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Technology of thin-rod Yb:YAG amplifiers with a high pulse energy and average power

I.I. Kuznetsov, S.A. Chizhov, I.B. Mukhin, O.V. Palashov

Abstract. **Technology for producing thin-rod Yb:YAG laser amplifiers is improved, which is aimed at increasing the output pulse energy and includes the development of a new method for mounting active elements into a cooling system and employment of more persistent dielectric coatings of rod ends. An influence of a thermal lens on the beam size in an active element is theoretically studied and the parameters are found, which provide equal beam sizes at input and output rod ends. The output pulse energy of 4 mJ is obtained without optical breakdown of the output end, which substantially exceeds the previously obtained results. The amplifier demonstrates an average power of 60 W and maintains a high beam quality.**

Keywords: *solid-state laser amplifier, diode-pumped Yb:YAG lasers, high-peak and average-power lasers.*

1. Introduction

Presently, the development of lasers with a high pulse energy and average power is an actively developing field in laser physics. Such sources are in great demand in industry and science [1 – 3]. The most promising are diode-pumped Yb:YAG lasers. In these lasers, an important role is played by the active element (AE) geometry, which affects the energy storage and extraction from the AE as well as the cooling process. Efficient heat removal from the AE requires the latter be thin in the direction of the heat sink.

One successfully employed AE geometry is based on using a thin rod (of diameter ~1 mm) with bright end-face diode pumping [4]. In this geometry, a high gain is attained, which makes it possible to realise simple single- and double-pass amplifiers. Efficient cooling through a side surface allows operation at an average power of above 100 W [5]. The maximal pulse energy of 2.5 mJ attained presently [6] is limited by the breakdown effect on AE output end. In [6], the technique of amplifying chirped pulses stretched in time to a duration of ~2 ns is used. In [7], the energy of 2 mJ was reached due to simultaneously amplifying the chirped pulses stretched to 8 ps and separating the pulse to four replicas with the following coherent recombining them back to a single pulse. The energy of up to 3 mJ was reached in [8] due to coherent combining of radiation from two thin channels.

The present paper describes a number of improvements for producing thin-rod Yb:YAG amplifiers, and results of theoretical studies are presented, which are aimed at increasing the output power of amplified pulses. As a result, the pulse energy is obtained, which is substantially above previous achievements. In addition, the possibility of operation with a high average power at high beam quality has been demonstrated.

2. Theoretical calculations

The key problem that limits the output energy of a thin-rod Yb:YAG amplifier is a breakdown of the AE output end. A reason for a substantial decrease in the breakdown energy may be the reduction of a beam diameter as the pulse propagates along the AE due to a strong thermal lens. This effect was estimated by calculating the temperature distribution and thermal lens in an amplifier based on a thin Yb:YAG rod (30-mm long, 1 mm in diameter, with the doping of 1 at.%), and by studying an influence of the thermal lens on a beam size inside the AE. The temperature was calculated by solving numerically a system of rate equations combined with a nonlinear nonstationary heat equation [9]. In the calculations, the pump power was 150 W. The pump distribution in an AE was found by the 3D ray tracing method [10]. The AE was divided to thin parts along the axis. In each part, phase distortions of the radiation wavefront were determined by using the parabolic approximation. Only the distortions related to the temperature dependence of the refractive index (dn/dT) were taken into account, because the face curvature may be neglected in the geometry of thin and long rod, and an electron lens in Yb:YAG is small under continuous pumping [11]. Then, the corresponding ray matrix of a distributed thermal lens was calculated for each of the parts by the formula [12]

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} \cos\left(L\sqrt{\dfrac{n_2}{n_0}}\right) & \dfrac{\sin\left(L\sqrt{\dfrac{n_2}{n_0}}\right)}{\sqrt{n_2 n_0}} \\ -\sqrt{n_2 n_0}\sin\left(L\sqrt{\dfrac{n_2}{n_0}}\right) & \cos\left(L\sqrt{\dfrac{n_2}{n_0}}\right) \end{pmatrix}, \qquad (1)$$

where the dependence of medium refractive index on radius is assumed as follows

$$n = n_0 - \frac{1}{2} n_2 r^2. \qquad (2)$$

I.I. Kuznetsov, S.A. Chizhov, I.B. Mukhin, O.V. Palashov Institute of Applied Physics, Russian Academy of Sciences, ul. Ulyanova 46, 603950 Nizhny Novgorod, Russia; e-mail: kuznetsov@ipfran.ru; s_chizhov@mail.ru; mib_1982@mail.ru; palashov@appl.sci-nnov.ru

