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Active elements in the form of thin rods of square cross section for multichannel laser amplifiers

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Abstract. **We study thermally induced phase distortions of laser radiation in active elements in the form of thin rods of square cross section. The absence of aberrations and beam quality deterioration is demonstrated for these elements, due to which they can be used along with rods having a round cross section, differing from the latter by much higher technological efficiency of fabrication and mounting in the cooling system. A concept of compact and reliable multichannel solid-state amplifier based on such active elements is proposed, which allows one to use a multichannel fibre laser as a master system.**

Keywords: *multichannel laser amplifier, coherent channel combining, high average and peak power lasers, diode-pumped Yb : YAG lasers, thermal effects in solid-state lasers.*

1. Introduction

One of the last tendencies in the development of physics of high energy densities and extreme light fields is the application of lasers characterised by not only high peak power but also high average power. Based on these lasers one can design X-ray and THz radiation sources with a high average brightness, which opens new possibilities for spectroscopy and visualisation [1]. They can be applied in dielectric [2] and plasma [3] laser accelerators to increase the average electron beam brightness and used as drivers for photocathodes [4] or Compton scattering sources [5]. Lasers with different peak powers are needed for different applications, but the problem of increasing average power is always urgent.

The achievement of high average radiation power is a separate problem for each range of peak powers or pulse energies; its solution requires application of special principles and approaches when designing a laser system. In the low-energy range (below 1 mJ) the most reliable and efficient way is to use fibre lasers, which can work at very high average powers with preservation of ideal beam quality but have limitations on the peak power (because of the nonlinear effects occurring in fibre). To achieve the millijoule energy level, fibres with a large mode diameter are applied jointly with chirped- and separated-pulse amplification circuits. Multichannel fibre systems with coherently combined channels are used to pass to the 10-mJ energy range [6]. There are projects aimed at reaching multijoule level via combining 10000 channels [7]; however, the usability and reliability of this approach seem doubtful.

An alternative way to increase the pulse energy is to use the so-called hybrid laser scheme with a fibre master unit and a solid-state final amplifier. The most appropriate amplifier is the one based on a thin rod or a 'single-crystal fibre' cut from a Yb : YAG crystal [8]. It has a large gain, due to which simple single- and double-pass optical schemes can be implemented, and can operate at sufficiently high average powers [9] and much higher peak powers and pulse energies than fibres can withstand [10]. Due to its simplicity and compactness, this approach has become very popular in laser schemes used in industry. The application of this approach in a multichannel laser system with coherent combining would provide much higher pulse energies as compared with a fibre laser having the same number of channels. Here, the key problem is to design a compact and reliable solid-state multichannel amplifier.

Within this study we developed a concept of solid-state multichannel amplifier based on thin Yb : YAG rods of square cross section, which are expected to be more technological than rods with a round cross section. A version of arranging these rods and mounting them in the cooling system is proposed. The specific features of thermal effects occurring in these rods are studied.

2. Thermal effects in a thin rod of square cross section

The key problem to solve when using an active element (AE) of square cross section is the axial asymmetry of cooling system, which may lead to the occurrence of thermal lens aberrations, including astigmatism or higher order aberrations. To perform an experimental study, we developed a laser head based on a thin rod of square cross section. The AE was cut from an Yb : YAG crystal (doped to a level of 1.5 at %) in the form of a rectangular parallelepiped $1 \times 1 \times 20$ mm^3 in size. Four plates of high thermal conductivity material (single-crystal silicon carbide) were glued on its lateral sides using epoxy resin. The outer surface of the design was directly cooled by continuous-flow water. Pumping was performed by a 940-nm diode source with power up to 120 W, having a fibre output with a fibre core diameter of 105 μm and a numerical aperture of 0.22. The image of output fibre end face was transferred to the AE using a telescope with a magnification of 3.75.

A theoretical analysis of phase distortions was performed within the model described in [11], which is based on the joint solution of the system of balance equations and the heat conduction equation. The problem was solved in the three-

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dimensional space. The pump radiation distribution in the AE was calculated by the three-dimensional ray tracing method. The found temperature distribution was used to calculate the phase distortion profile. Only the component related to the temperature dependence of the refractive index was taken into account, because thermal expansion can be neglected in the thin-rod approximation. The problem parameters used in the calculation are given below. The temperature dependences of the absorption cross section and thermal conductivity were taken into account. Phase distortions were separated into a parabolic component (thermal lens), for which the optical power was found, and a nonparabolic component (aberration), for which the beam quality factor M^2 was found by solving the integral equation, as in [12].

