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Elongation of the pulse duration of ArF laser with a solid-state pump generator

S.I. Moshkunov, V.Yu. Khomich, V.A. Yamshchikov

Abstract. **The possibility of increasing the pulse duration of an ArF laser (wavelength 193 nm) by using an artificial forming line with nonlinear chokes is studied. An ArF laser (maximum pulse energy 15 mJ, pulse duration 18 ns, pulse repetition rate 1 KHz) with an all-solid-state pump generator is described.**

Keywords: *solid-state switch, generator with magnetic compression of high-voltage pulses, long VUV pulse.*

1. Introduction

Excimer ArF lasers are high-power sources of VUV radiation (193 nm), which are widely used in industry, microelectronics, medicine, communication systems, etc. [1–9]. Designers of these lasers make significant efforts to increase the average power, repetition rate, and stability of laser pulses, as well as to increase the service life. In recent years, these problems are successfully solved using excitation systems with all-solid-state pump sources [5, 8, 9].

Another important problem is to increase the output beam quality and the corresponding spatial, temporal, and spectral characteristics of radiation. Some technological applications of ArF lasers (photolithography, writing of Bragg gratings in optical fibres, formation of diffractive optical microstructures, etc.) require good output beam characteristics and high service life of the optical units of laser systems. This runs into some problems: on the one hand, the beam has a relatively low monochromaticity and a high divergence; on the other hand, the high-power VUV radiation causes compaction of materials. The latter results in a change in the refractive indices of optical materials (fused quartz, calcium fluorite), which leads to degradation of cavity mirrors and scanning optical elements under action of the laser beam.

To solve these problems, we proposed an efficient method [10, 11] based on elongation of the pulse duration. This allows one to control the spatial coherence of the beam and the width of the emission spectrum by increasing the number of passes through the cavity. In addition, an increase in the laser pulse duration decreases the beam intensity and reduces the negative effect of material compaction. An increase in the laser pulse duration also makes it possible to increase the pulse energy and the average power of radiation transmitted through a waveguide.

The aim of the present work was to create and study an all-solid-state system for excitation of a compact (active volume ~ 9 cm^3) ArF laser to obtain radiation ($\lambda = 193$ nm) with an approximately twofold longer pulse duration and a pulse repetition rate up to 1 kHz.

2. Elongation of the laser pulse duration

The temporal profile of the optical pulse of a small ArF laser has a shape of a short single spike. For active media ~ 30 cm long, the laser pulse duration at half maximum is 5–7 ns. Therefore, for a cavity length of about 30 cm, the number of passes of radiation through the cavity did not exceed five, which is insufficient for formation of a highly monochromatic beam. That is why the authors of [10, 11] used methods of forced elongation of the pulse duration.

The most efficient method of laser pulse elongation is to increase the time of energy release in a volume self-sustained discharge that pumps the active medium. This can be achieved either using electric schemes with high inductance and capacity in the closed circuit feeding the laser gas-discharge gap or using artificial forming lines consisting of several series LC circuits [12]. However, in the latter case, it is necessary to increase the voltage pulse front duration at the laser electrodes to avoid additional losses of the pump generator energy.

At a high pump pulse repetition rate (~ 1 kHz), it is very important to ensure a high homogeneity of the volume self-sustained discharge to exclude the appearance of spark channels and cathode spots in the discharge gap, which lead to accelerated degradation of the mixture and to erosion of electrodes. To obtain a sufficiently homogeneous self-sustained discharge, the pump pulses sent to the discharge gap of the laser must have a short (tens of nanoseconds) front duration [3, 13]. In this connection, we propose to use schemes with nonlinear forming lines, which combine the possibility of controlling the pump pulse duration and the possibility of forming a sufficiently short voltage pulse front at the discharge gap. These lines are often called schemes of magnetic compression of high-voltage pulses.

