N_2 mixture under vacuum-ultraviolet radiation of electron beam-excited xenon. The results of first experiments on femtosecond pulse amplification in the active medium of the XeF(C-A) amplifier are presented to demonstrate that a laser beam peak power of 14 TW has been attained.

Keywords: Chirped pulses; Femtosecond pulses; Hybrid (solid/gas) laser system; Photochemical XeF(C-A) amplifier; Second harmonic

INTRODUCTION

At present, the development of ultra-high power laser systems with a pulse duration of 10–100 fs is based mainly on near-infrared solid-state titanium-sapphire or parametric amplifiers and amplification of positively chirped pluses, i.e., stretched in time (0.5–1 ns), by linear frequency modulation (Strickland & Mourou, 1985) with their subsequent compression to the initial duration. Stretching of a pulse is required to decrease its power below a threshold at which the beam is self-focused; in solid-state systems, pulses are normally stretched about 10^4 times. Pulse compression is realized with a vacuum compressor built around gold-coated gratings — one of the most elaborate and expensive devices, particularly for multi-petawatt laser systems.

In recent years, an alternative approach to the design of multi-terawatt and petawatt femtosecond laser systems has been developed at the Institute of High Current Electronics (Tomsk, Russia), Lebedev Physical Institute (Moscow, Russia), and LP3 Laboratory of the Marseille University (Marseille, France) (Losev *et al.*, 2006; 2010; 2011*a*; 2011*b*; Mikheev *et al.*, 2006; Ivanov *et al.*, 2009; Clady *et al.*, 2006; Tcheremiskine *et al.*, 2008). The approach is based on a solid-state femtosecond laser complex (second harmonic, 475 nm) and a photochemical XeF(C-A) amplifier with a gaseous active medium (Mikheev, 1992; Eckstrom & Walker, 1982). The advantage of this hybrid (solid/gas) design of high-power femtosecond systems is that due to the much lower optical nonlinearity of gas compared to a solid, the admissible stretch factor of femtosecond pulses before their amplification is three orders of magnitude smaller than that for solid-state systems. This allows amplification of picosecond chirped pulses and their subsequent compression by simpler and more efficient methods, e.g., by compression of negatively chirped pulses in the glass volume with positive group velocity dispersion. Another peculiarity of the hybrid system under consideration is the visible spectrum, which can be of advantage in interaction with plasma. The gaseous nature of the active medium also allows easy scaling of hybrid systems.

The nonlinear conversion to the second harmonic to spectrally match the solid-state system with the gaseous active medium and the low gain of the latter give reason to hope for high contrast without resort to any additional optical devices, and this is also a significant advantage of the hybrid system. Finally, similar hybrid systems provide an alternative to direct nonlinear conversion of infrared radiation to the

Address correspondence and reprint requests to: V.F. Losev, Institute of High Current Electronics SB RAS, 2/3 Akademichesky Ave., Tomsk, 634055, Russia. E-mail: losev@ogl.hcei.tsc.ru

second harmonic in solid-state systems in which many problems arise with scaling of output radiation parameters in the visible spectrum to tens and hundreds of terawatt (Begishev *et al.*, 2004; Mironov *et al.*, 2009; Ginzburg *et al.*, 2010).

This paper reports on a THL-100 multi-terawatt hybrid laser system with a 25-cm aperture developed at the Institute of High Current Electronics SB RAS and presents results of first experiments on the system to demonstrate its capabilities for femtosecond pulse amplification.

EQUIPMENT AND MEASUREMENT PROCEDURES

Femtosecond Pulse Generator

The laser system is driven by a Start-480M starting complex (Avesta Project Ltd). The complex is placed on an optical table and comprises the following main units: a femtosecond Ti:sapphire master oscillator pumped by a 532-nm continuous wave laser (Verdy-8), a pulse stretcher, regenerative and multipass amplifiers pumped by a 532-nm pulsed laser, a compressor, and a second harmonic generator. The complex is operated at a pulse repetition frequency of 10 Hz in the single pulse mode with external triggering and produces a laser beam with bandwidth-limited pulse duration of 50 fs and energy up to 5 mJ at a 475-nm second harmonic wavelength.

