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Optimisation of the optical scheme of a compact double-pass Nd : YAG amplifier for range finding

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Abstract. **It is shown that the use of misalignment and a divergent incident beam in a double-pass Nd : YAG amplifier of a master oscillator – amplifier system used in ranger finding makes it possible both to increase the output pulse energy and to improve the output beam quality. The misalignment suppresses the amplifier self-excitation caused by a finite contrast of the output polariser. The use of a divergent incident beam allows one to increase the efficiency of energy extraction from the amplifier and to decrease the vignetting effect. The experimental results agree with the results of numerical simulation.**

Keywords: *laser amplifiers, solid-state lasers, laser beam characteristics.*

1. Introduction

Compact, high-power and reliable diode-pumped *Q*-switched solid-state lasers are still in high demand [1]. These lasers are used, for example, in range finding [2 – 4], in lidars for the Earth's surface topography [5, 6] and remote probing of the atmosphere [7, 8], and in wind lidars [9, 10], which requires a rather high laser beam quality. In particular, to increase the probing distance and the measurement accuracy in range finding, the spatial profile of the output laser beam intensity must be close to the distribution corresponding to the TEM_{00} mode. The use of air- and space-borne laser systems imposes additional stringent constraints on their mass-dimensional characteristics, protection from external factors, reliability and efficiency.

At present, to fulfil the aforementioned requirements to diode-pumped solid-state lasers, one uses two schemes, i.e., a single laser [3, 4] and a master oscillator – power amplifier system (MOPA) [5 – 11]. In the first case, the lasers have a high efficiency, but their beam quality is much lower than that of MOPA systems. In addition, it is unreasonable to use acousto-optical and electro-optical *Q*-switches in on-board systems due to electromagnetic compatibility requirements. It is also important that scaling of a MOPA system is conceptually simpler because it consists of two blocks. However, it should be noted that the systems with a master oscillator (MO) and a high-power laser amplifier can encounter problems with the near-field uniformity as will be described below in this work. At the same time, there are several application fields in which a uniform near field is desirable. These are, e.g., high-order harmonic generation, plasma diagnostics and others, so the suppression of spatial intensity modulation in beams (spatial noise) could considerably extend the application range of MOPA systems.

A special MOPA system was developed in [12] for an altimeter-roll stabiliser used in the Fobos – Grunt spacecraft. The main problem in the development of a compact amplifier for the MOPA was to create a small-volume active medium of the amplifier and a compact diode pump system. This was achieved by using two parallel Nd : YAG rods 4 mm in diameter and 30 mm long instead of one long active element. The reflector of the pump system was $25 \times 14 \times 12$ mm in size. The emitting region of each of the two laser diode matrices used for pumping was 10×9 mm, and the pump radiation was coupled into the prism reflector through input windows with dimensions of 14×12 mm. This pump system is described in detail in [13].

While the use of a MOPA system allowed one to solve the main problem (compactness of the device), it led to the appearance of some supplementary problems. One of these problems is the self-excitation of the amplifier (parasitic lasing) caused by reflections of radiation from the side planes of the pump system reflector and by a high gain of the active medium, which, as well as the methods of its suppression, was considered in [13]. Apart from the parasitic lasing in the transverse direction, a finite contrast of the output polariser led to self-excitation of the amplifier. On the whole, this restricted the energy of output amplifier pulses. In addition, the beam of the amplifier in this compact configuration was spatially modulated in the near-field zone.

The aforementioned problems were overcome, in particular, by misaligning the double-pass amplifier cavity and increasing the geometrical divergence of the MO beam passed through a telescopic optical system [12]. The developed amplifier was $70 \times 30 \times 30$ mm in size and allowed the authors to achieve an energy of 65 mJ in the *Q*-switched regime and 160 mJ in the free-running regime.

In the present work, we describe in detail the effects of spatial beam intensity modulation and parasitic lasing in the used double-pass amplifier scheme with polarisation decoupling, as well as the methods of their suppression. We perform detailed numerical simulation of the optical scheme of the

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double-pass amplifier, the results of which agree well with experimental results. The presented results and approaches (numerical and experimental) may be helpful for solving similar problems in other laser systems.