S.I. Moshkunov, V.Yu. Khomich, V.A. Yamshchikov Institute for Electrophysics and Electric Power, Russian Academy of Sciences, Dvortsovaya naberezhnaya 18, 191186 St. Petersburg, Russia;
e-mail: serg-moshkunov@yandex.ru

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3. All-solid-state generator of high-voltage pulses

The ArF laser characteristics in many respects depend on the parameters of high-voltage pulses formed by the pump generator across the discharge gap of the laser. A volume self-sustained discharge initiated at the voltage rise stage pumps the laser active medium. The shorter the pulse front duration, the more homogeneous the discharge and the longer the dynamic service life of the gas mixture [13, 14].

In the repetitively pulsed regime of laser operation, the most efficient systems for voltage pulse front shortening are magnetic compression systems designed as a network of successive circuits consisting of capacitors and nonlinear saturable chokes. The number of successive circuits must be chosen to provide the optimally high amplitude and rise rate of the voltage across the discharge gap, as well as to ensure the required pump pulse duration. The systems of magnetic compression of high-voltage pulses can reliably operate at pulse repetition rates of several kilohertz [15].

Another important unit of the pump generator is a switch. Currently, widespread are high-power semiconductor switches, which have almost unlimited service life and highly stable parameters of voltage pulses. Usually, pump generator schemes are used with relatively low-voltage semiconductor switches operating in conjunction with step-up transformers [1].

In contrast to traditional pump generator schemes, we developed a high-voltage nanosecond pulse generator without a high-voltage transformer. The functional scheme of the generator is shown in Fig. 1. Its specific feature is the use of a high-voltage semiconductor switch proposed in [15, 16]. The generator is based on all-solid-state elements. It contains a stabilised high-voltage supply, a high-voltage solid-state switch (HVSSS) with a control circuit, a two-stage magnetic pulse compression system, and a control and monitoring unit. The HVSSS is completely controllable (both switching on and switching off is possible) and consists of 32 isolated gate bipolar transistors (IGBTs) connected in parallel and in series (Z1 – Z32). The transistors are controlled by transformers (not shown in Fig. 1). This connection of transistors allows one to develop a rather simple scheme of a generator with voltage doubling due to an incomplete discharge of a storage capacitor C1.

A control pulse from the generator opens the HVSSS, and a capacitor C2 is resonantly charged through a choke L1. The control pulse duration is chosen so that the HVSSS closes at the instant when the voltage across C2 reaches its maximum. At this instant, the current through the HVSSS is close to zero, which considerably reduces switching losses. Since capacitance C1 considerably exceeds capacitance C2, the voltage across the C2 capacitor tends to the doubled charging voltage $2U_1$. Then, the voltage pulse across the C2 capacitor is shortened by the magnetic compression system and is applied to the discharge-gap electrodes.

With the use of a high-voltage 2500-W power supply and forced air cooling, the generator reliably operated with an active load of 30 Ω, a pulse repetition rate up to 2 kHz, an output pulse amplitude of 20 – 27 kV, and a pulse front duration of $\sim$ 70 ns.

4. Experimental setup

The excitation system of an electric-discharge ArF laser included a solid-state magnetic pump generator and a laser chamber described in [3]. The active volume of the discharge gap was $V = dwl$ (where $d = 1.2$ cm is the interelectrode distance, $w = 0.3$ cm is the discharge width, and $l = 25$ cm is the discharge-gap length). The 34-cm-long optical cavity was mounted on the laser chamber housing. The cavity was formed by a highly reflecting plane mirror and an output window made of a CaF_2 plane-parallel plate.

A mixture of F_2, Ar, He and Ne gases was pumped through the discharge gap using a diametral fan. The mixture pressure in the laser chamber did not exceed 5000 mbar. The working mixture was cooled by running water; the diametral fan and the water cooling radiator were placed inside the chamber.

The output laser energy was measured with an Ophir pyroelectric detector; simultaneously, we recorded the pump generator voltage pulses across the discharge gap and the laser pulses using a Tektronix P6015A high-voltage probe, a FEK-22 coaxial photocell, and a LeCroy WaveSurfer 432 oscilloscope.