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Beam profiles in the AE were determined by solving the integral Rayleigh–Sommerfeld equation in Fresnel approximation [12]:

$$u(P_1) = -\frac{\mathrm{i}}{\lambda B}\mathrm{e}^{\mathrm{i}kL}\iint_S \mathrm{d}S u(P)$$

$$\times\exp\left\{\mathrm{i}\frac{k}{2B}[A(x^2+y^2)+D(x_1^2+y_1^2)\right.$$

$$\left.-2(xx_1-yy_1)]\right\}. \quad (3)$$

The cases where a collimated or diverging beam enters the AE input are considered. Dependences of the beam radius on a longitudinal coordinate in the AE are given in Fig. 1. The calculations show that in the case of a collimated beam, the radius at the output end is 20% less than at the input end, which results in an increase in amplified radiation intensity by 44% and substantially reduces the breakdown energy. However, if the beam divergence is properly chosen, then the beam radii on the input and output ends can be made equal. Figure 1 presents behaviour of a Gaussian beam with the waist of size 200 μm, which is located outside the AE at a distance of 5 cm from the input end.

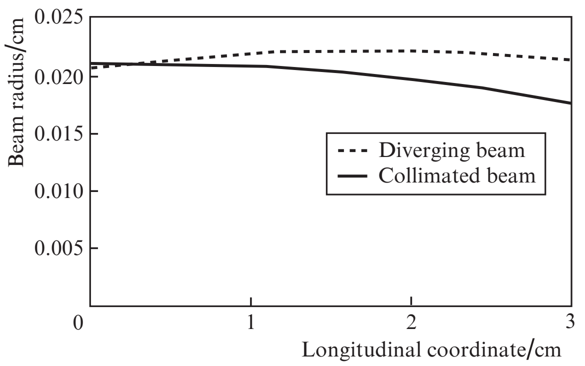

Figure 1. Calculated dependence of the Gaussian beam radius on the longitudinal coordinate inside the AE for collimated and diverging beams entering the AE.

3. Experimental results

Certain improvements have been made concerning production technologies for thin-rod Yb:YAG gain modules. A new design of the modules was elaborated, and the process of mounting an AE into a cooling system was developed (Fig. 2). The main difference is that processes of polishing and depositing an antireflection coating to the AE ends are performed after it has been mounted into a cooling system. This prevents the coating from contamination and damage during mounting, which is critical while operating with high-energy pulses. In order to increase the optical breakdown threshold for the AE ends, dielectric coatings on hafnium oxide with a high laser damage resistance are used. The modules with an AE diameter of 1 mm, length of 30 mm, and Yb:YAG doping level of 1 at.% have been produced.

Experiments on signal amplification to a high power have been performed in the double-pass amplification scheme bas-

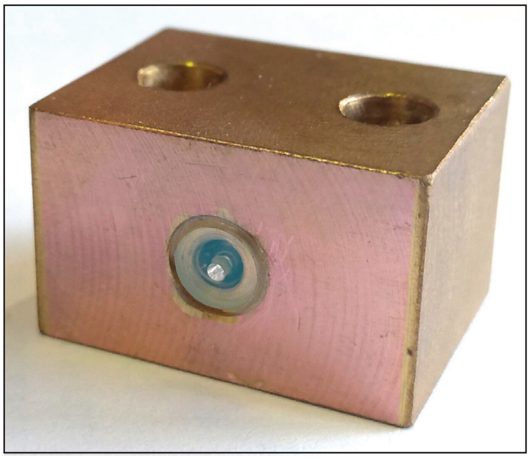

Figure 2. Photograph of the gain module with a thin-rod Yb:YAG AE.

ing on the module developed. As a signal, we used the radiation of a fibre laser with a pulse duration of 350 fs, energy of 1 μJ, and pulse repetition rate of 3 MHz, amplified to an average power of 20 W in a double-pass thin-rod amplifier. Two different pump sources were used: at a wavelength of 940 nm (the power is 110 W and diameter of output fibre core is 105 μm) and at wavelength of 969 nm (the power is 240 W and diameter of output fibre core is 200 μm). The second pump source makes it possible to pump a zero-phonon transition line in Yb:YAG. This substantially reduces heat release in the medium (by 30%), which is important while operating at a high average power.

An average power of present commercial bright diode sources with a fibre diameter of 105 μm is limited by 150 W. Hence, it is actual to study amplification by using less bright sources with a fibre diameter of 200 μm, however, a higher power. Amplifier dependences of an average output power on input power are shown in Fig. 3 for different pump sources. One can see that the pumping at greater power with a fibre diameter of 200 μm increases the output power by 30%. Nevertheless, the amplification efficiency (the ratio of the difference between amplifier output and input powers to the pump power) in this case is 17%, whereas with a lower-power pump source of higher brightness (the fibre diameter is 100 μm) it reaches 23%.