Photochemical XeF(C-A) Amplifier

A photo of the XeF(C-A) amplifier and its schematic are shown in Figures 1 and 2, respectively. The amplifier comprises two high-voltage pulse generators, a vacuum chamber with an electron diode, a gas chamber with xenon (an electron beam converter), and a laser cell with a mirror system for multipass laser beam amplification.

Fig. 1. Photo of the XeF(C-A) amplifier.

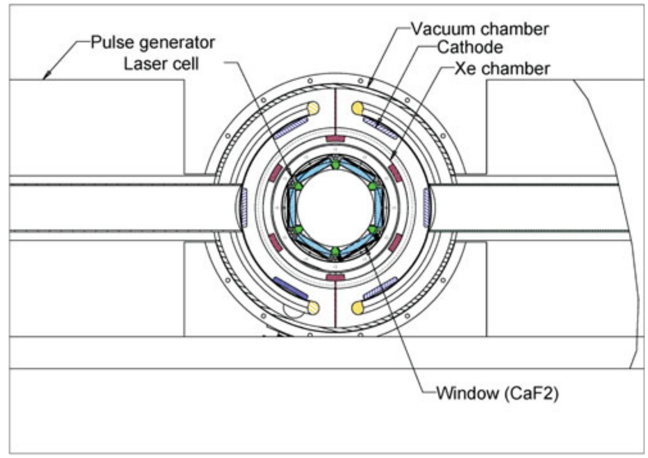

Fig. 2. Schematic of the pump circuit of the XeF(C-A) amplifier active medium.

The high-voltage pulse generators are line transformers, each with vacuum insulation of the secondary turn and 12 series-connected transformer stages. The primary energy store of a transformer stage is four parallel-connected capacitor banks. A capacitor bank consists of two capacitors of total capacitance 80 nF and a six-channel multigap spark switch; the capacitors can be charged to 90–100 kV. In the vacuum chamber, the secondary turns of the line transformers are connected to two cathode holders, each with three explosive emission cathodes (flock-coated metal). All cathodes are symmetrically positioned about the cylindrical gas chamber as shown in Figure 3; the chamber diameter is 45 cm. The outer sheath of the gas chamber serves as an anode of the vacuum diode. The chamber walls are stainless steel grids covered with titanium foil 40 μm thick. The vacuum diode forms six electron beams, each of area 15×100 cm^2, that are injected into the Xe-filled gas chamber at a pressure of 3 atm.

At a charge voltage of 95 kV, the energy stored in the capacitor banks of a line transformer is 34.6 kJ, the electron beam energy in the vacuum diode is about 21 kJ, and the energy delivered to the gas chamber through the foil is about 7 kJ. The accelerator provides an accelerating voltage of 550 kV and a diode current of 200 kA at a full width at

Fig. 3. Gas chamber of the XeF(C-A) amplifier with windows for electron beam injection.

https://doi.org/10.1017/S0263034612000870 Published online by Cambridge University Press

half maximum (FWHM) of 150 ns. When injected into the gas chamber, the electron beam on its path length (8 cm) is almost completely absorbed by xenon. The electron beam energy is converted to vacuum-ultraviolet (VUV) radiation of Xe_2^* excimer molecules with an efficiency of 30–40% (Eckstrom & Walkder, 1982).

The laser cell is placed along the gas chamber axis and contains a vapor mixture of XeF_2 at a partial pressure of 0.2–0.4 Torr and high-purity nitrogen at a pressure of 190–380 Torr. The active medium of the XeF(C-A) amplifier is excited by VUV radiation at a wavelength of about 172 nm due to photodissociation of XeF_2 molecules with the formation of XeF(B) excimer molecules. The XeF(C) state of the laser transition (C-A) results from relaxation of a XeF(B) molecule on collision with N_2 buffer gas molecules. The active medium is pumped through CaF_2 windows with dimensions 12×12 cm (54 units) on the side walls of the laser cell (Fig. 4) facing the foil through which the electron beams is injected into the gas chamber. This ensures the best geometric matching of the pump source with the active medium. The windows are placed in slots on rubber (viton) gaskets and vacuum sealed with clamping flanges. The cell at its faces is covered with fused quartz windows of diameter 30 cm. The cell cross-section is a hexagon with an exit aperture of 25 cm.

