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Generation of diffraction-limited nanosecond and subnanosecond pulses in a XeCl laser

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***Abstract*. The generation of nanosecond and subnanosecond pulses in a XeCl laser is studied. The short radiation pulses are generated in a resonator with a SBS mirror. By focusing laser radiation inside and on the surface of a nonlinear medium, it is possible to generate pulses of duration 3 ns and 150 ps, respectively. The laser beams obtained in this way contain more than 70 % of energy within the diffraction angle and have the signal-to-noise ration exceeding 10^4.**

Keywords: *excimer laser, active medium, SBS medium, divergence, subnanosecond radiation pulse.*

1. Introduction

Many studies of the interaction of radiation from excimer lasers with various materials require high radiation intensity, i.e. lasers should provide high output powers along with the minimal divergence of radiation. The output laser power can be increased by reducing the laser pulse duration. However, it is known that as the pulse duration is reduced, the conditions for obtaining a low divergence of the beam are complicated. That is why short and high-power low-divergence radiation pulses are usually generated in laser systems consisting of a master oscillator (MO) and an amplifier. The maser oscillator forms a low-power laser beam with the required parameters, while the amplifier is used to increase the beam energy.

One of the methods for generating beams with required parameters in excimer lasers involves the use of a nonlinear medium in which, as a rule, stimulated Brillouin scattering (SBS) can be observed. It is known that an SBS medium can be used both for phase conjugation (PC) to obtain laser beams with the minimal divergence and for generating short radiation pulses. The most popular methods employed for this purpose are the compression of a radiation pulse in a nonlinear medium [1] and 'truncated Brillouin scattering' (TRUBS) [2]. The first method is based on the pump-beam depletion in the nonlinear medium, and the second one uses the interruption of stimulated scattering due to optical breakdown. The first method requires the use of narrow-band pumping, while in the second method broadband radiation can be employed. The generation of picosecond pulses in excimer laser systems by the TRUBS method was studied in papers [2 – 5]. Laser systems used in these papers consisted of a master oscillator and an amplifier.

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Thus, the generation of low-divergence short pulses requires the development of laser systems containing non-linear media and expensive spectral and spatial selectors of radiation.

The complexity and high cost of such laser systems stimulate investigations aimed at simplifying optical schemes. One of the simple methods of generating short radiation pulses with the required parameters is based on the use of an SBS medium in a laser cavity without spectral selectors. The main problem in this case is related to a broad width of the gain band of excimer lasers. It is known that to perform PC upon SBS of broadband pump radiation, it is necessary to realise the interaction conditions as in the case of a monochromatic beam [6, 7]. For example, the PC of a beam from a KrF laser with the linewidth $\Delta\nu_p = 32$ cm^{-1} was performed in [3]. In this case, the interaction length was chosen smaller than the pump coherence length ($L_{int} < L_{coh}$) and the pump intensity was increased, according to [8], to the value exceeding the critical intensity $I_{cr} = 4\pi\Delta\nu_p/g$, where g is the SBS gain. However, the necessity of increasing the intensity of broadband pump radiation leads to the enhancement of other nonlinear processes competing with SBS. It was shown in [9, 10] that during the interaction of broadband radiation with heptane the SBS efficiency decreases and can cease at all due to dissociation of heptane molecules or the development of stimulated temperature scattering caused by two-photon absorption. The use of gases with a low two-photon absorption coefficient, for example, SF_6 eliminates these processes, but in this case the SBS efficiency is limited by the optical breakdown [1, 3]. The studies have shown that to perform PC upon broadband pumping, it is necessary to provide the fulfilment of rather strict conditions of the nonlinear interaction of radiation with a medium. In excimer lasers with the high gain of the active medium, high-power output pulses with a contrast of more than $10^2 - 10^3$ can be generated only by using a master oscillator and an amplifier.

Note that the authors of paper [11] have managed to generate a short nanosecond pulse by using one laser module. However, they have failed to obtain PC, and the divergence of the laser beam was considerably greater than in papers where a master oscillator and an amplifier were used.

