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Yb : YAG thin-rod laser amplifier with a high pulse energy for a fibre oscillator

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Abstract. **High (more than ten times) small-signal gain is demonstrated in an Yb : YAG single crystal thin rods with pumping by a fibre-coupled diode laser. A four-pass amplifier for a fibre master oscillator with an average output power exceeding 15 W at a pulse repetition rate of 3 MHz is fabricated based on this active element. The small-signal gain in the developed amplifier is 26 dB, which is comparable with the gain in regenerative amplifiers. The possibility of obtaining sub-millijoule pulse energy at a pulse repetition rate of tens of kilohertz is shown.**

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

1. Introduction

Reliable and inexpensive femto- and subpicosecond fibre lasers find wide application in science, industry, and medicine. However, their use is restricted by a too low pulse energy (not exceeding several microjoules). Regenerative amplifiers, which are usually used for these purposes, are difficult to align, have a low contrast upon pulse amplification, and may cause thermal distortions due to the Pockels cell. Thus, the development of reliable and inexpensive amplifiers with a high (two–three orders of magnitude) gain is undoubtedly important, and one of the most promising technologies in this way is the use of active elements (AEs) in the form of a thin rod [1, 2]. Amplifiers based on these AEs have a gain exceeding 100 times in a simple two-pass optical scheme, and the pulse energy can reach 1 mJ in the case of amplification of chirped pulses [3].

In this paper, we present the results of the development of an amplifier based on a laser head with a thin-rod AE made of an Yb:YAG single crystal using an original technology [1, 4]. We report the measured small-signal gain in the used laser head, describe the optical scheme of amplification, and present the measured energy characteristics of the amplifier (output power, small-signal gain, optical-to-optical efficiency), as well as the measured spatial, temporal, and spectral distortions upon amplification of chirped pulses.

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2. Thin-rod laser heads

We studied two laser heads with AEs of different shapes, namely, the first rod was a cylindrical Yb (1%) : YAG rod with a diameter of 1.2 mm and a length of 30 mm, while the second rod was made of the same crystal and had a shape of a cone (diameters of 1.2 and 0.6 mm and a length of 30 mm) [4]. Both AEs were soldered into a copper heat sink; the design of the laser heads is described in more detail in [1, 4]. Figure 1b presents a photograph of the laser head with mirrors for amplified and pump radiation. The amplified beam (wavelength λ = 1030 nm) 0.3 mm in diameter is coupled into the AE through dichroic mirror (*1*) and reflected by dichroic mirror (*2*) to a power meter. The radiation of a fibre-coupled (fibre diameter 105 μm, numerical aperture 0.22) pump diode

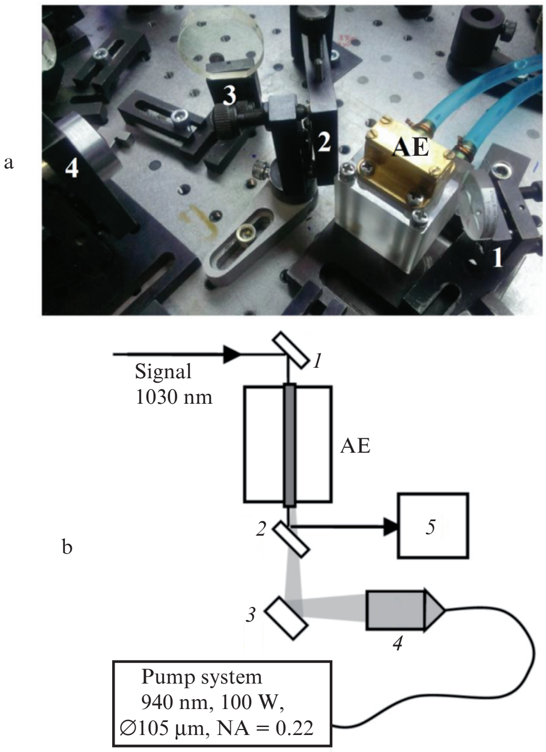

Figure 1. (a) Photograph of the thin-rod laser head and (b) principal scheme of the gain measurement: (*1*, *2*) dichroic mirrors, which reflect the signal at λ = 1030 nm and transmit pump radiation at λ = 940 nm; (*3*) input mirror; (*4*) pump collimator; (*5*) power meter.