2. Experimental setup

The experimental setup (see [12]) was a laser system designed according to the MOPA scheme. We used a Nd:YAG rod 1.6 mm in diameter and 30 mm long as an active element of the MO and a plane-parallel cavity 170 mm long. Both cavity mirrors were mounted on a common base, and the optical axis was bent using a block consisting of Malafeev–Porro and Dove prisms. This scheme allowed us to avoid the influence of mechanical deformations of the laser construction on the output beam quality. The MO was side-pumped by laser diode arrays with a power of 600 W and a wavelength of 808 nm. The pump pulse duration was 120 μs. Q-switching was performed by a Cr:YAG passive Q-switch. The laser generated trains of four 10-ns pulses with an energy of 3 mJ spaced by 4 ms. The repetition rate of trains was 1 Hz. The spatial MO beam intensity distribution corresponded to the TEM_{00} mode.

The role of the amplifier was to amplify the MO pulses to an energy of ~60 mJ without considerable deterioration of the beam quality. The double-pass amplifier scheme used in the present work is shown in Fig. 1. The active elements were two Nd:YAG rods 4 mm in diameter and 30 mm long with faces bevelled at an angle of 3°. The effective gain length was 60 mm. The MO pulses doubly passed through the amplifier due to polarisation decoupling based on a quartz polarisation rotator and a mirror–polariser (MP) unit. The distance between the prism and the MP unit edges was 85 mm, and the distance between the centres of the AEs was 4.8 mm. A π-polarised MO beam was coupled into the amplifier through the polariser of the MP unit and passed through the active elements and the polarisation rotator, which rotated the polarisation vector by 90°. Then, the radiation, which was now σ-polarised, was reflected from the polariser and once again passed through the AEs and the polarisation rotator and left the amplifier in the π-polarised state.

The finite contrast of the polariser in the case of polarisation decoupling leads to unwanted positive feedback in the amplifier. At present, the reflection coefficients of available polarisers are about 0.2% for π-polarised light, which restricts

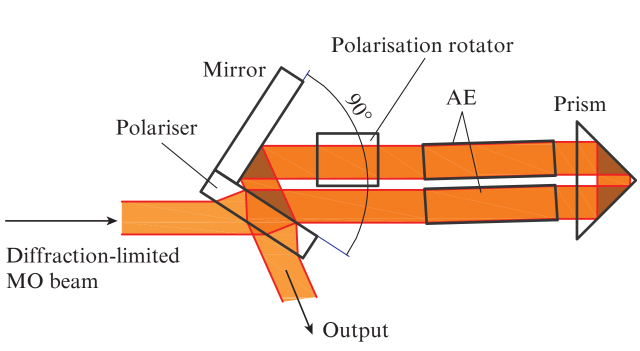

Figure 1. Aligned amplifier with polarisation decoupling (mirror and polariser form an MP unit).

the small-signal gain in the double-pass scheme by ~500, the gain in each of the AEs being below 5. It is this factor that limits the output pulse energy.

Another problem considered in [12] was related to the fact that the small size of the reflector inevitably leads to inaccuracy in positioning of the AEs, because of which their axes become nonparallel. This caused vignetting of the MO beam and the appearance of spatial noise at the amplifier output as a result of multiple-beam diffraction at the AE faces. Since the MO beam divergence was close to the diffraction limit, its wavefront curvature was comparable with the wavefront curvatures of beams diffracted on the AE faces. This caused the appearance of broad interference fringes in the near field of the amplifier. Despite the unchanged beam quality in the far-field zone, this effect may prevent the formation of field distributions close to the TEM_{00} profile.

Let us consider the mechanisms causing parasitic lasing in the amplifier scheme described above, which, in the ideal case, is a well aligned cavity formed by a rectangular prism and an MP unit with a reflectance of σ-polarized radiation from the polarizer of 0.2% The unsaturated gain of the active medium is $\sim g_0^4$ (g_0 is the gain for one AE). One can easily see that lasing in this cavity appears when g_0 reaches 4.8. The gain measured for one AE is $g_0 \approx 5$, which suggests the possibility of parasitic lasing in this amplifier scheme. Since one cannot use a Faraday isolator to suppress parasitic lasing in the considered on-board laser system due to electromagnetic compatibility requirements, it is necessary to use other approaches for this purpose.