We showed in [12] that the coherence of radiation from a XeCl laser with an intracavity SBS mirror emitting 120-ns pulses could be increased. The output radiation of the laser was a superposition of two beams propagating at an angle to each other. Each of the beams consisted of a train of short pulses of duration 6 – 8 ns. The laser linewidth was considerably smaller than in the free running regime, while the divergence of the output radiation was close to the diffraction limit.

In this paper, we continued investigations on the generation of short low-divergence radiation pulses by using an intracavity SBS mirror in a XeCl laser emitting 30-ns pulses [13, 14]. The aim of the paper was to study the possibility of generating nanosecond and subnanosecond pulses with nearly diffracted-limited divergence.

2. Experimental

We used in experiments a commercial electric-discharge XeCl laser of the EL type developed in the Institute of High-Current Electronics, Siberian Branch, Russian Academy of Sciences [13, 14]. The size of the active volume of the XeCl laser was $0.7 \times 2.2 \times 59$ cm. Upon excitation of the $Ne : Xe : HCl = 875 : 15 : 1$ mixture at a pressure of 3.6 atm, the output energy of the laser in the free-running regime was 350 mJ and the pulse FWHM was 29 ns. The maximum gain of the active medium was 0.15 cm^{-1}, while the unsaturated absorption coefficient was an order of magnitude lower.

Figure 1 presents the optical scheme of the resonator used for generating short pulses. The laser resonator was formed by a mirror with the reflectance $R = 0.07$ (plane – parallel quartz plate), a focusing lens, and an SBS cell filled with heptane. Radiation was focused by a lens with the focal distance $f = 10$ cm either inside the cell or on its surface by moving the cell.

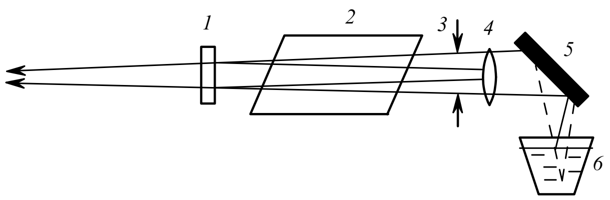

Figure 1. Optical scheme of the experiment: (*1*) plane – parallel quartz plate; (*2*) XeCl laser active medium; (*3*) 10-mm aperture; (*4*) biconvex lens with $f = 10$ cm; (*5*) aluminium mirror; (*6*) cell with heptane.

Nanosecond laser pulses were recorded with a FEK-22SPU photodiode connected with a TDS-3032 oscilloscope. Subnanosecond laser pulses were recorded by using an Agat SF3M streak camera with a time sweep of 0.15 ns cm^{-1}. The output radiation energy was detected with a Gentec-E calorimeter. The divergence of radiation was measured with the help of calibrated apertures mounted in the focal plane of a lens with $f = 10$ m.

3. Experimental results and discussion

The resonator with the SBS mirror used in our experiments provides a number of conditions required for generating radiation with specified parameters. The sequence of physical processes proceeding in the resonator can be described as follows. First a short radiation pulse is formed, which has a low divergence but poor contrast (high noise level). Then, the SBS mirror is 'switched on', the contrast of the useful signal increases, and a short radiation pulse is formed due to PC, which is amplified by passing through the active medium. The duration of the generated pulse could be varied in the nanosecond and subnanosecond ranges by slightly changing the optical scheme of the resonator. In the first case, radiation was focused by a lens inside a cell with heptane, and in the second one – on its surface. These two regimes differ only in the position of the beam waist with respect to the nonlinear medium.

In both regimes, a laser beam is initially generated in an unstable resonator formed by a convex lens of radius 10 cm and the output mirror separated from the lens by a distance of 133 cm. The feedback in the unstable resonator is achieved due to Fresnel reflection from optical elements. The feedback coefficient of the resonator is determined by the expression

$$\eta = \frac{R_1 R_2}{M^2} = 0.035\,\frac{0.07}{47^2} = 1.2 \times 10^{-6}, \qquad (1)$$

where R_1 and R_2 are the reflectances of one surface of the lens and the output mirror, respectively; and M is the magnification of the unstable resonator, which was 47 in our experiments.

