Quantum Electronics **45** (3) 207–210 (2015)

PACS numbers: 42.55.Rz; 42.60.By; 42.60.Lh
DOI: 10.1070/QE2015v045n03ABEH015699

Thin-disk laser based on an Yb : YAG / YAG composite active element

I.I. Kuznetsov, I.B. Mukhin, O.L. Vadimova, O.V. Palashov

Abstract. **A thin-disk laser module based on an Yb : YAG / YAG composite active element is developed with a small-signal gain of 1.25 and a stored energy of 400 mJ under cw pumping. The gain and thermally induced phase distortions in the module are studied experimentally. Based on this module, a thin-disk laser with an average power of 300 W and a slope efficiency of 42 % is designed.**

Keywords: *thin-disk laser, Yb:YAG, composite active element, amplified spontaneous emission, thermal effects, high average power.*

1. Introduction

The potentialities and rapid development of diode-pumped solid-state lasers based on Yb : YAG thin disks (thin-disk lasers) are explained by high average power, peak power and efficiency of these lasers [1]. Today, thin-disk lasers have kilowatt average powers with a good beam quality [2], as well as pulse energies of hundreds of millijoules at a high pulse repetition rate [3]. Thin-disk lasers are actively used for material microprocessing [4] and widely applied for generation of high-power radiation in the X-ray and far-IR regions [5]. This radiation becomes a unique tool for fundamental scientific research [6]. Scaling of thin-disk lasers in order to obtain higher average and peak powers opens the possibility of using them in new scientific and technological applications.

The thin-disk laser power is usually increased by increasing the pump beam diameter at the same pump power density. In this case, the temperature and the amplitude of thermally induced phase distortions in the crystal almost do not change. However, the effect of amplified spontaneous emission (ASE), which is related to a high gain along the radial coordinate, increases. This is caused by locking of luminescence in the laser crystal due to the total internal reflection from the crystal faces. An efficient method for decreasing the ASE effect is to use a composite active element (composite AE) composed of an Yb : YAG thin disk and a YAG thick disk attached to each other face-to-face by thermal diffusion bonding [7]. In this AE, total internal reflection from one of the Yb : YAG crystal faces is absent and luminescence easily leaves the doped region. In addition, heat release typical for Yb^{3+}-doped materials at high inversion densities is weaker in the case of composite AEs [8]. These advantages of composite AEs play the key role when they are used for producing pulsed laser amplifiers, which must have a high gain and high stored energy. The only drawback of composite AEs is, in our opinion, the thermally induced phase distortions of radiation in the undoped region of the AE.

In this work, we develop a thin-disk laser module based on an Yb : YAG / YAG composite AE. The gain and the thermally induced phase distortions in this element are experimentally studied. Using this module, a cw laser with an average power of 300 W at a slope efficiency of 42 % is fabricated.

2. Development of a laser module

The scheme of the developed laser module is presented in Fig. 1a. The composite AE was made by an original method

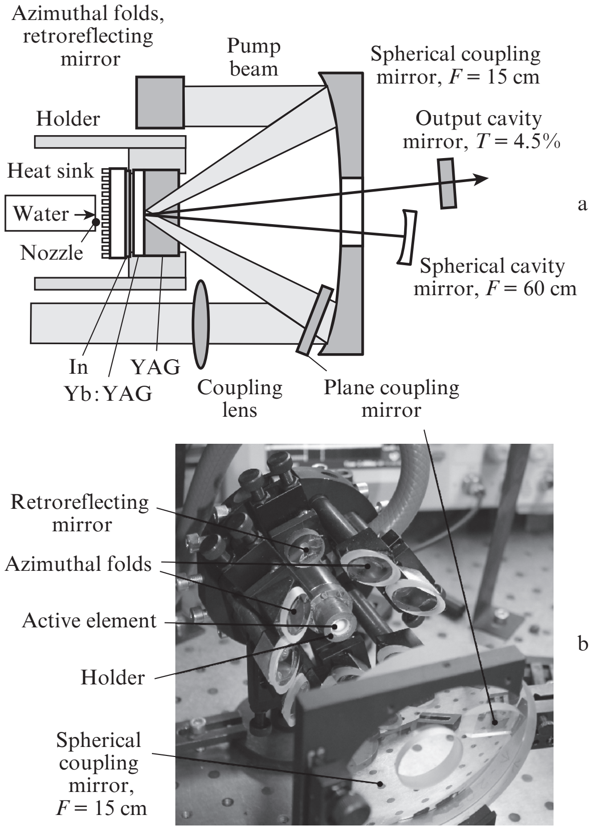

Figure 1. (a) Scheme of the laser module and laser cavity (the distance from the crystal to the spherical mirror is 20 cm and the distance from the crystal to the output mirror is 30 cm) and (b) photograph of the laser module.