laser (wavelength 940 nm) with a maximum power of 100 W passes through a collimator and is sent into the AE in a direction counter to the amplified beam propagation. Collimator (*4*) and mirrors (*3*) are used for coaxial alignment of the AE and the pump beam. The collimator objective transfers the image from the output fibre end to the input AE face with a fourfold magnification. The transmission of the scheme is 63% at the signal wavelength (1030 nm) (due to absorption in the Yb:YAG crystal) and 10% at the pump wavelength.

The results of measurements of small-signal gain in the pulsed (pulse duration 5 ms, repetition rate 5 Hz) and cw pump regimes are presented in Fig. 2. It is seen that the gain in the conical rod is considerably higher than in the cylindrical AE due to more uniform pumping of the AE volume. Owing to the use of pump radiation with a lower divergence than in work [1], we achieved a considerable increase in the small-signal gain. The gain in the cw regime is close to the gain in the pulsed regime, which confirms the smallness of thermal effects in the AE under study. The gain value is close to that obtained in [2, 3, 5].

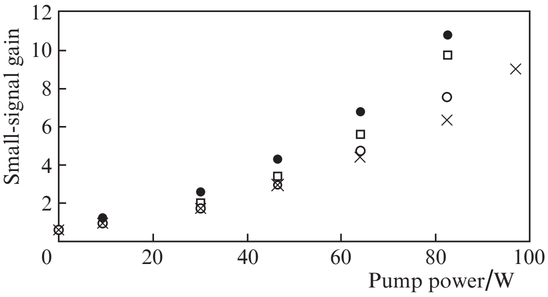

Figure 2. Dependence of the small-signal gain in pulsed and cw pump regimes for (×) a cylindrical rod at cw pumping, a conical rod in (●) pulsed and (□) cw pump regimes, and (○) broadband ($\Delta\lambda$ = 1.6 nm) radiation.

3. Thin-rod amplifier

As an input signal source we used the system described in [6]. A signal of a femtosecond fibre laser (~300 fs) was divided into two pulses, the duration of one of them being additionally stretched in bulk Bragg gratings up to 2 ns depending on the number of passes through the gratings. The scheme of the four-pass amplifier with a conical AE is shown in more detail in Fig. 3. The average power of the signal at the entrance to the amplifier is 0.22 W and can be decreases by rotating a $\lambda/2$ plate placed in front of the Faraday isolator (F1). The pulse repetition rate is 3 MHz. Then, the beam propagates through the Faraday isolator, which both protects the front-end laser system and ensures the propagation of two last passes. Lens L1 (f = 70 cm), which is placed in front of the AE at a distance of 60 cm from it, focuses the radiation so that the beam diameter was 400 μm at the entrance to the AE and 300 μm at the exit from it. Lens L2 is chosen and adjusted to collimate the radiation passed through the focus of lens L1, which allows one to simultaneously compensate for a rather strong thermal lens in the active rod. Then, the beam is reflected back by mirror (*6*), and a $\lambda/4$ plate lets it pass through polariser P1. Two last passes through the AE are ensured by retroreflecting mirror (*7*) and by isolation of radiation in Faraday isolator F1. The required diameter and divergence of the beam in the last two passes in the region of the AE are obtained by the choice and alignment of lens L3, as well as by the distance between this lens and mirror (*7*). The amplifier occupies an area of 70 × 50 cm, which can be decreased approximately by two times using defecting mirrors.