Despite a small feedback coefficient of the resonator, a high gain of the active medium provided the achievement of the lasing threshold near the maximum of the amplification band. As a result, the duration of a pulse formed in the unstable resonator was ~ 5 ns, which is considerable lower than the excitation pulse duration. The output laser beam of the resonator had a spherical wavefront and diverged (due to reflection from a convex lens). The beam was focused by the lens to a small spot owing its low divergence. The total light flux from the unstable resonator directed to the SBS mirror contained, along with the short radiation pulse, a great contribution of one- and two-passage amplified spontaneous emission (ASE). The fraction of ASE in the pump beam incident on the SBS mirror was more than 80 %.

It has been shown [15] that the ASE component can be efficiently suppressed by using SBS media in excimer laser systems as nonlinear filters. The filtration of the ASE component, which has the same bandwidth as that of the useful signal, can be performed due to different angular directions of these radiations. By assuming that the threshold gain increment is $G = 25 - 30$, we obtain the threshold pump power for the SBS medium

$$P_0 \approx \frac{30S}{gL}, \qquad (2)$$

where S is the cross section of the scattering medium; L is the interaction region length; and g is the gain of the SBS medium; and

$$S = \frac{\pi d^2}{4} = \frac{\pi f^2 \alpha^2}{4} \sim f^2 \alpha^2, \qquad (3)$$

where α is the radiation divergence. One can see that the threshold pump power increases linearly with increasing the pump radiation divergence. This leads to a considerable difference between threshold pump powers for generation of a short low-divergence pulse in the unstable resonator and ASE. In our case, the ratio of threshold powers was $\sim 10^4$. Such a high threshold power ratio provides the efficient scattering of the PC signal and filtering of the ASE component.

The realisation of PC is confirmed by the fact that radiation reflected from the SBS mirror propagates exactly in the same path along which it emerged from the active medium. The output laser beam was converging, the convergence angle being equal to the angular divergence of radiation propagating through the active medium and incident on the focusing lens (Fig. 1). In addition, we recorded the radiation intensity distribution in the beam cross section at a distance of 50 cm from the output window of the laser. This distribution coincided with good accuracy with the distribution calculated for a uniform beam propagating through an aperture of diameter 1 cm and a focusing lens with $f = 266$ cm. Figure 2 shows the experimental and calculated intensity distributions in the beam cross section at this point.

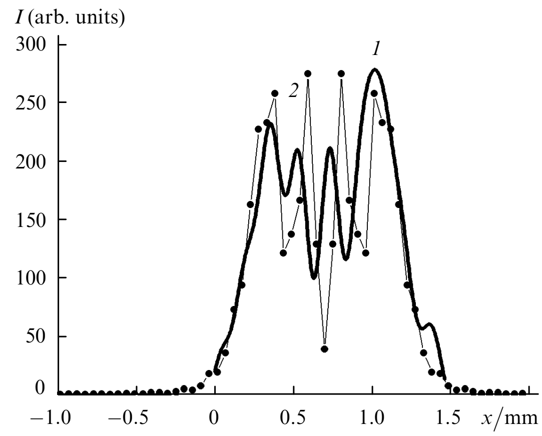

Figure 2. Experimental (*1*) and calculated (*2*) radiation intensity distributions in the beam cross section at a distance of 50 cm from the output window of the laser.

The output radiation energy was 0.5 – 1 mJ and the pulse duration was 3.5 ns. A 5-ns pulse incident on the SBS medium is shortened to 3.5 ns because SBS scattering has a threshold and the radiation power at the leading edge of the incident pulse was insufficient for SBS. Figure 3 shows oscillograms of the discharge current, voltage across a discharge capacitor, and radiation pulses generated by using a plane – parallel resonator and a SBS mirror resonator. One can see that a short pulse is formed at the moment corresponding to the maximum of the pulse power in the free-running lasing regime. The laser pulse FWHM was 3.44 ns and its energy was 0.5 mJ.

The divergence of the laser pulse was considerably lower than in the case the plane – parallel resonator and approached the diffraction limit. Figure 4 illustrates the angular dependences of the output energy for the plane – parallel and SBS mirror resonators. One can see that $\sim 75\,\%$ of the output energy is contained within the diffraction angle φ_0. The noise level was quite low and the signal-to-noise ratio exceeded 10^4.