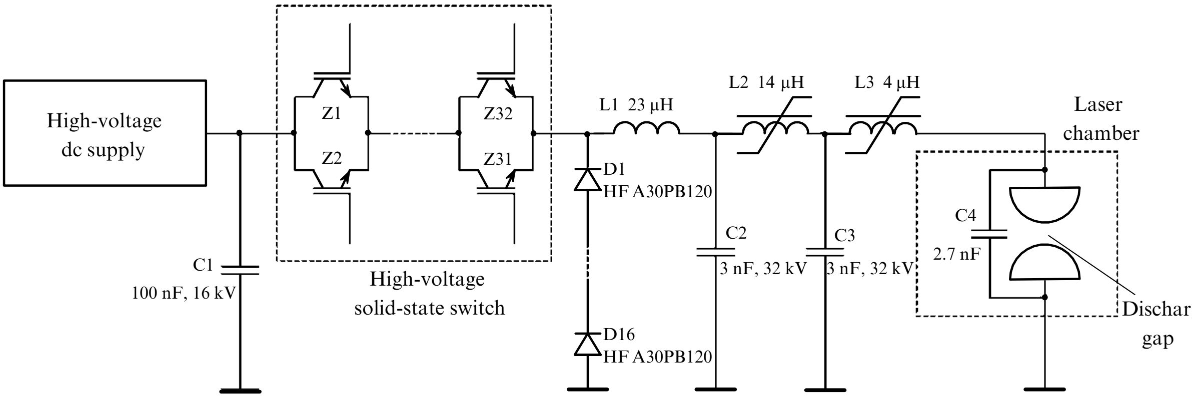

Figure 1. Functional scheme of the pump generator: (C1) storage capacitor; (Z1 – Z32) isolated gate bipolar transistors; (D1 – D16) protective diode array; (L1) charging choke; (C2) capacitor of the first magnetic compression circuit; (L2) saturable choke of the first magnetic compression circuit; (C3) capacitor of the second magnetic compression circuit; (L3) saturable choke of the second magnetic compression circuit; (C4) peaking capacitor of the laser chamber.

5. Output laser parameters

The experimental dependences of the laser pulse energy W, the maximum discharge-gap voltage $U_{\max}$, and the laser pulse FWHM $\tau_{0.5}$ on the charging voltage U_1 of the pump generator are shown in Figs 2 and 3.

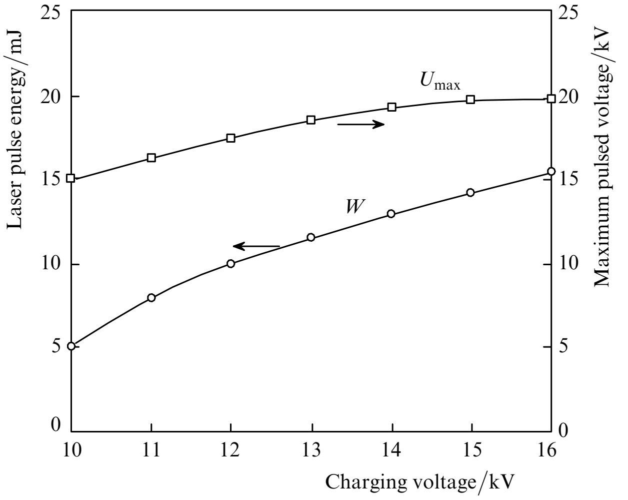

Figure 2. Experimental dependences of the laser pulse energy W and the maximum discharge-gap voltage $U_{\max}$ on the charging voltage U_1.

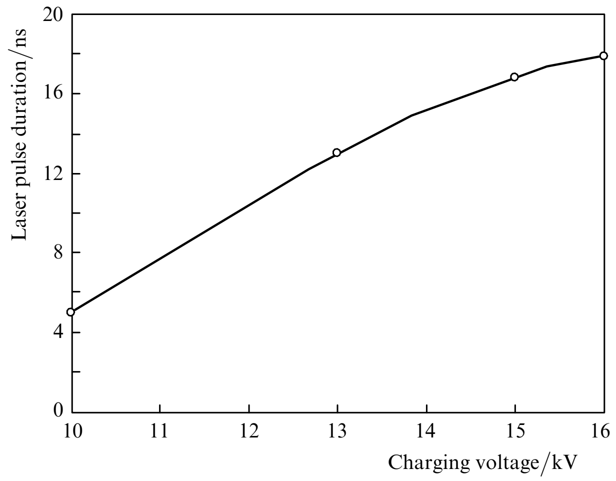

Figure 3. Experimental dependence of the laser pulse FWHM $\tau_{0.5}$ on the charging voltage U_1.