Absorption cross section/cm^2 [13]	$2.07 + 6.37\exp[-(T+273)/288] \times 10^{-21}$
Lifetime/ms [14]	0.95
Quantum defect (%) [15]	6.8 %
Thermal conductivity/W^{-1} m^{-1} K^{-2}, approximation from [16]	$13.27 - 0.016T$
$\frac{dn}{dT}$/K^{-1} [17]	12.1×10^{-6}
Heat transfer coefficient on the lateral rod surface/W cm^{-2} K^{-1} [11]	12

Figure 1a shows a theoretical phase distortion profile in the laser head under consideration. Figure 1b presents transverse profiles of phase distortions along the x (or y) axis and along the diagonal axis, for which the difference is maximum. It can be seen that the dependences coincide very well at the AE centre. Having approximated the presented dependences by a parabola, we determined the thermal lens optical power D to be 30.9 and 29.6 m^{-1} along the x and diagonal axes, respectively. Thus, the difference in the thermal lens optical powers along different axes is only 4.4%, a small value that does not affect much the laser system operation. The beam quality factor M^2 was also calculated along the x and diagonal axes of the AE. The calculated dependence of the beam radius on longitudinal coordinate along the beam caustic is shown in Fig. 2. It can be seen that the positions of waists for the two axes coincide with good accuracy, which confirms the equality of thermal lens optical powers. The values of parameter M^2 along the two aforementioned axes are also very close: $M_x^2 = 1.083$ and $M_{45}^2 = 1.088$.

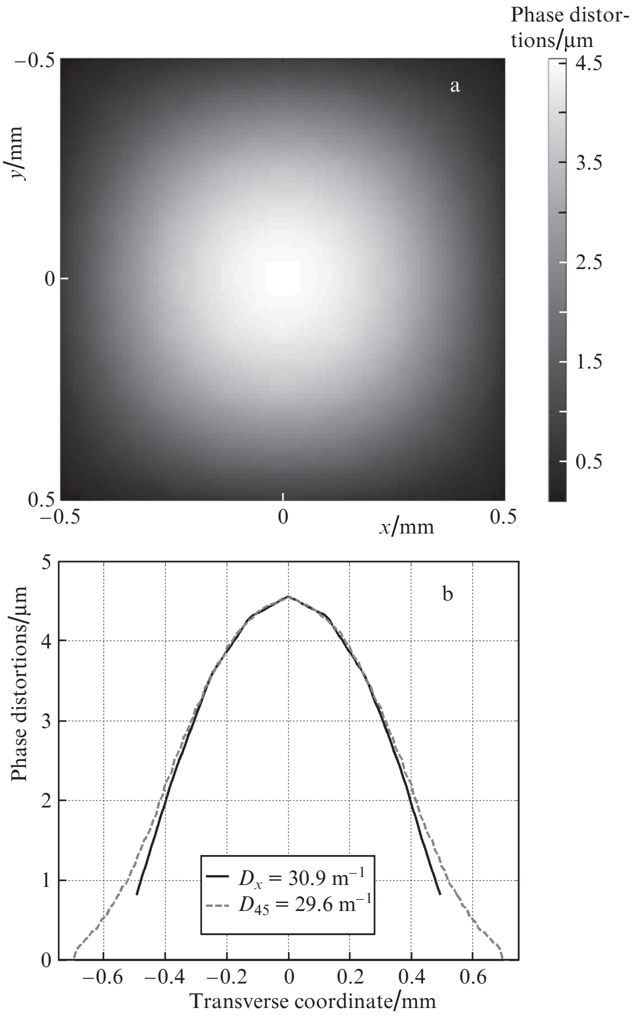

Figure 1. (a) Calculated profile of thermally induced phase distortions and (b) dependences of phase distortions on transverse coordinate along the x and diagonal axes of the AE.

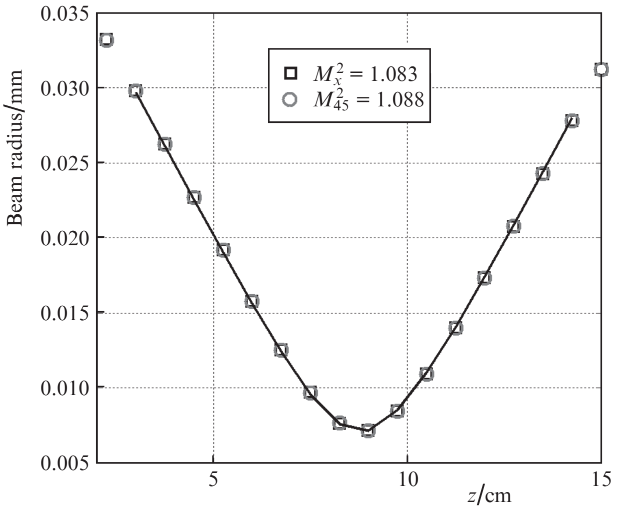

Figure 2. Calculated dependence of the beam radius on the longitudinal coordinate z along the beam caustic.