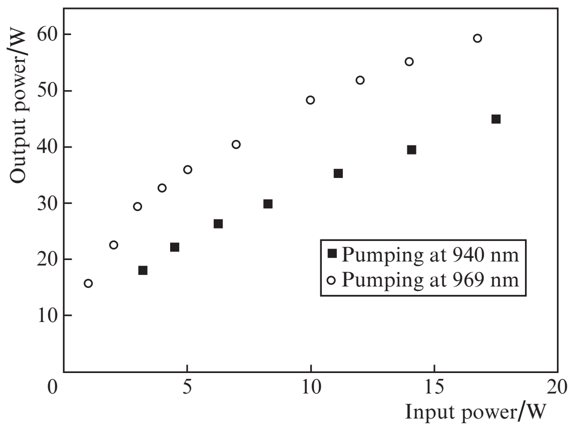

Figure 3. Dependences of the output power of the two-pass amplifier utilising a thin rod of length 30 mm on the input signal power at various pump sources.

We also determined the beam quality parameter M^2. For this purpose, the transverse beam profiles were measured along its waist with a step of 1 cm; profile dimensions D were calculated by 4-σ method, and the caustic approximated by hyperbola was plotted, and the parameter M^2 was found [13] (Fig. 4). The value obtained for M^2 is 1.35 at the input beam value M^2 equal to 1.2, which testifies small distortions of radiation in the amplifier.

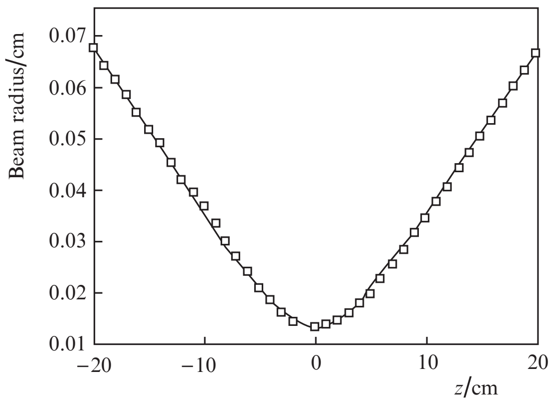

Figure 4. Measured dependence of the radius of amplified beam along the caustic (solid line is hyperbolic approximation).

Experiments on amplification of laser pulses to a high energy have been performed in the single-pass amplification scheme by using the chirped pulse amplification technique. As a signal to be amplified, the radiation of the same fibre laser amplified in two stages on thin Yb : YAG rods was used. The signal passed through an optical shutter on a Pockels cell, where the signal pulse repetition rate reduced to 1.5 kHz. Then the pulses were stretched to a duration of 1 ns in a volume Bragg grating stretcher. A scheme with two reflections from the grating at a small angle was used. The pulses were amplified in a regenerative amplifier on a thin Yb : YAG rod with a length of 10 mm and diameter of 0.8 mm to an energy of 0.3 mJ. Then the pulses were amplified in a single-pass amplifier on a rod with a length of 15 mm and diameter of 1 mm to the energy of 1 mJ.

The signal was focused by a lens providing a waist size of 200 μm. The waist was located at a distance of 5 cm from the input end of the AE, which, according to calculations, made equal the beam radii on the input and output ends. A power of the input signal was constant during measurements, whereas the pump power smoothly increased. The employed pump source had a fibre core diameter of 100 μm, numerical aperture of 0.22, wavelength of 940 nm, and power of up to 100 W. The size of the pump beam waist in the AE was 400 μm, and the absorption coefficient was about 90%. A dependence of the pulse output energy on the pump power is given in Fig. 5. The maximal energy obtained was 4 mJ, which is almost twice the result obtained in old gain modules that was a record value for the AE in the thin-rod geometry [6].

A substantial increase in the output energy became possible due to the new technology of producing gain modules that improved the quality of AE ends, and due to the employment of an antireflection coating based on hafnium oxide and optimised adjustment of the amplifier with a diverging input beam. A calculated threshold energy density on the AE output end was ~6 J cm^{-2}, which is below the breakdown threshold for high-quality antireflection coatings. No breakdown of the output end was observed, and the output energy was only limited by the power of a pump source employed.

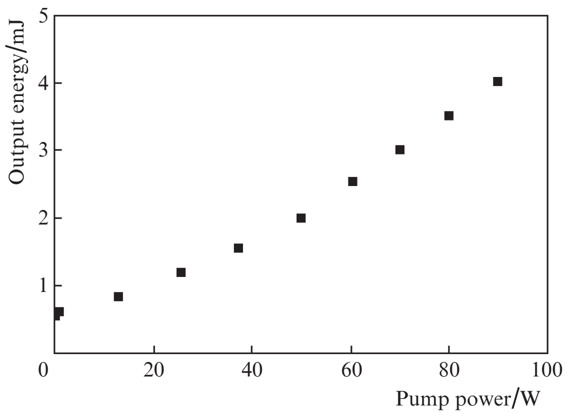

Figure 5. Dependence of the pulse energy at the output of the thin-rod amplifier on the pump power.