I.I. Kuznetsov, I.B. Mukhin, O.L. Vadimova, O.V. Palashov Institute of Applied Physics, Russian Academy of Sciences, ul. Ul'yanova 46, 603950 Nizhnii Novgorod, Russia; e-mail: ivanushka911@yandex.ru

Received 23 October 2014; revision received 13 November 2014
Kvantovaya Elektronika **45** (3) 207–210 (2015)
Translated by M.N. Basieva

of thermal diffusion bonding [9] of two crystal samples 10 mm in diameter, one of which was an Yb:YAG disk (Yb concentration, 10 at%; thickness, 300 μm) and the second was a 4-mm-thick YAG crystal. One of the AE faces was coated with a dielectric mirror and a metallising film, while the other face was antireflection coated with a dielectric material. The AE was soldered from the side of the metallised face to a heat sink using an indium solder, and the pump and signal beams were coupled into the AE through the other face. The lateral surface of the AE was soldered into a copper holder. The heat sink was a 1-mm-thick composite metal (molybdenum and coper) plate. The use of molybdenum allows one to minimise the difference between the crystal and heat sink thermal expansion coefficients. The copper coating makes it possible to solder the crystal to the heat sink. The back side of the heat sink was finely grooved (with a step of 300 μm) in order to increase the water cooling efficiency. The heat sink was cooled by a flow of water. The distance from the heat sink to the end of the pipe was 0.5 mm. To avoid stagnation of water in the flow centre, the pipe ended with a nozzle with small holes. The pressure of water in the system was 1.7 atm, and the water flow rate was 3 L min^{-1}.

To achieve complete absorption of pump power, the authors of [10] used an optical scheme with ten V-shape passes of the pump beam through the AE, which consisted of a spherical coupling mirror (curvature radius 15 cm), the AE in the focus, four azimuthal folds and a retroreflecting mirror. Our scheme differed from the scheme of [10] by the use of a plane coupling mirror for the first pass (Fig. 1a). The size and shape of the beam on the crystal was formed by a coupling lens. The beam shape on the crystal for all passes was identical to the beam shape for the first pass. The laser radiation was coupled out through an aperture in the spherical coupling mirror. A photograph of the developed laser module is presented in Fig. 1b.

3. Experimental results

In the experiments, the pump beam diameter was 6 mm. The small-signal gain per V-shape pass through the AE upon pulsed (pulse duration of 2.5 ms, repetition rate of 10 Hz) and cw pumping was measured using a probe beam (in the latter case, the gain was measured after achieving a steady-state regime). The gain was numerically calculated using the model of [11], which takes into account pump saturation, heating of the system and ASE. The experimental and calculated results are shown in Fig. 2. The difference between the dependences for pulsed and cw pumping is related to heating of the AE. One can see that the effect of heating is strong. The gain achieved in the experiment is 1.25, which corresponds to a stored energy of 400 mJ. The calculation shows that it is possible to achieve a gain of 1.3. The slight difference between the experimental and calculated data can be caused by a higher temperature of the AE than expected. To achieve a higher gain, it is necessary to further optimise the cooling system. Analysis of the literature data shows that even at small (2 mm) pump beam diameters [12] the gain in Yb:YAG thin-disk AEs is weaker than that obtained in the present paper and decreases further with increasing diameter [13, 14]. Thus, owing to attenuation of the effect of ASE in the composite geometry, we achieved an increase in the gain and stored energy.