The amplification in the developed laser head was experimentally studied using weak and strong signals. The weak-signal source was a diode laser having a single-mode fibre output with power of 10 mW, wavelength of 1030 nm, and spectral width of 1.5 nm. The strong-signal source was a laser system consisting of a fibre oscillator and a solid-state amplifier based on a thin Yb:YAG rod with average radiation power up to 30 W, pulse repetition rate of 3 MHz, and pulse duration of about 50 ps. A simple single-pass amplifier scheme was applied. The dependence of the small-signal gain on the pump power is shown in Fig. 3a. Figure 3b presents the dependences of gain and amplifier efficiency on the input signal power. The small-signal gain reaches 30, and the amplifier efficiency at strong signal (20 W) reaches 30%, a value comparable with the results for amplifiers based on thin rods with a round cross section.

The slowdown of rise in the small-signal gain at high pump powers is related to the shift of pump spectrum to the region above 940 nm, which leads to a decrease in the absorption coefficient. The decrease in the amplifier efficiency at a maximum signal power is likely due to the radiation loss in the optical scheme of amplifier. The values of gain and output

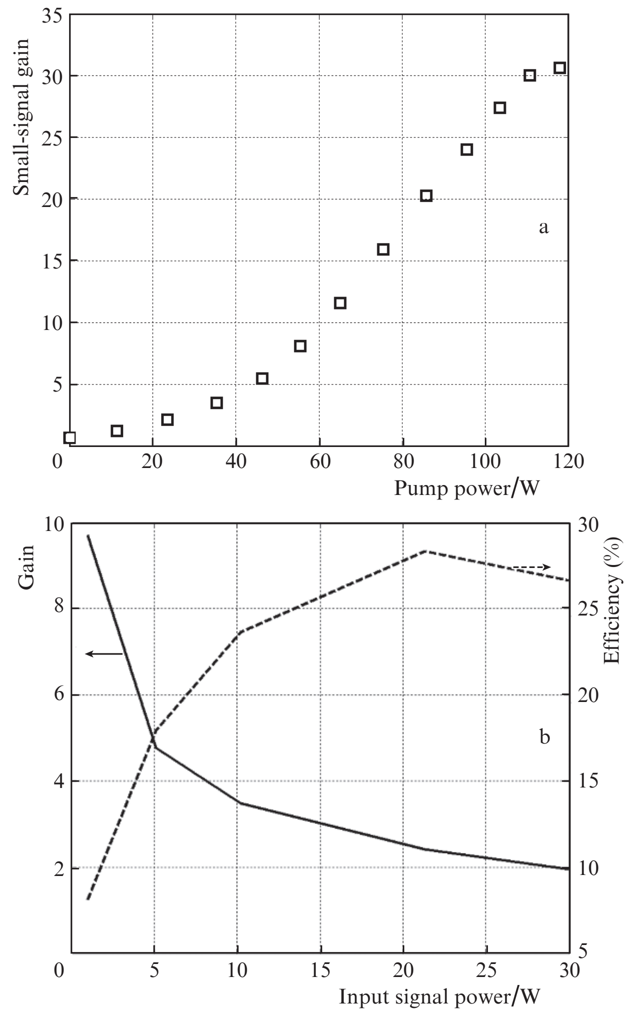

Figure 3. Experimental dependences of (a) the small-signal gain on the pump power and (b) the amplifier gain and efficiency on the input signal power.

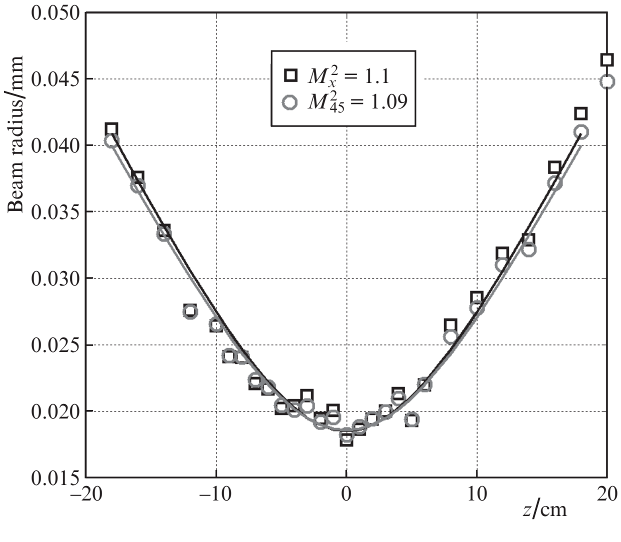

Figure 4. Experimental dependence of the beam radius on the longitudinal coordinate z along the beam caustic.