Experiments on compression of amplified laser pulses have been performed. For this purpose, a compressor was used with two reflections from the Bragg grating that was similar to that in the stretcher. To prevent grating damage, the experiments were carried out at a smaller output energy. For compression at a full pulse energy, it is necessary to employ a grating with the beam incidence angle of 0° (along the normal direction), which allows one to increase the beam aperture. The duration of pulses was 1.8 ps, whereas the transform-limited pulse duration is 1 ps. The longer pulse duration can be explained by a residual angular chirp of radiation after two reflections from the lattice. The employment of gratings with normal beam incidence will solve the problem.

4. Conclusions

A thermal lens in the AE and its influence on the propagation of an amplified pulse have been modelled. It was shown that the size of the collimated beam substantially reduces in the process of amplification (by 20%), and the optimal divergence of an input beam was found, which allows one to make the beam sizes on the AE input and output ends equal. The calculation results were used for adjusting amplifiers in the experiments. Some improvements are made concerning the technology of producing gain modules with an AE based on a thin Yb : YAG rod, which increased the pulse output energy. A new scheme of mounting the AE into a cooling system is elaborated, in which polishing and depositing antireflection coatings to the AE ends are performed at the final stage of gain module production. This prevented contamination and damage of the coatings. For increasing the breakdown threshold, hafnium oxide coatings were used.

Experiments on amplifying a signal to a high average power with two different pump sources have been performed. The first one was a low-power high-brightness laser operated at a wavelength of 940 nm. The second was a high-power laser with less brightness and operation wavelength of 969 nm. The maximal output power has been obtained with the high-power source and was 60 W; however, the amplification efficiency in this case was lower than that with the low-power pump source of higher brightness. The beam quality parameter M^2 in both the cases was 1.35, which testifies small phase distortions in the AE.

Experiments on signal amplification to a high energy have been performed by the scheme of a chirped pulse amplifier. Due to the new technology of producing gain modules, which improved the quality of AE ends, employment of antireflection coatings based on hafnium oxide, and optimised adjustment of the amplifier without reducing the beam size at the output end, we avoided an optical breakdown and obtained the energy of 4 mJ, which substantially exceeds previous results. Pulses have been compressed to 1.8 ps in a compressor based on a volume Bragg grating.

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References

1. Reagan B.A., Berrill M., Wernsing K.A., Baumgarten C., Woolston M., Rocca J.J. *Phys. Rev. A*, **89**, 053820 (2014).
2. Hädrich S., Klenke A., Rothhardt J., Krebs M., Hoffmann A., Pronin O., Pervak V., Limpert J., Tünnermann A. *Nat. Photonics*, **8**, 779 (2014).
3. Leemans W., Esarey E. *Phys. Today*, **62** (3), 44 (2009).
4. Délen X., Zaouter Y., Martial I., Aubry N., Didierjean J., Hönninger C., Mottay E., Balembois F., Georges P. *Opt. Lett.*, **38** (2), 109 (2013).
5. Markovic V., Rohrbacher A., Hofmann P., Pallmann W., Pierrot S., Resan B. *Opt. Express*, **23** (20), 25883 (2015).
6. Kuznetsov I., Mukhin I., Palashov O., Ueda K.-I. *Opt. Lett.*, **43** (16), 3941 (2018).
7. Lesparre F., Gomes J.T., Délen X., Martial I., Didierjean J., Pallmann W., Resan B., Druon F., Balembois F., Georges P. *Opt. Lett.*, **41** (7), 1628 (2016).
8. Kienel M., Müller M., Demmler S., Rothhardt J., Klenke A., Eidam T., Limpert J., Tünnermann A. *Opt. Lett.*, **39** (11), 3278 (2014).
9. Kuznetsov I.I., Mukhin I.B., Silin D.E., Vyatkin A.G., Vadimova O.L., Palashov O.V. *IEEE J. Quantum Electron.*, **50** (3), 133 (2014).
10. Kuznetsov I., Mukhin I., Palashov O., Ueda K.-I. *Opt. Lett.*, **41** (22), 5361 (2016).
11. Anashkina E., Antipov O. *JOSA B*, **27** (3), 363 (2010).
12. Bykov V.P., Silichev O.O. *Lazernye rezonatory* (Laser Cavities) (Moscow: Fizmatlit, 2004).
13. Siegman A.E. *Proc. SPIE*, **1868**, 2 (1993).