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Degree of variation in the pattern of radiation amplified by a XeCl laser system

N G Ivanov, V F Losev, Yu N Panchenko

Abstract. The radiation divergence is measured upon amplification of a beam 1.5 – 150 mm in diameter. The radiation wave front with a spatially nonuniform intensity distribution caused by diffraction from a small-diameter aperture is shown to experience significant changes upon amplification in the active medium. The amplifier active medium excited by an electron beam permits amplification of the radiation with a divergence ~ 10 μrad without introducing appreciable distortions. In the transportation and the amplification of a beam more than 75 mm in diameter, the main distortions of the wave front arise from turbulent air flows and the aberrations of the optical elements.

1. Introduction

One of the main problems of quantum electronics is the production of radiation with minimum divergence. The minimum divergence is known to be limited by the diffraction of radiation from an aperture and is proportional to the ratio λ/D, where λ is the radiation wavelength and D is the aperture diameter. In this respect, wide-aperture excimer lasers, which are high-power sources of UV radiation [1 – 3], hold the greatest promise today. However, difficulties are always encountered in attaining nearly diffraction-limited divergence in practice, especially for laser beams of large diameter. This is related to the distortions of the radiation wave front in the optical path and to the effect of amplified spontaneous emission.

In this paper, we studied the wave-front distortions and the possible causes for their appearance upon amplification of a XeCl laser beam having a nearly diffraction-limited divergence.

2. Experimental equipment and results

The laser system (Fig. 1) used in our experiments comprised an electric-discharge long-pulse laser and a wide-aperture amplifier excited by two electron beams. The electric-discharge laser with an active volume size 1 cm × 3 cm × 70 cm [4] simultaneously played the parts of a master oscillator (MO) and a preamplifier. With the use of a plane parallel cavity, its output energy was 100 mJ for a pulse length of 150 ns (FWHM). The initial formation of radiation of a minimum divergence was effected by introducing into the cavity two apertures 1.4 mm in diameter. The wide-aperture laser had an active volume size 25 cm × 25 cm × 100 cm; its energy reached 200 J in the free-running mode [5]. The divergence of radiation in the system was measured in two ways: from the energy, employing calibrated apertures; and from the intensity, by using a wedged mirror attenuator.

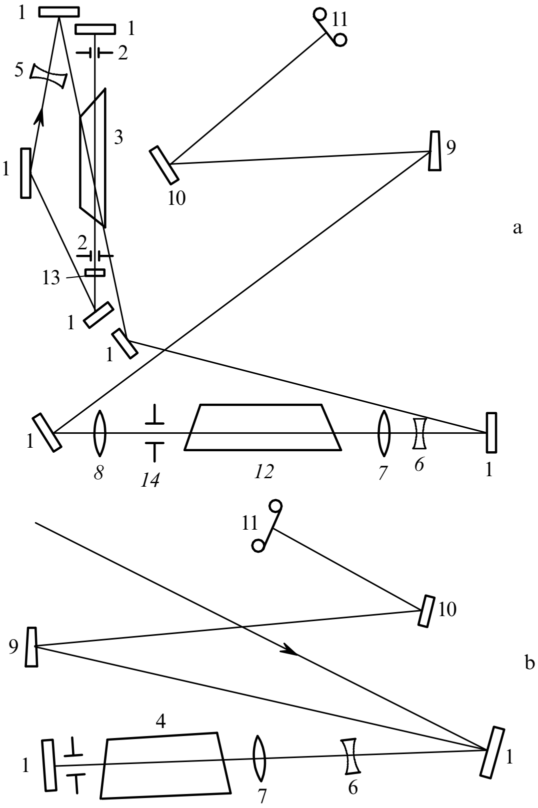

Figure 1. Optical layout of the experiment: (1) totally reflecting mirrors; (2) aperture 1.4 mm in diameter; (3) active medium of the electric-discharge laser; (4) active medium of the amplifier; (5 – 8) lenses with $F = -80$, -20, 150, and 1000 cm; (9) quartz wedge; (10) mirror wedge; (11) photographic film; (12) active medium of a wide-aperture amplifier; (13) semitransparent mirror (14) aperture ∅35, 75, 150 mm.

The radiation diffraction from the aperture was calculated from the Kirchhoff integral for a uniform intensity distribution of the incident wave. High-quality optical elements were used in the experiments. In particular, the surface error did not exceed $\lambda/2$ for the optical elements with diameters below 100 mm, and λ for those with diameters above 100 mm.

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As already mentioned, the output radiation of a MO in our optical scheme came back to the active medium of the first laser for additional amplification. Our measurements showed that the divergence of the amplified radiation was strongly affected by the distance L_0 to the amplifier traversed by the MO radiation. Fig. 2 shows the angular distributions of the energy at the MO output and after its amplification for L_0 equal to 1 and 3 m. As follows from Fig. 2, the radiation pattern for $L_0 = 1$ m is significantly broader than that for $L_0 = 3$ m. Measurements of the near-field MO-radiation pattern as well as calculations of the diffraction from the output aperture were indicative of a strong spatial nonuniformity of the radiation, both along and across its axis of propagation (Fig. 3). The discrepancy between the results of measurements and calculations for small distances was due to the complexity of including the entire angular spectrum of diffracted waves. Beginning with a distance of about 3 m, the changes in the distributions became insignificant and the main fraction of the energy was concentrated in the central kernel.