Picosecond pulses were generated in the second operation regime, when radiation was focused into heptane near its surface. We selected experimental conditions under which

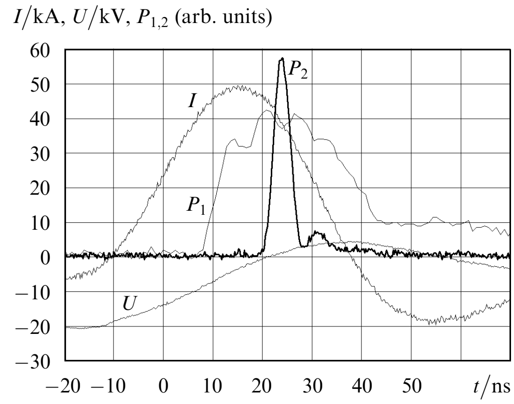

Figure 3. Oscillograms of the discharge current *I*, voltage *U* across a discharge capacitor, and radiation pulses in the case of the plane – parallel resonator (P_1) and SBS mirror resonator (P_2).

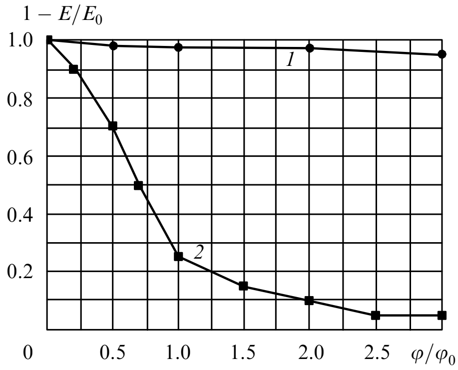

Figure 4. Far-field angular distributions of the radiation energy *E* in the case of the plane – parallel resonator (*1*) and the SBS mirror resonator (*2*) (E_0 is the total output energy, $\varphi_0 = 2.44\lambda/d_0$ is the diffraction angle and d_0 is the laser beam diameter).

the short pulse intensity was sufficient both for the appearance of SBS and the development of an optical breakdown on the nonlinear medium surface, i.e. for realisation of the TRUBS regime. At the same time, the ASE intensity was insufficient to reach the thresholds of these processes. As a result, we have managed to control and reduce considerably the duration of output laser pulses. The minimum pulse FWHM observed from pulse to pulse was 150 ps (Fig. 5).

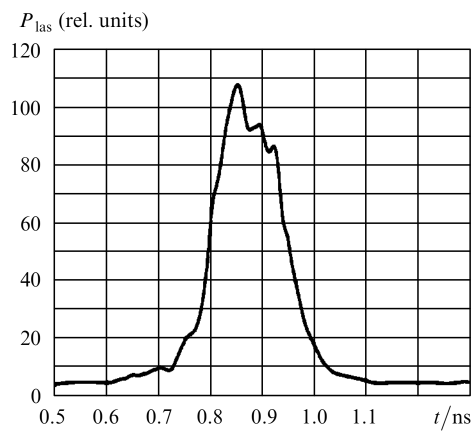

Figure 5. 0.2-mJ laser radiation pulse generated in the TRUBS regime.

The pulse energy was ~ 0.2 mJ. Because the output radiation was converging, PC was realised in this regime as well. The measurements of the spatial characteristics of this pulse showed that its divergence and contrast almost coincided with these characteristics for a short nanosecond pulse. Note that no provision has been made in experiments to produce polarised radiation, and the pump and scattered radiations were depolarised.

4. Conclusions

We have studied the generation of nanosecond and picosecond pulses with nearly diffraction-limited divergence in a XeCl laser. Short radiation pulses were generated in an SBS mirror resonator. The duration of scattered radiation pulses could be changed in a broad range by varying the position of the pump beam waist with respect to the nonlinear medium surface. By focusing the pump radiation inside the SBS medium, 3–4-ns laser pulses of energy up to 1 mJ were generated. By focusing the pump beam on the nonlinear medium surface, the 150-ps, 0.2-mJ laser pulse was generated. More than 70 % of energy of the output laser beams was contained within the diffraction angle and the signal-to-noise ratio did not exceed 10^4.

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