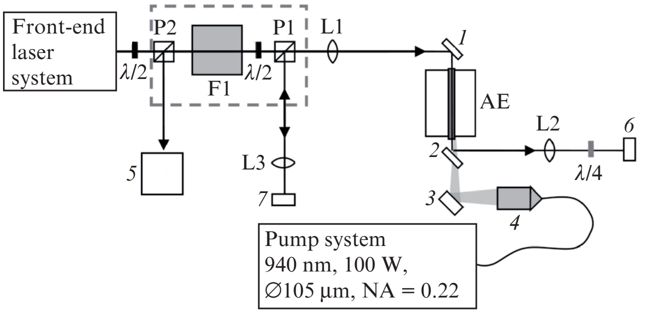

Figure 3. Scheme of a four-pass amplifier with a thin-rod AE: (*1*, *2*) dichroic mirrors, which reflect the signal at λ = 1030 nm and transmit pump radiation at λ = 940 nm; (*3*) input mirror; (*4*) pump collimator; (*5*) power meter; (*6*, *7*) plane mirrors.

At an input power of 0.22 W and a pump power of 82 W, we achieved an output amplifier power up to 15 W (Fig. 4a). The total gain was 18 dB at an optical-to-optical efficiency of 18.3%. Taking into account that 10% of the pump radiation leaves the AE, we can estimate the optical-to-optical efficiency to be 20.3%, because this radiation can be focused and send back to the AE. At a pulse repetition rate of 3 MHz, the energy in each pulse was 5 μJ. Figure 5 presents the dependence of the gain on the output power at a pump power of 64 W. At an input pump power of 2.3 mW, the output power was 1.1 W, which corresponds to a gain exceeding 26 dB and coincides with the fourth power of the small-signal gain per pass (black square in Fig. 5). The achieved gain is comparable with the gain in regenerative amplifiers.

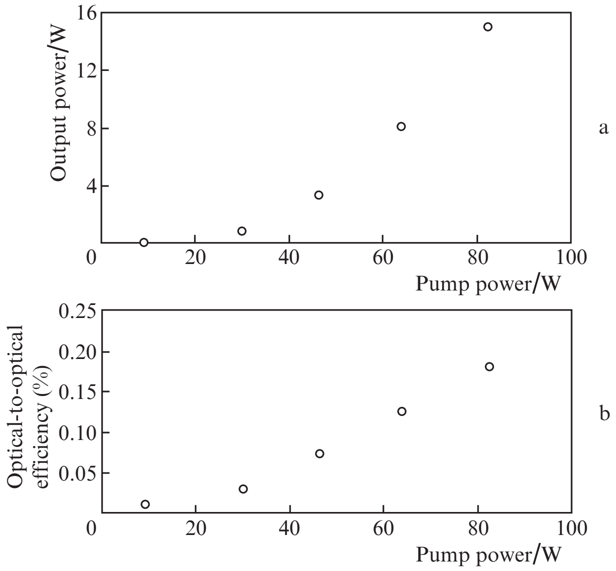

Figure 4. Dependences of the (a) output power and (b) optical-to-optical efficiency of the amplifier on the pump power.

According to the dependence in Fig. 4, the amplification efficiency linearly increases with increasing pump power. This means that, from the viewpoint of the balance between the

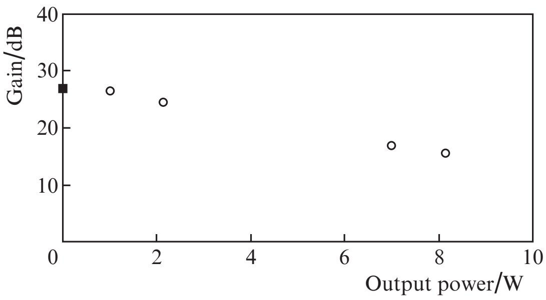

Figure 5. Dependence of the gain on the output power at a pump power of 64 W. The black square corresponds to the small-signal gain per pass raised to the fourth power.

stored energy, the amplified signal power, and the losses in the amplifier, there exists the possibility to further increase the output power and efficiency by increasing the pump power. Unfortunately, the 64-W pump power in the absence of an input signal corresponds to the self-excitation threshold of the amplifier. Probably, the self-excitation will be absent in the gain saturation regime, but this question requires additional investigations.