For the electron beam to VUV radiation conversion to be of maximum efficiency, high-purity xenon (99.9997%) was supplied to the gas chamber preliminary pumped to a pressure of 10^{-4} Torr. During the operation of the amplifier, the VUV radiation intensity of xenon gradually decreased due to gas release from structural materials exposed to the electron beam. For gas purity recovery, xenon was pumped through a Sircal MP-2000 purifier.

The complex and amplifier were synchronized to an accuracy of ± 10 ns using the trigger unit of the complex. The mixture in the laser cell was changed after each pumping pulse, because repeated pumping of the mixture decreased the gain by 20–30%.

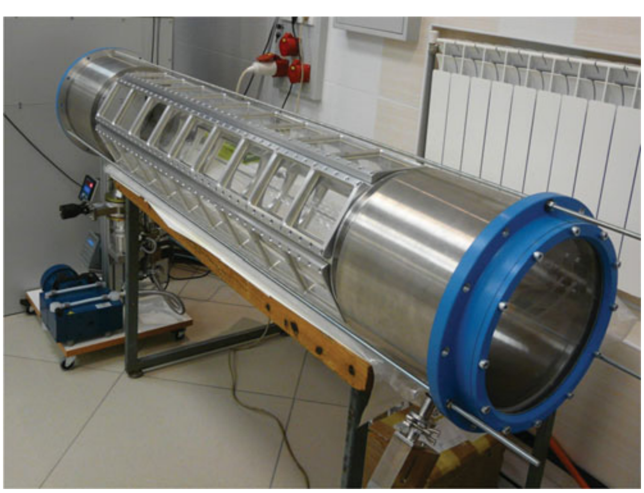

Fig. 4. Laser cell of the XeF(C-A) amplifier.

Measurement Procedures

The electron beam energy and VUV radiation in the laser chamber was measured with a TPI-2-7 calorimeter. The small signal gain distribution over the laser cell cross-section was measured in four passes through the active medium using a Sapphire-488 continuous semiconductor laser that emits at a wavelength of 488 nm, which is coincident with the maximum of the amplification band for the XeF(C-A) transition. The femtosecond laser beam was amplified in a multipass optical scheme (33 passes) consisting of 32 round mirrors differing in diameter. The mirrors were fixed along the perimeter of the internal flanges of the laser cell. The reflectance of the mirrors was 99.7%. Before entering the XeF(C-A) amplifier, the laser beam was set to a certain divergence angle with a reflecting telescope. Thus, as the beam was amplified, it grew steadily in diameter from 2 cm (at the inlet) to 6 cm (at the next to last mirror), making two circular passes in the active medium. The penultimate mirror (convex) guided the beam to a flat mirror of diameter 10 cm located on the optical axis. When reflected from this mirror, the beam propagated along the optical axis and was ejected with a diameter of 12 cm.

In experiments on femtosecond pulse amplification, the pulse was preliminary stretched in a prism stretcher to 1 ps. The amplified negatively chirped laser pulse was compressed by a double passage of the collimated beam of diameter 20 cm through three fused quartz plates of thickness 4 cm located at a Brewster angle. The energy loss in the compressor was no greater than 2%. For measurements of the pulse duration, the central part of the beam, being preliminary attenuated by two quartz wedges, was tapped to an ASF-20-480 autocorrelator using a spherical mirror of diameter 90 mm and focal length 12 m. In the focal plane of the spherical mirror upstream of the autocorrelator inlet, a diaphragm of diameter 0.25 mm was arranged.

For measurements of the output energy of the photodissociation amplifier, the beam was focused to a 2.5-cm diameter on the fused quartz wedge by a positive lens. The beam reflected from one wedge face was measured with an OPHIR energy meter. Downstream of the wedge, there was a photographic paper to record an autograph of the laser beam.