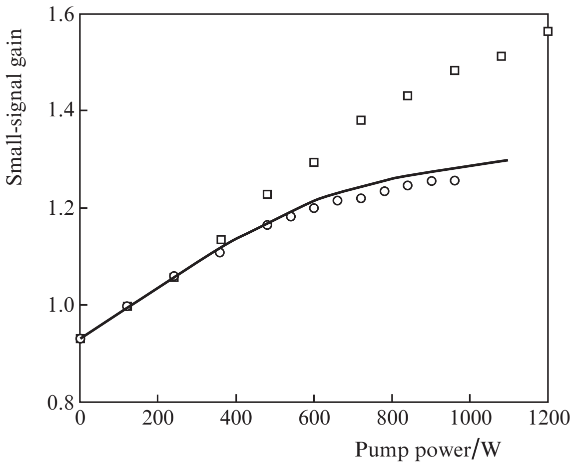

Figure 2. Experimentally measured small-signal gain per V-shape pass through the composite AE upon pulsed (pulse duration of 2.5 ms, pulse repetition rate of 10 Hz) (□) and cw (○) pumping. The solid line corresponds to calculation in the case of cw pumping.

Thermally induced phase distortions are believed to be the only drawback of composite AEs compared to ordinary Yb:YAG thin-disk AEs [15]. This drawback is explained by the propagation of laser radiation though one more optical element, i.e., YAG crystal. The thermally induced phase distortions in the developed laser module were measured by phase-shift interferometry [16]. To do this, the laser module was placed in a Michelson interferometer, in which the AE played the role of one of reference mirrors. The optical phase profiles in the interferometer arm were measured when the pump source was switched on and off. The thermally induced phase distortions, i.e., the difference between these two optical phase profiles, were measured in the presence and absence of lasing. The measured distortion profiles are shown in Fig. 3. We can approximate these profiles in the pumped region by a parabola (Fig. 3a) and find the optical power of the parabolic component of the thermal lens. The dependence of the optical power of a thermal lens formed in the composite AE per V-shape pass on the pump power is shown in Fig. 3b. One can see that this thermal lens is rather strong and must be taken into account when developing optical schemes of lasers; moreover, the thermal lens is stronger in the presence of lasing than in its absence. This can be explained by the fact that the laser radiation quantum defect for laser radiation is higher than for luminescence, because of which the heat release in the presence of lasing should be higher [17]. This situation considerably differs from the results obtained for Yb:YAG thin disks. Usually, the thermal lens in a thin disk without lasing is stronger than in the presence of lasing, which is explained by nonlinear heat release in Yb^{3+}-doped crystals at a high population inversion density [12]. Thus, the obtained results show that nonlinear heat release in a composite AE decreases [8]. Therefore, the nonlinear heat release is caused by luminescence absorption occurring in the Yb:YAG crystal at a high inversion density.

The most important factor restricting the scaling of thin-disk lasers is the non-parabolic phase distortions, which lead to parasitic losses and deterioration of the beam quality. To determine the non-parabolic phase distortions, one must subtract the parabolic component from the measured phase distortions. The profiles of non-parabolic phase distortions are shown in Fig. 3c. The distortions in the AE centre are related to the small-scale inhomogeneities of the system (inhomogeneities of the pump beam, crystal, and cooling system). In addition, there exist distortions related to the pump region boundaries, where a transverse heat flow in the Yb:YAG crystal appears. The amplitude of non-parabolic phase distortions in the pumped region in experiments without lasing was 200 ns, which does not exceed the corresponding parameter in ordinary Yb:YAG thin disks [18]. In the presence of lasing, the amplitude of non-parabolic phase distortions is two times higher (400 nm), which may be caused by increasing heat release. Thus, the measurement results show that, from the viewpoint of phase aberrations, the composite AE is as good as an ordinary thin-disk AE.

The developed laser module was used for assembling a highly efficient multimode cw laser (the laser cavity scheme is shown in Fig. 1a). The dependence of the output laser power on the absorbed pump power is given in Fig. 4. We achieved output radiation with an average power of 300 W and a slope efficiency of 42%. To further increase the laser efficiency, we plan in the near future to improve the AE cooling system and to study the possibility of decreasing the parasitic losses. The average laser power will be increased by increasing the pump power.