The oscillograms of voltage pulses across the discharge gap [curves (*1*)] and pulses of laser radiation at $\lambda = 193$ nm [curves (*2*)] at different U_1 are presented in Fig. 4. The oscillograms demonstrate the evolution of laser pulses with changing the charging voltage. At $U_1 = 10$ kV, the voltage pulse oscillogram has a flat top (Fig. 4a). This means that the discharge gap breakdown occurs during the time period when the total pump energy is concentrated in the capacitor C4. Therefore, the laser pulse has a single-peak shape determined only by the discharge of the capacitor C4 through the discharge gap. In the voltage region $U_1 = 10 - 12$ kV, the amplitude of the maximum voltage $U_{\max}$ across the discharge gap increases linearly, which leads to an increase in the laser pulse amplitude. However, due to a decrease in the delay time of the discharge gap breakdown with respect to the instant of the voltage pulse front rise, breakdown begins to occur at the voltage pulse front even at $U_1 \geqslant 12$ kV. Under these conditions, the pump energy is redistributed between the capacitors C3 and C4, because of which the laser pulse observed at $U_1 = 13$ kV has two peaks (Fig. 4b) caused by the discharge of both capacitors. With a further increase in U_1 (Fig. 4c), the voltage $U_{\max}$ increases only slightly, because of which the amplitude of the first laser peak also changes insignificantly, while the second peak amplitude increases stronger and may even exceed the amplitude of the first peak. At the same time, the laser pulse duration $\tau_{0.5}$ becomes approximately equal to the doubled duration of the single pulse and, at $U_1 = 16$ kV, reaches 18 ns.

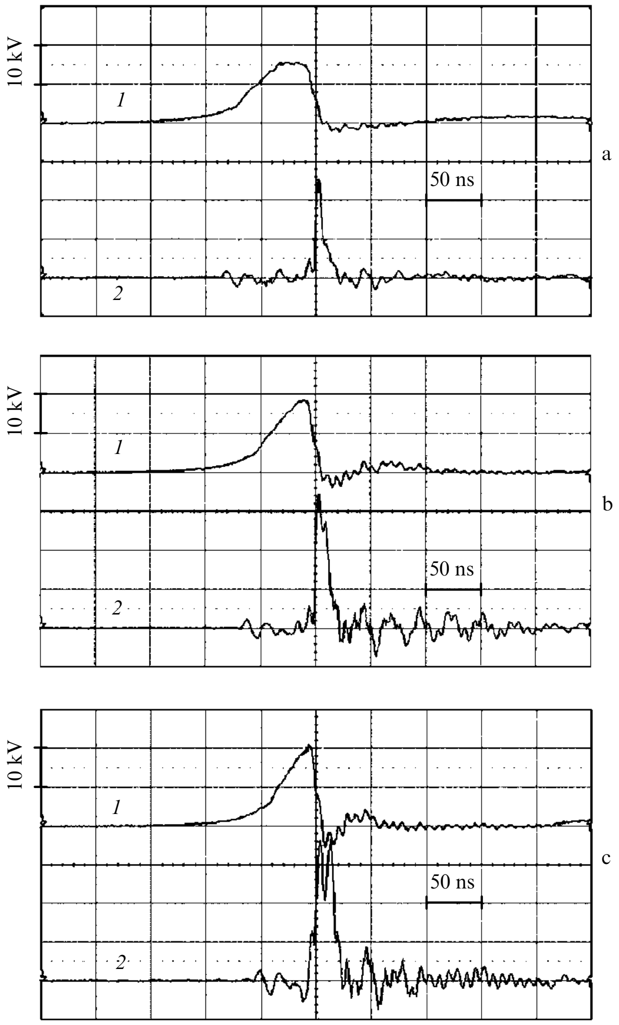

Figure 4. Oscillograms of the discharge-gap voltage pulses (*1*) and laser pulses (*2*) for the charging voltage $U_1 = 10$ (a), 13 (b), and 16 kV (c).