4. Distortions of radiation upon amplification

In addition to the energy characteristics, the main amplifier parameters are the polarisation, phase, and amplitude distortions of radiation in the process of amplification. The question about thermal distortions of radiation in thin-rod AEs is considered in more detail in [1]. We did not find considerable thermal distortions of the signal when adjusting and studying the amplifier. The polarisation distortions of the amplified signal were insignificant and partially compensated in the process of backward propagation of radiation [7, 8]. The beam profile almost did not change after amplification, which confirms the smallness of thermal phase distortions in the amplifier (Fig. 6). A strong thermal lens formed in the rod was compensated using lenses L2 and L3 (see Fig. 3).

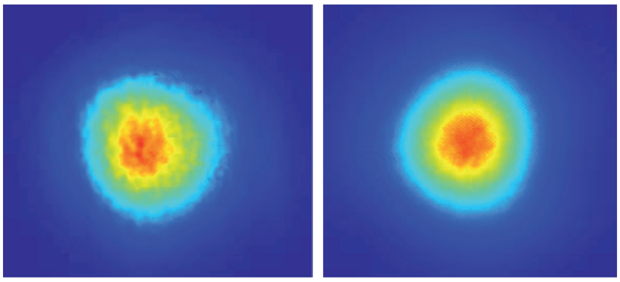

Figure 6. Transverse profiles of (left) incident and (right) amplified beams.

To amplify chirped laser pulses, it is important not only to provide the maximum pulse energy and a satisfactory transverse beam profile but also to control the temporal and spectral profiles of the amplified pulse, especially in the saturated gain regime. The temporal and spectral profiles at a pump power of 64 W were measured by a DFD70M photodiode with a Tektronix DPO 7254C oscilloscope and a Solar TII spectrometer, respectively. The signal at the entrance of the amplifier has two peaks in both temporal and spectral profiles at a total pulse duration of 1.25 ns and a spectral width at half maximum of 1.6 nm (Fig. 7). The second peak in the spectrum (Fig. 7a) corresponds to the maximum gain cross section, provided that the signal is stretched by the bulk Bragg gratings so that the first spectral peak at shorter wavelengths corresponds to a lower gain. Using this signal, it is possible to decrease the sharpening of the leading edge of the amplified pulse when the distance between pulses is comparable with the upper laser level lifetime. The grey curves in Fig. 7 show the temporal and spectral profiles of the amplified pulse. One can see that the width of the amplified spectrum is decreased to 1 nm and the pulse duration is shortened to 0.8 ns. This signal can be compressed to a duration below 1 ps. The maximum gain is achieved at the trailing part of the pulse. Probably, at a lower pulse repetition rate (to 10 Hz), we can expect equalisation of the intensity in the leading and trailing pats of the pulse due to sharpening of the leading edge.

