FORMATION OF FUNDAMENTAL MODE OF THE PERIODIC-PULSE XeCl-LASER RADIATION AND DECREASE OF ITS DIVERGENCE

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Received October 9, 1997

A beam divergence of the excimer XeCl *laser is investigated. Directional patterns of radiation for different unstable resonators have been measured in the far-field zone. The influence of the gas mixture circulation velocity and the pulse repetition frequency on the* XeCl-*laser beam divergence has been investigated.*

INTRODUCTION

Beams of excimer XeCl lasers with stable resonators, as a rule, have divergences $<10^{-2}$ rad. However, although the maximum radiation energy level and high efficiency are achieved, the application range of the laser with large beam divergence is severely limited, primarily because the beam cannot be focused into a small spot. The decrease of the beam divergence of excimer lasers is primarily achieved with the use of unstable resonators (Refs. 1–3), which serve to narrow the beam directional pattern ten times and under some favorable conditions to achieve 1.2–1.5 of diffraction-limited divergence of the fundamental radiation mode. But it should be noted that the achievement of such critical beam parameters leads to the significant decrease of the output energy (Ref. 3). Only in special cases the output energy losses can be prevented.[4]

The unstable resonators are described in detail in Refs. 4–8, where one can find seemingly exhaustive information about the choice of the optimum resonator for any laser. However, because of the essential influence of laser parameters such as the duration and energy of radiation pulse, the size of active medium, and the gain of the medium on the beam divergence as well as because of the aberration on the optical parts of the resonator, the formation of the fundamental radiation mode with the diffraction divergence without significant losses of the radiation energy is a very complex problem in each particular case.

At present, the papers devoted to investigations of the effect of the circulation velocity of gas mixture and the pulse repetition frequency on the XeCl-laser beam divergence are practically absent in the literature.

In this paper, the results of investigation of the influence of different resonators, gas circulation velocity, and pulse repetition frequency on the beam divergence and laser beam focusing are presented.

EXPERIMENTAL SETUP

The beam divergence was investigated for the LGE–100/400 excimer XeCl laser with the output radiation power up to 100 W and the pulse repetition frequency up to 400 Hz. The volume of a laser gas cavity was 235 L. The circulation of gas mixture through the interelectrode gap with a velocity of 18 m/s was performed with the use of a diametral fan with a magnetic coupling. The frequency of rotation of the fan was smoothly increased from zero to 2000 min^{-1} with the use of the EPU–1–2 actuator. The volume of the active zone between two profiled copper electrodes was $1.5\times2.6\times100$ cm^3. The pressure of the gas mixture He:Xe:HCl:H_2 = 1000:10:1:0.5 was 25 atm and remained constant during the experiments.

A high-voltage pulse generator connected in the Blumlein circuit with a magnetic compression system was used for excitation of the active medium. The special EKSTRA 3–15000/35 thyratron was used as a commutator.

Resonators of three types shown in Fig. 1 were used during the experiments.

In case of using the unstable resonators A and B, the distance between the mirrors M_1 and M_2 was 178 cm. The curvature radii of the mirror of the resonator A were R_1 = 360 cm and $R_2 = \infty$ and for the resonator B R_1 = 360 cm and R_2 = 544 cm.

The focal distances of the cavity mirrors of self-filtering resonators were F_1 = 206.5 cm and F_2 = 30.2 cm. The diameter of the aperture in the output mirror drilled at an angle of 45° was 2 mm. During the experiments the screen with calibrated apertures was placed at the focal points of the mirrors M_1 and M_2 to increase the aperture from 0.5 to 2 mm.

The IKT–1N and IMO–2N calorimeters were used for measuring the beam energy and power. The radiation of the laser with the resonators A and B was focused in the far-field zone with a telescopic system.

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A lens with the focal distance $F = 580$ cm was used to focus the radiation of the laser with the resonator C.

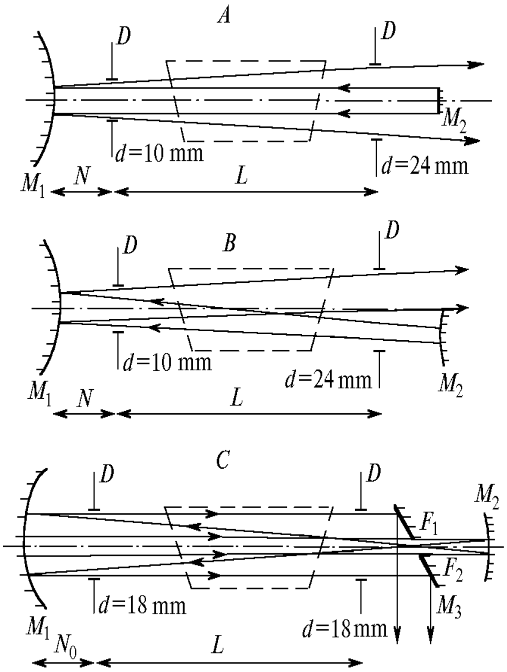

FIG. 1. Optical schemes of unstable resonators of different types: A is the resonator with the plane front mirror, B is the resonator with two convex mirrors and asymmetrical extraction of radiation, C is the self-filtering unstable resonator, D are the collimating apertures; M_1, M_2, and M_3 are the mirrors of full reflection; F_1 and F_2 are the focal points of the mirrors M_1 and M_2, $L = 1610$ mm, $N = 160$ mm, *and* $N_0 = 70$ mm.