The amplification of radiation in the wide-aperture amplifier was accomplished for $L_0 = 3$ m for beams of three diameters: 35, 75, and 150 mm. A lens (5) was additionally introduced into the configuration of Fig. 1 to increase the energy of the signal being amplified. The results of measurements of the far-field intensity distribution for the initial (amplifier off) and amplified radiation are presented in Fig. 4. Figs 4a – 4c correspond to a single-pass amplification in the configuration shown in Fig. 1a. One can see that divergences of initial and amplified radiation for beam diameters of 35 and 75 mm are close to the diffraction limit; for a beam 150 mm in diameter, the radiation divergence far exceeds θ_d, whereas the focal spot splits into a multitude of separate spots. This is most probably caused by the air fluctuations in the optical path, because in this case the distance between the lens (5) and the focal waist is $\sim$ 25 m.

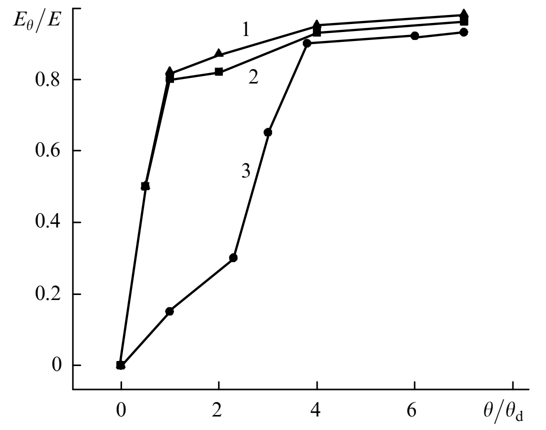

Figure 2. Angular energy distribution at the MO output (1) and after amplification (2, 3) measured in the focal plane of the $F = 10$ m lens for $L_0 = 3$ (2) and 1 m (3); (E) total beam energy, (E_θ) beam energy residing within angle $\theta_d = 2.44\lambda/D$.

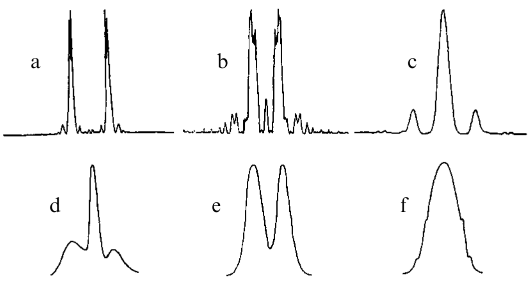

Figure 3. Calculated (a – c) and measured (d – f) MO-radiation intensity distributions for distances to the output aperture stop of 50 (a, d), 100 (b, e), and 300 cm (c, f).

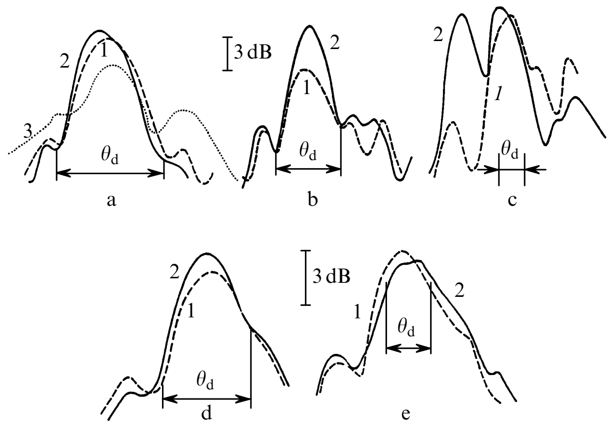

Figure 4. Densitograms of the focal spots of the initial (1) and amplified (2) radiation for an output beam diameter of 35 (a), 75 (b, d), and 150 mm (c, e) and also of the initial radiation through the amplifier several seconds after its actuation (3); $\theta_d = 2.44\lambda/D$.

To diminish the possible effect of air, the optical configuration was modified. In the new configuration (see Fig. 1b) the radiation under amplification passes through the amplifier twice to be subsequently compressed by the same telescope (6, 7). To record the divergence of the output radiation, the mirror on the right (1) was tilted with respect to the optical axis of the system. The densitograms of the radiation focal spots obtained with the modified configuration are given in Figs 4d and 4e. One can see that the focal spot retains its entire form, including in the case of a beam 150 mm in diameter. Our calculations show that its minor broadening relative to the diffraction limit arises from the spherical aberration of the telescope.

The densitograms presented above were recorded a long time after the amplifier actuation (no less than 30 min). When the delay time was shortened to several seconds, the divergence of the initial radiation increased drastically, even for a beam diameter of 35 mm (Fig. 4a). Nevertheless, no distortions were observed in the MO radiation when it passed through the working medium of the amplifier immediately after the pump pulse.