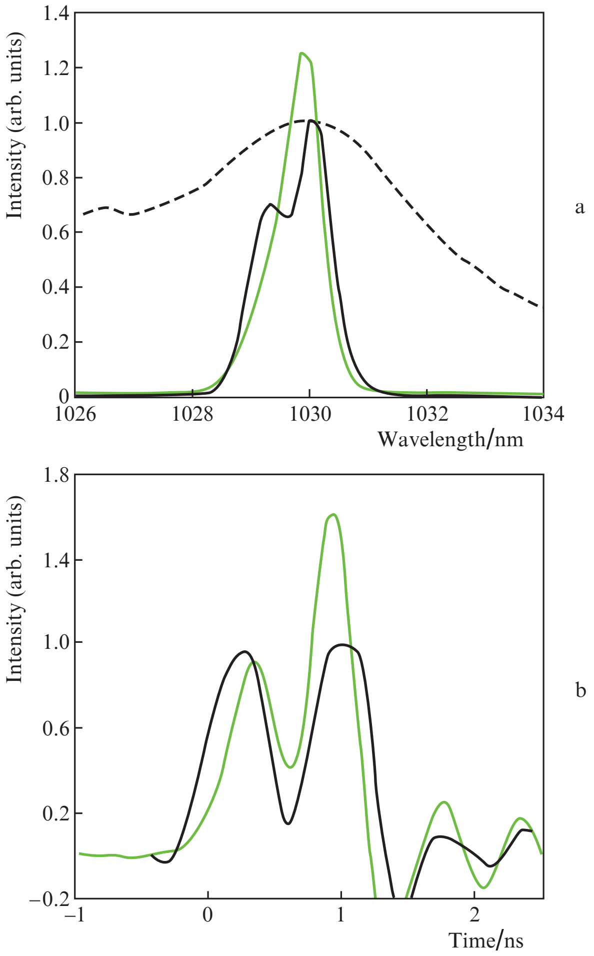

Figure 7. (a) Spectral and (b) temporal profiles of the (black curves) input and (gray curves) amplified pulses at a pump power of 64 W and an output power of 8 W. The dashed curve shows the normalised gain cross section.

5. Conclusions

We have presented the first results on the development of a highly efficient amplifier with an active element in the form of a thin rod. A combination of a high efficiency and a high gain, which is comparable with the gain achieved in regenerative amplifiers, is demonstrated. The gain achieved in a laser head with an Yb : YAG thin rod prepared by the method described in [1, 4] is close to the gain obtained in [2, 3, 5]. The amplified output power was 15 W at an optical-to-optical efficiency of 18 %, which corresponds to a pulse energy of 5 μJ at a pulse repetition rate of 3 MHz. The specific features of amplification of chirped pulses are studied and a slight narrowing of the spectral and temporal profiles after amplification is demonstrated.

The use of a new original method of fabrication of thin-rod laser heads allowed us to use a conical rod to achieve more efficient pumping of the AE and, as a result, a higher gain. In addition, the use of a new method of fabrication of AEs makes it possible to make them of other optical materials, for example, of laser ceramics. Thus, it will be possible to use media with a broader gain band (for example, Yb : Y_2O_3 ceramics) and create an amplifier of pulses with a duration shorter than 500 fs.

The main drawback of the developed amplifier it its self-excitation at a high gain. This effect can be weakened by improving isolation of radiation in backward passes. In the future, the pulse repetition rate of the front-end system will be decreased to 10 kHz or lower, which will allow one to increase the energy of amplified pulses to a sub-millijoule level with an average output power of several watts. It will be possible to compress this signal back to subpicosecond durations by the same Bragg gratings or to use it for further amplification to higher energies.

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References

1. Kuznetsov I., Mukhin I., Vadimova O., Palashov O., Ueda K.-I. *Appl. Opt.*, **54** (25), 7747 (2015).
2. Zaouter Y., Martial I., Aubry N., Didierjean J., Hönninger C., Mottay E., Druon F., Georges P., Balembois F. *Opt. Lett.*, **36** (5), 748 (2011).
3. Délen X., Zaouter Y., Martial I., Aubry N., Didierjean J., Hönninger C., Mottay E., Balembois F., Georges P. *Opt. Lett.*, **38** (2), 109 (2013).
4. Kuznetsov I.I., Mukhin I.B., Vadimova O.L., Palashov O.V., Ueda K.-I. *Advanced Solid-State Lasers Congress* (Berlin, 2015); *OSA Techn. Dig.*, AM5A.33 (2015).
5. Délen X., Piehler S., Didierjean J., Aubry N., Voss A., Ahmed M.A., Graf T., Balembois F., Georges P. *Opt. Lett.*, **37** (14), 2898 (2012).
6. Perevezentsev E.A., Mukhin I.B., Kuznetsov I.I., Vadimova O.L., Palashov O.V. *Kvantovaya Elektron.*, **45** (5), 451 (2015) [*Quantum Electron.*, **45** (5), 451 (2015)].
7. Andreev N.F., Kuznetsov S.V., Palashov O.V., Pasmanik G.A., Khazanov E.A. *Kvantovaya Elektron.*, **19** (9), 862 (1992) [*Quantum Electron.*, **22** (9), 800 (1992)].
8. Hua R., Wada S., Tashiro H. *Opt. Commun.*, **175** (1-3), 189 (2000).