EXPERIMENTAL RESULTS

The potentialities of the active medium of the XeF(C-A) amplifier were evaluated by measuring the VUV radiation energy of xenon passed into the laser cell through the CaF_2 windows. This energy was 240–260 J. In view of the quantum efficiency of laser transition and 100% quantum yield of XeF(C) molecules, the integral value of the energy stored in the active medium was about 90 J. However, considering that the actual lifetime of the XeF(C) state, determined from its radiative decay and quenching, is much shorter than the pumping time, the current value of the

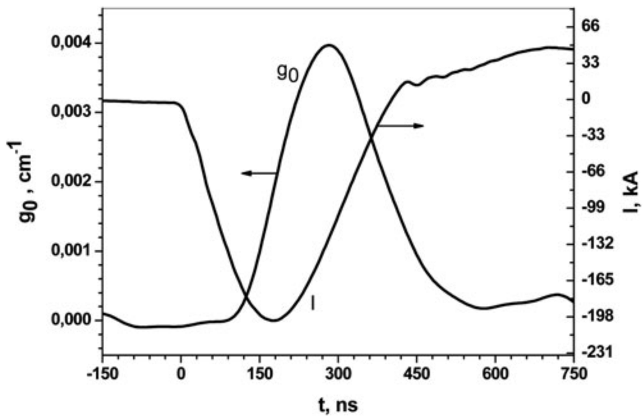

Fig. 5. Time profile of the e-beam current in the diode and gain measured near the CaF_2 windows with the continuous laser at 488 nm for a XeF_2 vapor pressure of 0.25 Torr.

energy stored in the C state is time variant and its maximum is about an order of magnitude lower than the integral value.

Figure 5 shows the time profile of the gain near the CaF_2 windows. The gain was measured using the continuous laser in the four-pass scheme through the active medium. The results of these measurements correlate well with those found in femtosecond pulse amplification. It is seen from Figure 5 that the maximum gain is 0.004 cm^{-1} and the FWHM of the amplified signal is about 200 ns. The experiments on femtosecond pulse amplification were performed on the time interval with the highest gain, and the total time of femtosecond pulse amplification in 33 passes was thus 146 ns.

The measurements demonstrate that the gain of the active medium strongly depends on the XeF_2 vapor concentration and distance from the laser cell axis. For determination of optimum conditions of femtosecond pulse amplification, the small signal gain distribution over the active medium cross-section was measured at different XeF_2 vapor pressures (Fig. 6). These measurements show that decreasing the vapor pressure enhances the gain distribution uniformity but at the

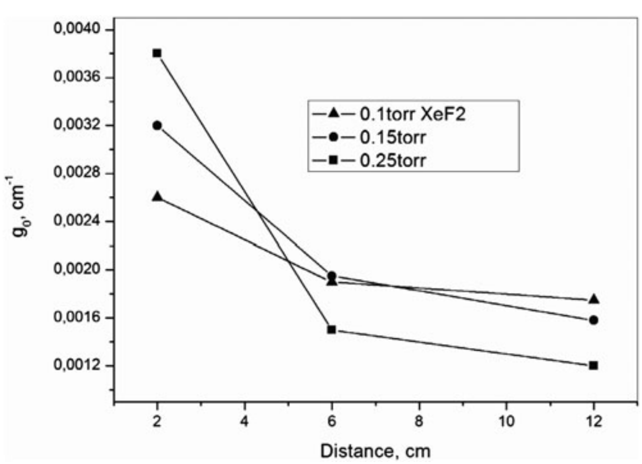

Fig. 6. Small signal gain distribution from the window toward the centre of the laser cell for different XeF_2 vapor pressures. The nitrogen pressure is 190 Torr.

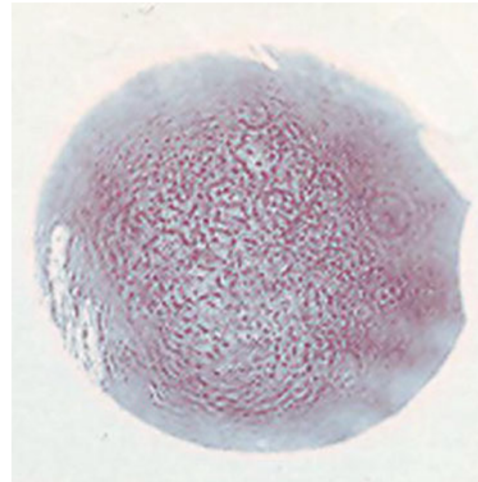

Fig. 7. Autograph of the output laser beam.

same time greatly decreases the gain near the pump windows. Final optimization of the mixture was made from the output energy of the amplified femtosecond pulse in the real optical scheme of multipass amplification. The best results were obtained for a XeF_2 vapor pressure of 0.2–0.25 Torr.