The first way is to fabricate an output polariser with a residual reflectance of σ-polarised radiation not exceeding 0.15%. The second way is to misalign the apex angle of the MP unit [14]. The problem of the first method is that it is difficult to maintain a minimum residual reflectance at a given (working) angle, because a change in the environment humidity may cause a considerable change in the working angle of the polariser. This problem is aggravated by the fact that this laser is constructed and aligned in the air atmosphere but used in air-free space, which makes it difficult to predict the behaviour of the polariser working angle. Another drawback of this method is the fundamental limit of the AE gain on the level of the fourth root of the reciprocal residual reflectance of the polariser. Because of this, despite considerable efforts to maintain the residual reflectance at a level of 0.1% (instead of 0.2%), the achieved increase in the admissible AE gain is relatively modest, only to 5.6 from 4.8.

A more promising way to suppress parasitic lasing is to misalign the MP unit, but this method leads to inevitable vignetting of the laser beam. This problem can be solved by using the MO beam with a small diameter in the first pass through the amplifier and then artificially increasing the beam divergence. To increase the extraction of energy stored in the amplifier and prevent vignetting in the second pass, the MO beam in the first pass must propagate noncollinearly to the optical axis of the amplifier, i.e., at an angle twice as large as the MP unit misalignment angle (Fig. 2).

To achieve this direction of the beam propagation through the amplifier, we used a 1.8-fold telescope to form the input beam with a diameter of 2.7 mm and a divergence of 2.8 mrad, which exceeds the diffraction limit by a factor of eight. In this case, the distance between the telescope lenses was decreased with respect to their confocal position. The beam axis in the first pass through the active elements was nonparallel to their axes. After reflection from the misaligned MP unit, the beam axis becomes parallel to the AE axes. The beam broadens as it propagates in the amplifier and finally fills the entire aperture of the AEs. This approach allowed us to completely suppress parasitic lasing in the double-pass amplifier scheme with the MP unit misaligned by 0.25°.

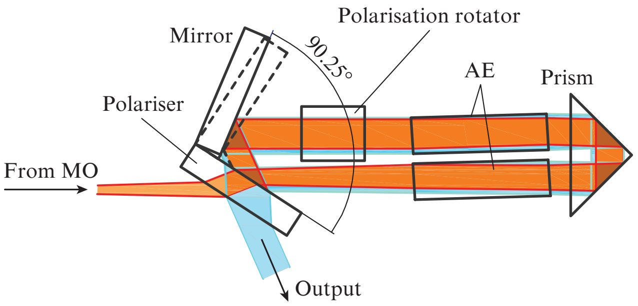

Figure 2. Misaligned amplifier (beams in the first and second passes are shown by dark and light grey, respectively).

After exit from the amplifier, the beam is collimated and its quality becomes close to the diffraction limit. However, the increased divergence leads to a decrease in the beam quality in the near-field zone due to multiple diffractions on the apertures of the AEs.

3. Numerical simulation

The numerical optimisation of the output pulse energy and the beam quality (spatial intensity distribution) of the amplifier was performed by changing the width and divergence of the MO beam using a telescope in the aligned and misaligned amplifier schemes. To this end, we developed two models, namely, a model of beam amplification upon propagation through the amplifier and a model of beam diffraction on successive apertures, i.e., on the faces of the AEs.

As the initial (input) beam in both models, we used a Gaussian beam with a diffraction-limited divergence of 1.3 mrad, which propagated through a magnifying telescope designed according to the Galilean scheme. The distance between the telescope lenses was decreased with respect to the distance corresponding to infinite focal length. This made it possible to achieve the desired divergence of the input beam.

The radiation pulse amplification was simulated by iterative use of the Frantz–Nodvik formula [15] for propagation of a divergent beam through an amplifier. The initial pulse energy was 1 mJ. The pump system efficiency was taken to be 0.4, and it was assumed that the amplifier is pumped by 300-μs pulses with a wavelength of 808 nm and a total power of 1800 W.

Figure 3 presents the simulation results of pulse amplification upon propagation through the aligned (Fig. 3a) and misaligned (Fig. 3b) amplifiers in the case when the MO beam propagates noncollinearly to the AE axes in the first pass through the amplifier (to compensate misalignment) and collinearly in the second pass. The calculation results show that the optimal variant for obtaining the maximum gain in the scheme with self-excitation suppression is transformation of the MO beam by a telescopic optical system that has a magnification of 1.8 and is misaligned so that the MO beam after this system had a divergence of 2.8 mrad.