3. Discussion

It is worthwhile to highlight the two most important results of the collection of experimental data. First, for a small beam diameter and a nonuniform distribution of its intensity, there occurred a significant increase in the energy distribution of the amplified radiation. Second, for relatively large beam diameters, up to 150 mm, the active medium of the wide-aperture amplifier did not introduce noticeable distortions in the wave front of the radiation under amplification. Let us perform a qualitative analysis of the results obtained.

As already mentioned, our MO oscillator had two hard apertures. According to the experimental and calculated data, this resulted in a nonuniform and rapidly varying distribution of the MO output radiation intensity. The principle put forward by Young suggests that the radiation propagation after an aperture can be represented as an interference of the two waves: the incident wave, which obeys the laws of geometrical optics, and the diffracted wave reflected from the opening boundary. If we adhere to this principle, the presence of an active medium after the aperture implies that the interference pattern, in the domain where the intensity distribution is nonuniform due to diffraction, may differ from the pattern occurring in the case of an empty space.

It is well known that under conditions close to saturation the gain depends on the radiation intensity at different points. As a result, waves propagating in different directions will experience different amplification. As a consequence, the wave front of the summary field will be different from that existing in the absence of the active medium. Moreover, under these conditions the latter is possible also due to the difference in the phase velocities of the interacting waves. The reason is that, for a $XeCl^*$ molecule in the range of anomalous dispersion, there exists a phase shift between the domains of the active medium where gain coefficients are different [6]. Therefore, upon amplification of radiation with a nonuniform intensity distribution, the wave front may change considerably in the active medium even upon uniform pumping.

In a wide-aperture amplifier with a nearly uniform input signal intensity distribution, the wave front of the beam experiencing amplification can change only in response to the inhomogeneity of the active medium. The effect of anomalous dispersion was discussed above. According to calculations made by Adamovich et al. [6], the phase incursions for the strongest $0-2$ and $0-1$ transitions are $0.096g$ and $-0.058g$ per unit length (g is the gain). For broadband radiation and a small-signal gain $g_0 = 0.065\ \mathrm{cm}^{-1}$ [5], assuming a 100% nonuniformity of the energy deposition in the amplifier ($g_0 = 0$ at the periphery of the laser beam), the phase incursion due to the anomalous dispersion should not exceed $\lambda/6$.

Another type of distortion may be the radiation refraction by the electron density gradients in a plasma; Demyanov et al. [7] believe that this is the primary distortion. The change in the refractive index Δn in the presence of free electrons in the medium depends on the plasma frequency ω_p:

$$\Delta n = -\frac{1}{2}\frac{\omega_\mathrm{p}^2}{\omega^2}\,, \qquad \omega_\mathrm{p}^2 = \frac{4\pi n_\mathrm{e} e^2}{m_\mathrm{e}}\,, \tag{1}$$

where n_e is the electron density, and e and m_e are the electron charge and mass, respectively. Kinetic calculations [5] in our case yield an electron density of $4 \times 10^{14}\ \mathrm{cm}^{-3}$. Therefore the phase shift would be no greater than $\lambda/10$ for a maximum difference in n_e.

The existence of turbulent gas flows in the active medium is another factor which may be responsible for the increase in the divergence upon the passage of radiation through the medium. The consideration of this factor is hampered by the fact that the degree of turbulence depends on the geometry of the laser chamber, on the energy deposition and its uniformity, and also on the time elapsed after the energy deposition. Fulghum et al. [8] estimated the influence of these factors by comparing it with the effect of gas heating by the laser radiation itself. In this case, the change in the refractive index depends on the specific energy deposition:

$$\Delta n = (n_0 - 1)\,\frac{v^2\nabla^2 S t^3(\gamma - 1)}{6\gamma p_0}\,. \tag{2}$$

Here n_0 is the refractive index of the unperturbed medium, v is the sound velocity, S is the specific pump power, γ is the ratio of specific heat capacities, p_0 is the medium pressure, and t is time. For our pump energies and a maximum pump nonuniformity, Δn for a time $t \sim 1$ μs, according to formula (2), does not exceed 10^{-7}, which corresponds to a phase incursion $\sim\lambda/4$. The results of measurements of the divergence of the initial radiation, which passes through the amplifier immediately after its actuation, are consistent with these estimates. Formula (2) takes into account the effect of the temperature gradient arising exclusively from the pump nonuniformity. By and large, the turbulence-induced change in the refractive index is a function of the fluctuations of temperature and particle density, which quite often depend on the time elapsed after the preceding energy deposition. The inclusion of this factor involves serious difficulties.

Therefore, the estimates performed above and the results of divergence measurements show that the wave front of the radiation passing through a wide-aperture amplifier is scarcely affected by the nonuniformity of the amplifier pumping. In the absence of turbulent flows in the active medium it permits amplifying radiation with a divergence ~ 10 μrad without appreciable distortions.

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