EXPERIMENTAL RESULTS AND THEIR DISCUSSION

With the use of the unstable resonators shown in Fig. 1 for a pump power density of 0.1 J/cm^3, the following output energies were obtained: 190 (A), 160 (B), and 90 mJ (C). Moreover, the radiation from each of three resonators was multimodal, and the beam divergence for the unstable resonators A and B was $\sim 10^{-3}$ rad.

A reason for the appearance of additional modes was in the fact that the real laser resonator, in the strict sense, is voluminous rather than open and the electrode surfaces that form the lateral walls of the volume resonator also take part in the formation of the radiation in the resonator together with the end mirrors. The radiation multiply reflected from the electrode surfaces and mirrors forms the parasitic transverse modes.

To eliminate the effect of the electrodes on the radiation modes in the resonator, the variable apertures were used. We succeeded in the elimination of the additional modes through the decrease of the aperture diameters down to the values indicated in Fig. 1. But therewith the volume of the active medium participating in the generation was essentially decreased and hence the output energy, which in this case was only half the total energy radiated without collimating apertures, was decreased. The autocalibration method was used to measure the intensity distribution over the beam cross section (Ref. 9). The measurements for unstable resonators of three types are shown in Fig. 2.

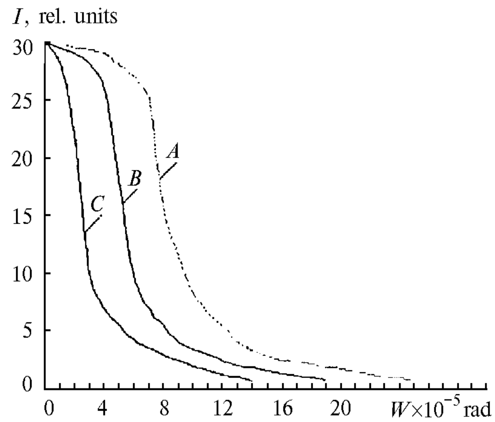

FIG. 2. Directional pattern of radiation for different configurations of unstable resonators: A is the cavity with the plane front mirror, B is the cavity with two convex mirrors and asymmetrical radiation output, C is the self-filtering unstable cavity.

The divergences determined at a level of 0.83 of the total radiation energy for the cavities A, B, and C, respectively, were $2.5\cdot10^{-4}$, $1.9\cdot10^{-4}$, and $1.4\cdot10^{-4}$ rad for diffraction divergences of $5.8\cdot10^{-5}$, $5.4\cdot10^{-5}$, and $2\cdot10^{-4}$ rad. The beam divergence was measured for all types of cavities for an output energy of ~ 40 mJ. The minimum divergence was obtained with the use of the self-filtering unstable cavity C. Therefore, the electrode surface influence on the generation of laser radiation reduced to minimum in this case. Nevertheless, without collimating apertures the beam divergence was $\sim 4\cdot10^{-4}$ rad.

Thus, the single-mode radiation cannot be obtained without angular filters and limitation of the beam aperture by the apertures irrespective of the type of the chosen cavity.

The gas mixture in the interelectrode gap is heated under the action of the discharge pulse. The power pumped for one pulse attains several MW/cm^2 in this case. As this take place, the nonuniformities in the gas-mixture temperature inevitably occur and still retain for 15 min without circulation of active medium, as shown in Ref. 8. This, in its turn, leads to the optical nonuniformity of the medium inside the cavity and to the increase of the beam divergence. It is of interest how this situation can be improved when the gas mixture is circulated through the gap. This data are given in Table I, from which it can be seen that the quicker the gas is renewed in the interelectrode gap, the less the previous discharge pulse influences the beam divergence of the following pulse. The experiment was performed at a pulse repetition frequency of 1 Hz, a pump energy of

0.1 J/cm^3, and current pulse duration on the base of 60 ns. The beam divergence decreased by 8% as the circulation velocity increased from zero to 18 m/s.

TABLE I. Dependence of the laser beam divergence on the gas mixture circulation velocity for d_{dif} = 2 μm.

Circulation velocity, m/s	0	3	6	9	12	15	18
Beam divergence, W×10^{-5} rad	19.3	19.1	18.85	18.6	18.4	18.15	17.9

Using similar reasoning (Ref. 8), the deterioration of the beam divergence can be expected as the velocity of gas mixture circulation through the gap increases to V = 18 m/s. The dependence of the beam divergence on the pulse repetition frequency is shown in Fig. 3. It can be seen that as the pulse repetition frequency increases up to 300 Hz, the beam divergence increases by 7%.