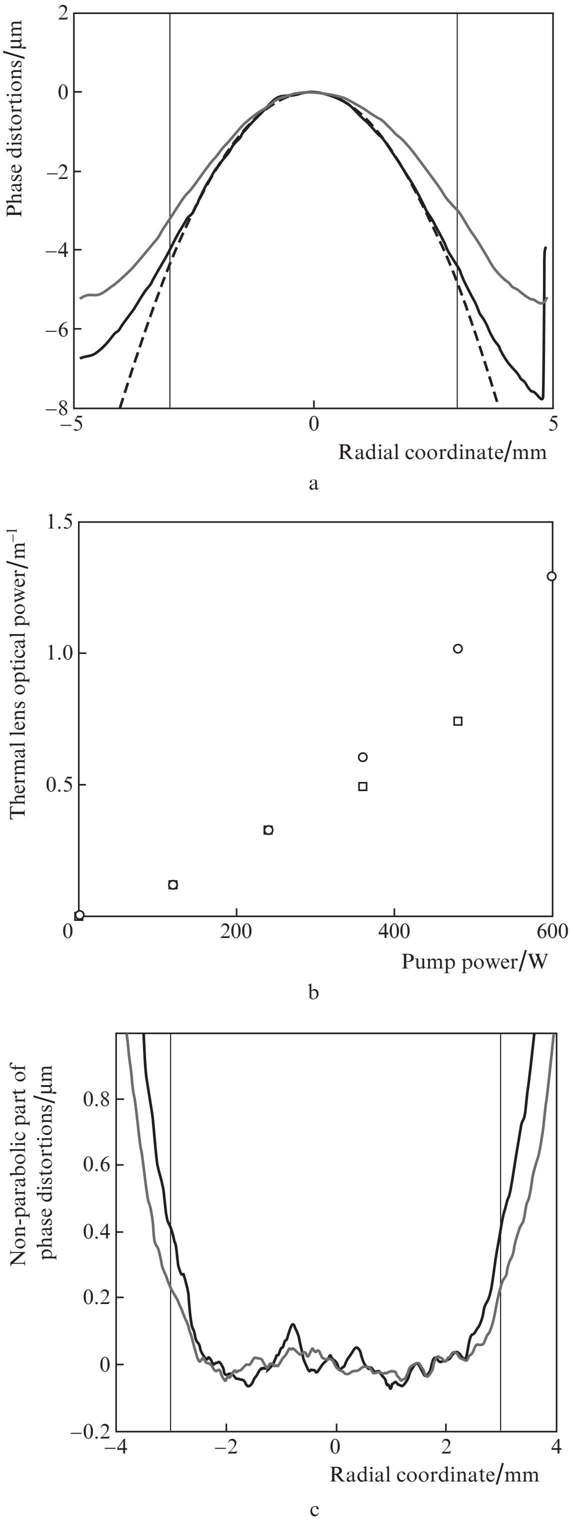

Figure 3. (a) Profiles of thermally induced phase distortions per V-shape pass through a composite AE at a pump power of 500 W (black solid curve corresponds to experiment in the presence of lasing, grey solid curve corresponds to experiment without lasing, dashed curve is a parabola, and vertical lines show the pumped region boundaries); (b) dependence of the optical power of the thermal lens formed in the composite AE per V-shape pass on the pump power in the absence (□) and presence (○) of lasing; and (c) non-parabolic part of thermally induced phase distortions per V-shape pass in the composite AE at a pump power of 500 W (black solid curve corresponds to experiment in the presence of lasing, grey solid line corresponds to experiment without lasing, and vertical lines show the pumped region boundaries).

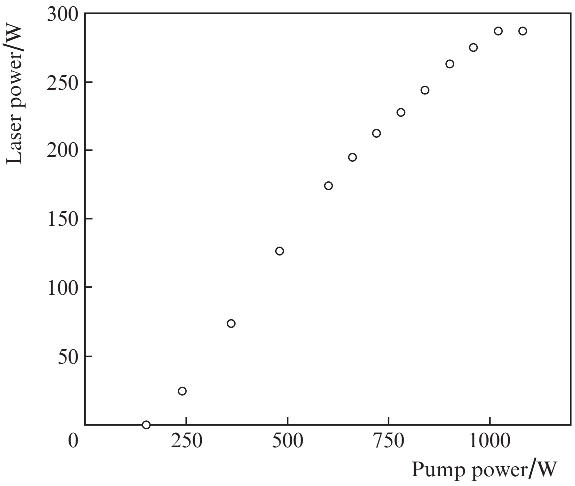

Figure 4. Dependence of the output power of a cw thin-disk laser with a composite Yb:YAG/YAG AE on the pump power.