Our investigations showed that the laser stably operates at a pulse repetition rate up to 1 kHz. The average laser output power exceeded 10 W. The maximum laser efficiency with respect to the energy stored in the capacitor C2 (Fig. 1) was 1.2 % at a charging voltage of 13 kV.

6. Conclusions

It is proposed to use schemes with nonlinear forming lines to control the pump pulse duration, as well as to obtain a short pump voltage pulse front ensuring the formation of sufficiently homogeneous self-sustained discharges. An efficient system of excitation of excimer lasers is developed based on using an all-solid-state magnetic pump generator. The scheme allows the ArF laser to generate pulses with a duration up to 18 ns and an energy up to 15 mJ at a pulse repetition rate exceeding 1 kHz.

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References

1. *Excimer Laser Technology*. Ed. by D.Basting et al. (Gottingen: Lambda Physik AG, 2001).
2. Borisov V., Khristoforov O., Kirykhin Yu., Vinokhodov A., Demin A., Vodchits V., Eltzov A. *Proc. SPIE Int. Soc. Opt Eng.*, **4184**, 348 (2001).
3. Vartapetov S.K., Zhigalkin A.A., Lapshin K.E., Obidin A.Z., Khomich V.Yu., Yamshchikov V.A. *Kvantovaya Elektron.,* **36** (5), 393 (2006) [*Quantum Electron.,* **36** (5), 393 (2006)].
4. Klerk J., Wagner C., Droste R., Levasier L., Jorritsma L., Setten E., Kattouw H., Jacobs J., Tilmann Heil T. *Proc. SPIE Int. Soc. Opt Eng.*, **6520**, 65201Y (2007).
5. Kakizaki K., Sasaki Y., Inone T., Sakai A. *Rev. Sci. Instrum.*, **77**, 035109 (2006).
6. Tokarev V.N., Khomich V.Yu., Shmakov V.A., Yamshchikov V.A. *Dokl. Ross. Akad. Nauk*, **419** (6), 754 (2008).
7. Tokarev V.N., Khomich V.Yu., Shmakov V.A., Yamshchikov V.A. *Fiz. Khim. Obrab. Mater.*, **4**, 18 (2008).
8. Vartapetov S.K., Gryaznov O.V., Malashin M.V., Moshkunov S.I., Nebogatkin S.V., Khasaya R.R., Khomich V.Yu., Yamshchikov V.A. *Kvantovaya Elektron.*, **39** (8), 714 (2009) [*Quantum Electron.*, **39** (8), 714 (2009)].
9. Khasaya R.R., Malashin M.V., Khomich V.Yu., Yamschikov V.A. *Proc. X Intern. Conf. 'Laser and Laser-information Technologies: Fundamental Problems and Applications'* (Smolyan, Bulgaria, 2009) p. 205 – 215.
10. Kakizaki K., Saito T., Mitsuhashi K., Arai M., Tada T., Kasahara S., Igarashi T., Hotta K. *Proc. SPIE Int. Soc. Opt Eng.*, **4000**, 1397 (2000).
11. Hofmann T., Johanson B., Das P. *Proc. SPIE Int. Soc. Opt Eng.*, **4000**, 511 (2000).
12. Mesyats G.A., Osipov V.V., Tarasenko V.F. *Impul'snye gasovye lazery* (Pulsed Gas Lasers) (Moscow: Nauka, 1991).
13. Osipov V.V. *Usp. Fiz. Nauk.*, **170** (3), 225 (2000).
14. Apollonov V.V., Yamshchikov V.A. *Kvantovaya Elektron.*, **24** (6), 483 (1997) [*Quantum Electron.*, **27** (6), 469 (1997)].
15. Ivanov E.V., Moshkunov S.I., Khomich V.Yu. *Generator vysokovol'tnykh nanosekundnykh impul'sov na osnove bipolarnykh tranzistorov s izolirovannym zatvorom* (Generator of High-Voltage Nanosecond Pulses Based on Isolated Gate Bipolar Transistors) (Moscow: Preprint IPEF RAN) 2004.
16. Ivanov E.V., Moshkunov S.I., Khomich V.Yu. *Prib. Tekh. Eksp.*, **1**, 88 (2006).