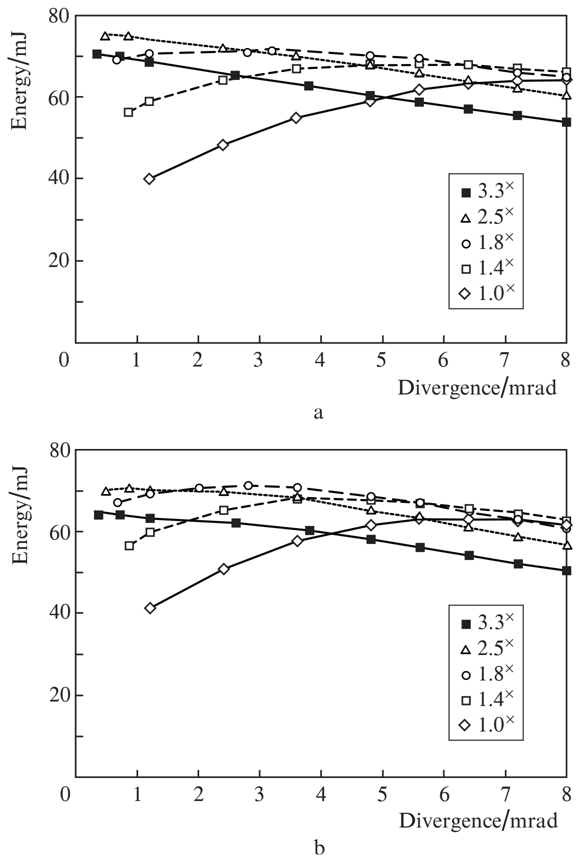

Figure 3. Simulated output pulse energies for (a) aligned and (b) misaligned laser amplifiers with telescopes with different magnifications and different input beam divergences.

The beam diffraction on successive apertures (faces of the AEs) was modelled using the band-limited angular spectrum and shifted angular spectrum methods [16]. This method is based on the fast Fourier transform and was iteratively applied using the output fields as sources for subsequent iterations. The field attenuation due to reflection on interfaces between media was ignored. Refraction was naturally taken into account by changing wavelength λ according to the refractive index. To take into account the non-orthogonality between the aperture planes and the radiation field propagation direction, we used the approximate shift operator according to [17]. In the case of the misaligned amplifier scheme, this operator was additionally used before the beginning of the second pass of the beam through the amplifier to take into account the amplifier misalignment.

To estimate the spatial noise acquired by the beam in the near-field zone (compared to an ideal Gaussian beam), we used the following measure of diffraction distortion based on the root-mean-square deviation:

$$\sigma_{\mathrm{I}} = \frac{1}{N}\sqrt{\sum_{j=1}^{N}\sum_{i=1}^{N}(I_{i,j}^{\mathrm{D}} - I_{i,j}^{\mathrm{G}})^2},$$

where $I_{i,j}^{\mathrm{D}}$ is the intensity at the point (i,j) found using simulation by the method described above, $I_{i,j}^{\mathrm{G}}$ is the intensity of the ideal Gaussian beam at the same point, and N is the number of discretisation points.

The diffraction distortion σ_{I} calculated as a function of the beam divergence using telescopes with different magnifications are presented in Fig. 4. As is seen, the use of a 1.8-fold telescope chosen above as optimal with respect to amplification efficiency also leads to a slight diffraction distortion of the beam as it propagates through the compact solid-state amplifier. The initial MO beam undergoes the lowest distortions but is nonoptimal from the viewpoint of extraction of energy stored in the amplifier.