power obtained in the experiment are not ultimate; they are limited by only the available pump power. The dependences in Fig. 3b can be used to design a multichannel amplifier for input signals of different powers.

The parameter M^2 was experimentally studied by measuring the beam profiles along the waist. As well as in the theoretical analysis, the beam radii were calculated along the x and diagonal axes of the AE. Measurements were performed with amplification of both weak and strong signals, which made it possible to estimate the influence of the gain on the beam quality. Figure 4 shows an experimental dependence of the beam radius along the beam caustic for the case of a weak signal. The values of the M^2 parameter along both axes are almost identical and close to unity. The waist positions along both axes also coincide. The experimentally found M^2 values are in good agreement with the calculated data. A similar result was obtained for the strong-signal regime. Thus, neither calculation nor experiment revealed any deterioration of the beam quality due to the use of AEs of square cross section.

3. Concept of a multichannel amplifier

Due to their technological efficiency, AEs in the form of thin rods of square cross section can successfully be used to design a multichannel solid-state amplifier. We proposed a concept of this amplifier, whose key element is a multichannel ('matrix') laser head. This laser head is a set of parallel, equidistantly located AEs, the space between which is filled with the cooling system. The equidistance of AEs allows one to use a multichannel fibre laser as a master system, with extraction of radiation through a lens array for subsequent coherent combining in the far-field zone [18]. The lens array should have a square structure and focus beams into AEs. The cooling system consists of layers of high thermal conductivity material, containing channels for coolant flow. Such a design can be easily and technologically efficiently implemented using thin-rod AEs of square cross section, whose lateral surfaces are glued to layers of high thermal conductivity material. The design of a 'matrix' laser head is shown in Fig. 5.

In this design the equidistance of AEs with an error less than 10 μm can easily be obtained using layers of high thermal conductivity material of strictly identical thickness. The

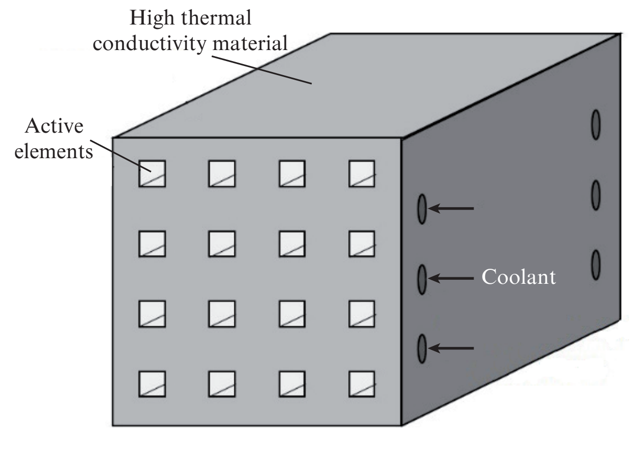

Figure 5. General view of the multichannel ('matrix') laser head.

pump system is an array of diode sources with a fibre output; the beam from each source is supplied to the corresponding AE. It is preferred to use high-brightness sources, providing high radiation intensity throughout the entire AE length. The beams at the amplifier output are collimated by another lens array and then are focused by a general lens to be coherently combined in the far-field zone.

4. Conclusions

In this work we have performed theoretical and experimental investigation of thermally induced phase distortions of laser radiation in an AE in the form of a thin rod of square cross section. It is shown that the axial asymmetry of the cooling system introduces a weak aberration and does not affect much the beam quality factor. Thus, AEs in the form of thin rods of square cross section can be applied along with rods of round cross section; however, the former are much more technologically efficient in the context of their fabrication and mounting in the cooling system. A concept of a multichannel solid-state amplifier based on AEs in the form of thin rods of square cross section is proposed. The main unit of the amplifier is a multichannel (matrix) laser head, in which AEs are located equidistantly and parallel to each other, and the space between them is filled with a cooling system, consisting of layers of high thermal conductivity material with channels for coolant flow. A multichannel fibre system with radiation extraction through a lens array can be used as a signal source for this amplifier.

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