In the experiments on femtosecond pulse amplification, the amplifier input energy was varied from 0.04 to 2 mJ. In this case, the output energy without pumping the amplifier reduced by half or more due to the loss in the laser cell windows, mirrors of the multipass optical system, and alignment accuracy. In unsaturated conditions, the total gain reached 5×10^3. In near-saturation conditions of the amplifier (50 mJ/cm^2), the output radiation energy increased by a factor of 10^3. The maximum energy of the amplified pulse was 1 J. Figure 7 shows an imprint (autograph) of the laser beam at the amplifier output.

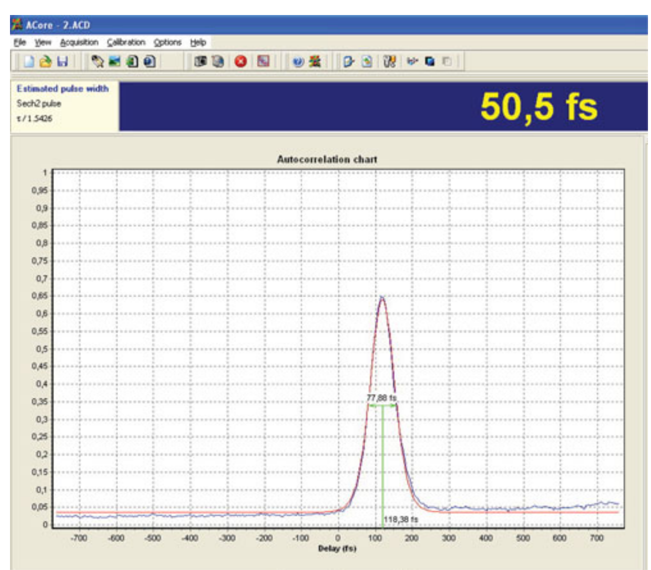

Fig. 8. Auto-correlated function of output pulse radiation with energy of 0.7 J.

https://doi.org/10.1017/S0263034612000870 Published online by Cambridge University Press

The pulse duration after compression was measured with no pumping of the amplifier and with its pumping at beam energy of 0.5–0.75 J. In both cases, the pulse duration was 50–60 fs. Figure 8 shows an example of the autocorrelation function of the compressed pulse at a 0.7-J output energy that corresponds to pulse duration of 50 fs. This result suggests that the peak power reached 14 TW. According to available data, the highest power of femtosecond pulses in the visible spectrum was attained earlier on direct amplification of 250-fs pulses in an electron beam-excited XeF(C-A) amplifier (1 TW by Hofmann *et al.* (1992)) and on nonlinear conversion to the second harmonic in a Ti:Sapphire laser (4 TW by Ozaki *et al.* (2006)), and these values are far below the power attained in the present work.

CONCLUSION

Thus, at the Institute of High Current Electronics SB RAS, the THL-100 fs hybrid laser system consisting of a titanium-sapphire starting complex with nonlinear conversion of 50-fs radiation to the second harmonic (475 nm) and a photodissociation XeF(C-A) amplifier with a 25-cm aperture excited by VUV radiation of the electron beam converter has been created and tested. In the first experiments on amplification of femtosecond pulses negatively chirped to 1 ps, the output energy reached 1 J. At the output energy 0.7 J, compression of the amplified pulses in the quartz glass volume to an initial duration of 50 fs was realized. Thus, a record-breaking peak power of 14 TW in the visible spectrum has been attained.

The results of studies point to prospects of the developed hybrid approach to the design of ultra-high power visible laser systems. The advance into the visible spectrum extends the possibilities of experimental studies of the interaction of ultrahigh optical fields with a matter.

ACKNOWLEDGMENTS

The work was supported by RFBR (projects Nos. 10-08-00022, 11-08-98050-r_sibir_a) and Federal target program "Scientific and scientific-pedagogical personnel of innovative Russia" (state contract No. 02.740.11.0560). The authors express their gratitude to the Kurchatov Institute LNS Research Center for providing with xenon difluoride used in the experiments.

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