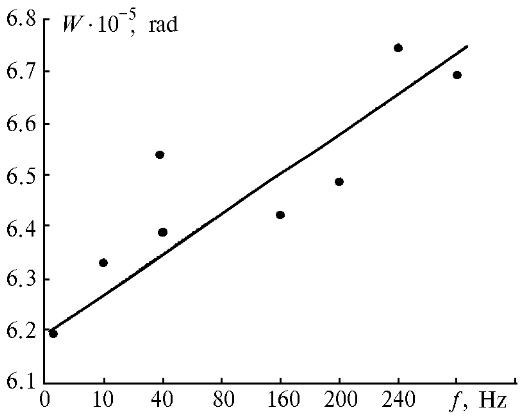

FIG. 3. Dependence of the beam divergence of XeCl *laser on the pulse repetition frequency.*

The diameter of the spot for cavities of different types was measured as well. The quartz lenses without correction for spherical aberration with focal distances F = 60, 100, and 150 mm and the corrected lenses with F = 60 and 150 mm were used for this aim.

The measurements of the spot diameter for unstable cavity with asymmetrical extraction of radiation (the cavity B in Fig. 1) are given in Table II.

TABLE II. The spot diameter, in mm *(divergence* W = 1.9·10^{-4} rad).

Conditions	F, mm		
	60	100	150
Without correction for spherical aberration (experiment)	90	50	45
Size caused by spherical aberration (theory)	76	30	12
Corrected lens (experiment)	20	–	30
Size caused by the beam divergence (theory)	11	19	28

The minimum spot diameter equal to 20 μm was obtained with the use of the corrected lens with the focal distance F = 60 mm. To estimate the spherical aberration influence on the beam divergence, the following formula was used (Ref. 10):

$$d = \frac{1}{n^4(1 - r_1/r_2)^3\,(1/n - 1)^2}\,\frac{D^3}{32F^2}\,.$$

During the investigation of the resonator properties near the focal waist it was discovered that the spot shape was changed from rectangular to circular as the beam passed through the focal point. The photographs of spots on a substrate plate are shown in Fig. 4a. The changes of the size and the shape of the spot are shown schematically in Fig. 4b.

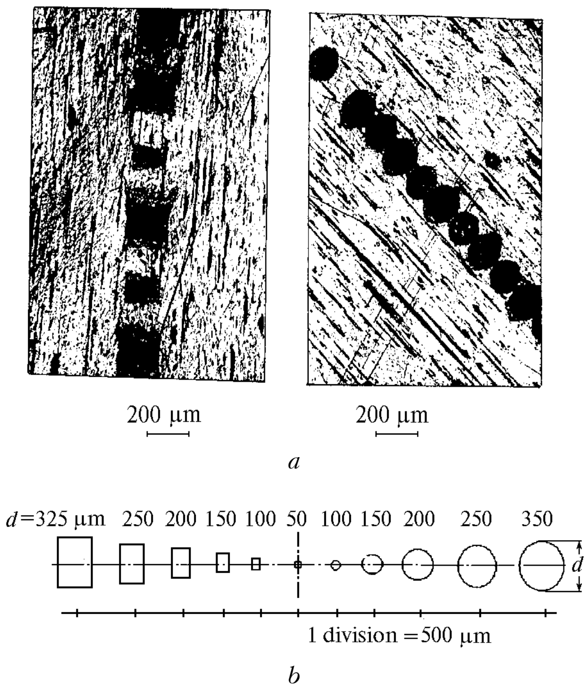

FIG. 4. Change of the spot shape after focusing: spot photographs from a substrate plate (a), schematic change of the spot shape (b).

The output pulse energy during this experiment was 10–50 kJ, the pulse duration at half maximum was 25–30 ns, and the beam divergence was ~2·10^{-4} rad. There was no optical breakdown in the focal plane of the beam. At large beam divergences the spot shape remained unchanged. From the viewpoint of the wave theory and geometric optics, near the focus the intensity distribution in the meridianal plane must be symmetrical (Ref. 11). We believe that such behavior of the spot shape is connected with a large fraction of the lowest-quality radiation (the highest modes of the resonator and re-reflected and amplified portion of radiation) before the focal waist and its small fraction after the waist.

As a result of our investigations, we can draw the following main conclusions:

1. Formation of single-mode XeCl-laser radiation is impossible without the use of the angular filter and without the collimating apertures, irrespective of the type of a chosen optical cavity.

2. The minimum divergence $W = 1.4 \cdot 10^{-4}$ rad was obtained with the use of the self-filtering unstable cavity.

3. It has been shown that under typical experimental conditions the influence of the gas circulation velocity and the pulse repetition frequency is relatively small and is about 10%.

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