4. Conclusions

A thin-disk laser module was developed based on an Yb:YAG/YAG composite AE. Attenuation of the ASE effect in the composite AE allowed us to achieve a small-signal gain of 1.25 and a stored energy of 400 mJ in the steady-state operation regime of the system upon cw pumping. Based on the developed module, we fabricated a cw laser with an average power of 300 W at a slope efficiency of 42%. The thermally induced phase distortions in the developed module are studied experimentally. It is shown that the phase aberrations in the strong thermal lens formed in the composite AE do not exceed aberrations for ordinary Yb:YAG thin disks. The developed laser module can be successfully used for producing cw and repetitively pulsed lasers with high average power and different output radiation parameters. The high gain and stored energy make it especially attractive for application in pulsed laser amplifiers with high (above 1 kHz) pulse repetition rates. At present, a laser with a pulse energy of 100 mJ and a repetition rate of 1 kHz is being developed based on the developed module.

Acknowledgements. This work was supported by the Megagrant of the Government of the Russian Federation executed at the Institute of Applied Physics (Grant No. 14.B25.31.0024) and by the Russian Foundation for Basic Research (Grant No. 13-02-97119 r_povolzh'e_a).

References

1. Giesen A., Speiser J. *IEEE J. Sel. Top. Quantum Electron.*, **13** (3), 598 (2007).
2. Peng Y.H., Lim Y.X., Cheng J., Guo Y., Cheah Y.Y., Lai K.S. *Opt. Lett.*, **38** (10), 1709 (2013).
3. Tümmler J., Jung R., Stiel H., Nickles P.V., Sandner W. *Opt. Lett.*, **34** (9), 1378 (2009).
4. Killi A., Stolzenburg C., Zawischa I., Sutter D., Kleinbauer J., Schad S., Brockmann R., Weiler S., Neuhaus J., Kalfhues S., Mehner E., Bauer D., Schlueter H., Schmitz C. *Proc. SPIE Int. Soc. Opt. Eng.*, **7193**, 71931T (2009).
5. Hong K.-H., Lai C.-J., Siqueira J.P., Krogen P., Moses J., Chang C.-L., Stein G.J., Zapata L.E., Kärtner F.X. *Opt. Lett.*, **39** (11), 3145 (2014).
6. Pohl R., Antognini A., Nez F., et al. *Nat. Lett.*, **466**, 213 (2010).
7. Kouznetsov D., Bisson J.-F. *J. Opt. Soc. Am. B*, **25** (3), 338 (2008).
8. 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).
9. Mukhin I., Perevezentsev E., Palashov O. *Opt. Mater. Express*, **4** (2), 266 (2014).
10. Erhard S., Giesen A., Karszewski M., Rupp T., Stewen C., in: *Advanced Solid State Lasers* (Boston, Massachusetts: OSA, 1999) Vol. 26.
11. Vadimova O.L., Mukhin I.B., Kuznetsov I.I., Palashov O.V., Perevesentsev E.A., Khazanov E.A. *Kvantovaya Elektron.*, **43** (3), 201 (2013) [*Quantum Electron.*, **43** (3), 201 (2013)].
12. Larionov M., Schuhmann K., Speiser J., Stolzenburg C., Giesen A., in: *Advanced Solid-State Photonics. Techn. Digest* (Vienna, Austria, 2005) TuB49.
13. Speiser J., Giesen A. *Proc. SPIE Int. Soc. Opt. Eng.*, **6871**, 68710J (2008).
14. Schulz M., Riedel R., Willner A., Düsterer S., Prandolini M.J., Feldhaus J., Faatz B., Rossbach J., Drescher M., Tavella F. *Opt. Express*, **20** (5), 5038 (2012).
15. Aleknavicius A., Gabalis M., Michailovas A., Girdauskas V. *Opt. Express*, **21** (12), 14530 (2013).
16. Creath K. *Prog. Optics*, **26**, 349 (1989).
17. Brown D.C., Vitali V.A. *IEEE J. Quantum Electron.*, **47** (1), 3 (2011).
18. Mende J., Schmid E., Speiser J., Spindler G., Giesen A. *Proc. SPIE Int. Soc. Opt. Eng.*, **7193**, 71931V (2009).