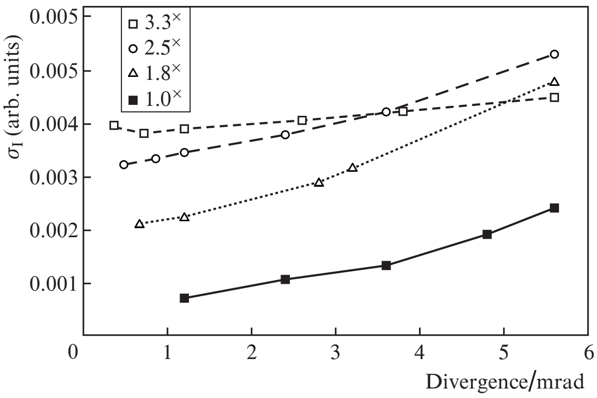

Figure 4. Beam quality parameter σ_I at the exit of a misaligned amplifier with the use of telescopes with different magnifications versus the divergence caused by the telescope misalignment (in the case of 1.8-fold magnification, the input beam propagates at an angle to the AE axes).

Figure 5 shows the radiation intensity distributions simulated using the above-described methods for a beam passed through an aligned 3.3-fold telescope and an aligned amplifier, as well as for a beam with a divergence of 2.8 mrad passed through a misaligned 1.8-fold telescope and a misaligned amplifier. The simulation results qualitatively agree with experimental results (see below), which allows us to conclude that this model is at least adequate and can be used to estimate the near-field diffraction distortion of laser systems.

4. Comparison of numerical simulation and experimental results

The beam characteristics determined in experiments with aligned and misaligned double-pass amplifiers [12] were compared with the results of numerical simulation performed in the present work. In the first case (aligned amplifier), the MO beam passed through a telescope with a magnification of 3.3, while the telescope used in the second case (misaligned amplifier) had a magnification of 1.8 and was adjusted so that the beam divergence at the entrance to the amplifier was 2.8 mrad.

The dependences of the output energies of the amplifiers on the pump energy are shown in Fig. 6. One can clearly see that the aligned amplifier characteristics become worse at a pump pulse energy of 0.65 J due to parasitic lasing reducing the growth of the output energy, while parasitic lasing in the misaligned amplifier is suppressed. As a result, the divergent beam doubly passes through the amplifier without vignetting, and the output pulse energy can reach 65 mJ.

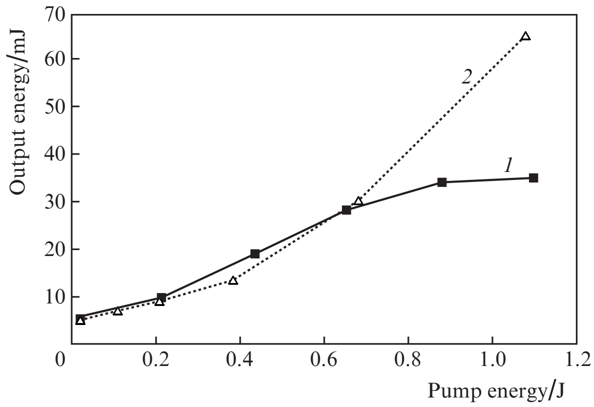

Figure 6. Experimental dependences of the output pulse energy on the pump pulse energy for (*1*) aligned and (*2*) misaligned amplifiers.

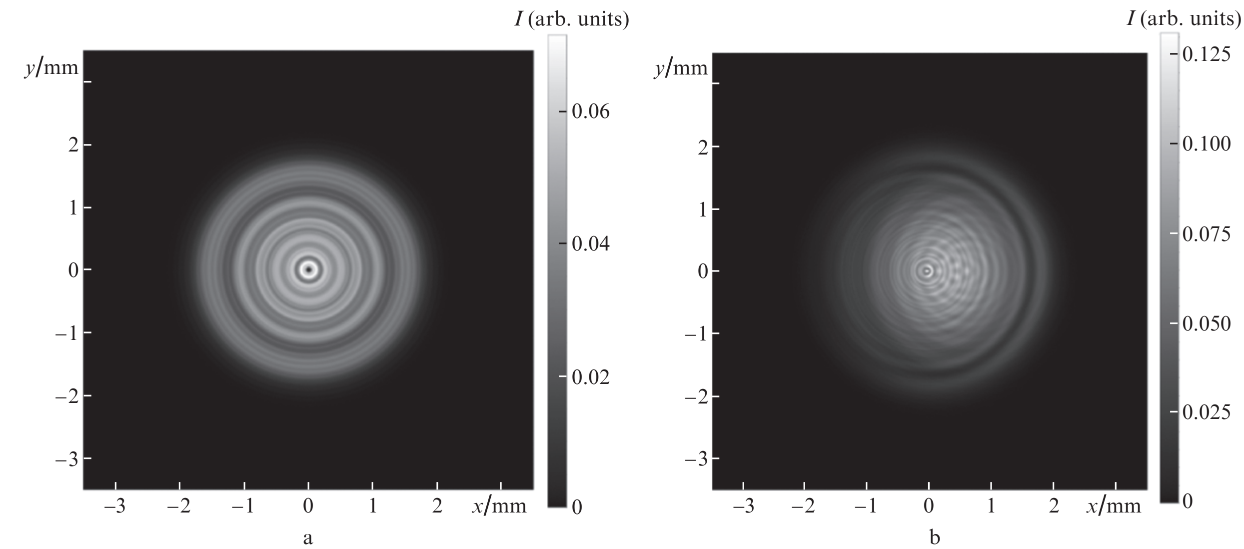

Figure 5. Intensity distributions for simulated (a) beam passed through an aligned 3.3-fold telescope and an aligned amplifier and (b) beam with a divergence of 2.8 mrad passed through a misaligned 1.8-fold telescope and a misaligned amplifier.

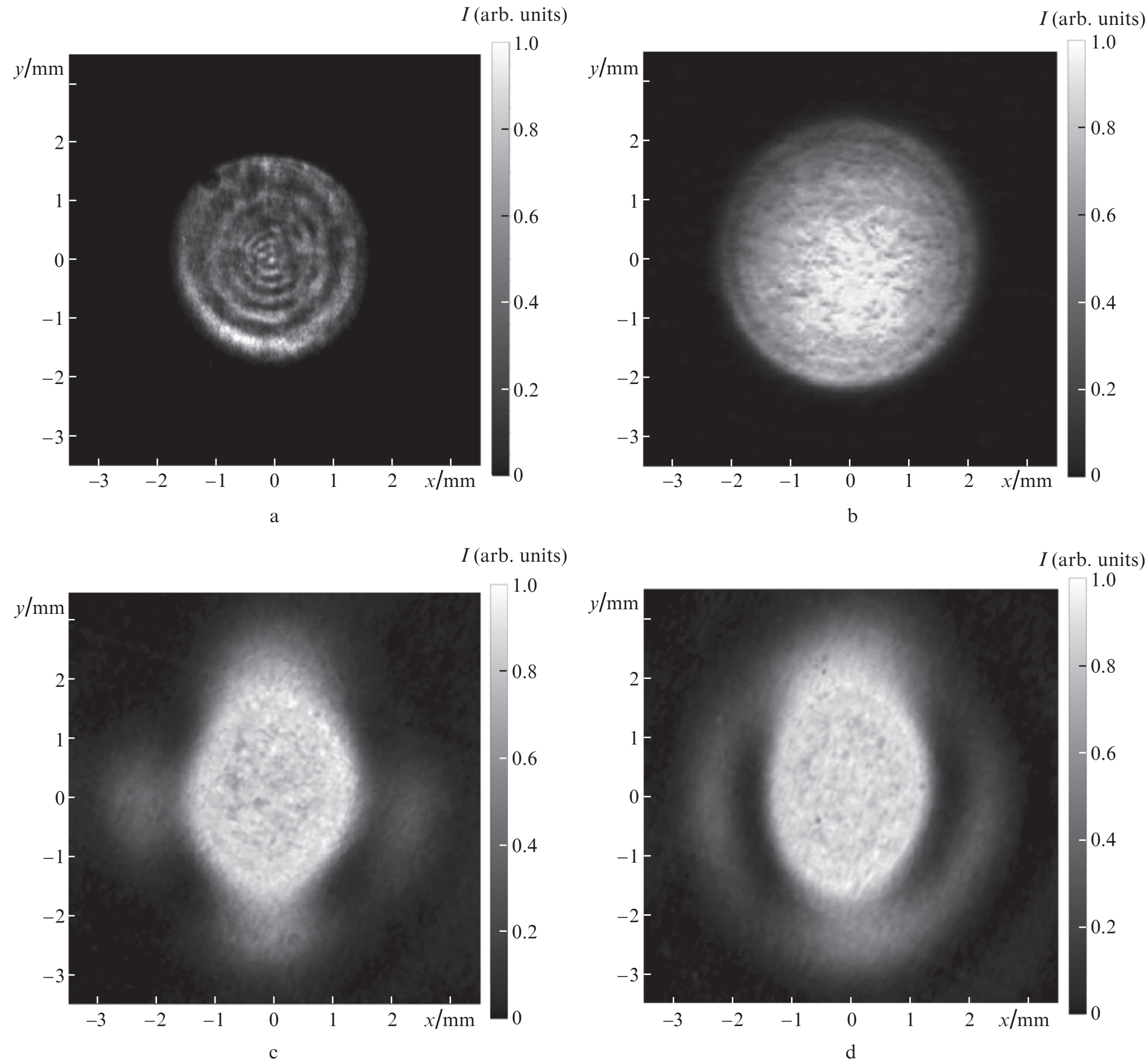

Figure 7. Experimental beam intensity distributions in the (a, b) near-field and (c, d) far-field zones for (a, c) diffraction-limited and (b, d) diverging beams.

The radiation intensity distributions obtained in experiment at the exit from the amplifier are shown in Fig. 7. It is seen that the intensity in the diffraction-limited beam is modulated according to the results of numerical calculations (see Fig. 5a). In turn, Fig. 7b demonstrates a uniform intensity distribution in the near field, which corresponds to a diverging beam (see Fig. 5b). The intensity distributions in the far field for both beams are close to the TEM_{00} profile (Fig. 7c, 7d).

5. Conclusions

It is shown that the characteristics of commercially available polarisers do not provide required polarisation decoupling and suppression of self-excitation in double-pass amplifiers designed for application in laser systems with strict requirements for operating conditions and that misalignment of the laser amplifier leads to suppression of parasitic lasing. However, this causes vignetting of laser beams and, hence, decreases the MO beam amplification efficiency and deteriorates the beam uniformity in the near field. These problems are most pronounced in the case of compact amplifiers. The use of a telescopic system increasing the MO beam diameter and divergence, as well as the use of an amplified beam propagating noncollinearly to the AE axes in the first pass, allowed us to increase the efficiency of energy extraction from the amplifier and to decrease the vignetting effect. The parameters of the optical scheme of a compact solid-state laser amplifier are optimised. The influence of the telescopic system amplification and the input MO beam divergence on the gain and the near-field beam quality is analysed. This analysis makes it possible to choose the optical parameters of the beam-forming optical system, which is confirmed by experimental results.

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References

1. Grechin S.G., Nikolaev P.P. *Quantum Electron*., **39**, 1 (2009) [*Kvantovaya Elektron*., **39**, 1 (2009)].
2. Sun X. et al. *IEEE J. Sel. Top. Appl*., **6**, 1939 (2013).
3. Santovito M.R. et al. *Mem. S.A.It. Suppl*., **16**, 35 (2011).
4. Coyle D.B. et al. *Opt. Laser Technol*., **63**, 13 (2014).
5. Yu A.W. et al. *Proc. SPIE*, **8599**, 85990P (2013).
6. Sawruk N.W. et al. *Proc. SPIE*, **8599**, 85990O (2013).
7. Alvarez II R.J. et al. *J. Atmos. Ocean Tech*., **28**, 1258 (2011).
8. Stephan C. et al. *Proc. SPIE*, **8159**, 815908 (2011).
9. Schroder T. et al. *Appl. Phys. B*, **87**, 437 (2007).
10. Chuang T. et al. *Proc. SPIE*, **8599**, 85990N (2013).
11. Peuser P. et al. *Opt. Lett*., **31**, 1991 (2006).
12. Polyakov V., Pokrovskiĭ V., Soms L. *J. Opt. Technol*., **78**, 640 (2011).
13. Vitkin V. et al. *J. Opt. Technol*., **79**, 632 (2012).
14. Storm M.E. *J. Opt. Soc. B*, **9**, 1299 (1992).
15. Frantz L.M., Nodvik J.S. *J. Appl. Phys*., **34**, 2346 (1963).
16. Matsushima K. *Opt. Express*, **18**, 18453 (2010).
17. Matsushima K. *Appl. Opt*., **47**, D110 (2008).