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Disk laser heads based on Yb:YAG for multikilowatt average power lasers

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Abstract. **The main factors affecting the cooling efficiency of Yb:YAG disk active elements have been investigated, and key technologies for designing disk lasers with high average power and efficiency have been developed. The main parameters of a disk active element operating in the cw regime are optimised using numerical calculation. Disk laser heads are fabricated based on calculations and developed technologies, and lasing with optical efficiency up to 50% is demonstrated. An average power at the kilowatt level is obtained in a cavity with two laser heads, and a possibility of its further increasing is demonstrated.**

Keywords: *disk laser, ytterbium-doped yttrium aluminum garnet, high average power.*

1. Introduction

The combination of high average power, high efficiency, and good beam quality makes disk lasers one of the most promising oscillators for high-power laser systems. To date, disk lasers with extremely high average power have been developed [1], including lasers with radiation of diffraction quality. However, the main limiting factors for further improvement of laser characteristics are, as previously, thermal effects [2], amplified spontaneous emission (ASE) [3], optical quality of the materials in use [4], and available technologies for cooling active elements (AEs). Despite the great success of Trumpf and Dausinger&Giesen in the development of disk lasers, many of these factors remain scarcely studied, which is a hindrance for further progress in this field.

In the presented work, we investigated the influence of heating of an ytterbium-doped yttrium aluminum garnet (Yb:YAG) AE, caused by the quantum defect, lattice absorption of the medium, and the presence of nonlinear sources [5]; determined the optimal doping level; and calculated the disk thickness necessary for balancing such parameters as gain, temperature, and number of pump beam passes through the AE. The influence of the disk AE mounting technology on the high thermal conductivity heat sink was also investigated. As a result, a high-power disk laser head was developed based on domestic elemental base, and its high efficiency at the kilowatt average power level was demonstrated.

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2. Optimisation of disk AE cooling

The standard scheme of a disk AE with a heat sink is presented in Fig. 1. Pump radiation (λ = 940 nm) and laser radiation (λ = 1030 nm) propagate from the same side of the disk and are reflected from its mirror surface, whereas cooling is performed from the other side through a mirror surface. The main advantages of disk AE geometry are heat removal in the beam propagation direction and the heat exchange through the AE mirror surface. This approach makes it possible to scale the laser power by increasing the aperture of the disk with its thickness retained; the latter, in turn, is an important parameter and can be varied to provide efficient heat removal from the entire AE volume, sufficiently high laser gain, and complete absorption of pump radiation [6]. At a specified doping level, the disk thickness must be increased to satisfy the two latter requirements; at the same time, it should be reduced to increase the cooling efficiency. Increasing the doping level of material, one reduce the AE thickness, thus satisfying all the aforementioned requirements.

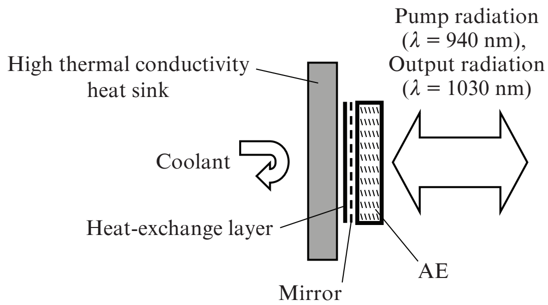

Figure 1. Schematic diagram of an Yb:YAG disk AE with a heat sink.

An increase in the doping level of Yb:YAG crystal is known to reduce its thermal conductivity [7, 8], which may be a limiting factor when choosing the optimal thickness. However, as was shown in [5,9], there is a more important factor limiting the doping level from above: additional nonlinear heat release, which manifests itself in heavily doped materials. The mechanism of this effect has not been reliably established. However, it was suggested in [10,11] that this heat release is caused by the occurrence of photoconductivity in the medium and the formation of the corresponding wide absorption band, which, as a consequence, leads to heating. This effect significantly increases the heat release power (in comparison with the heat release caused by the laser quantum defect) in the presence of inversion in the medium. It was shown in [4] that the additional heat release depends on the doping level and correlates with the factor of the heat release caused by a beam with λ = 1030 nm passing through the medium. This factor is defined as follows. A beam with a known wavelength and power is transmitted through the sample, and some part of absorbed radiation is converted into heat. The heat release factor is defined as the power of this radiation (thermal power) divided by the sample length and the beam power incident on the sample. The thermal power measurement is based on the known temperature field in the sample (recorded with a thermal camera), as well as the specific heat and thermal conductivity of the medium. The measurement procedure was described in detail in [4]. This technique was used to measure the heat release factor at λ = 1030 nm in Yb:YAG crystals with different doping levels. Note that the average luminescence wavelength in Yb:YAG is ~1010 nm; therefore, the absorption of radiation with λ = 1030 nm due to the quantum defect causes cooling of the medium in the absence of other heat sources. As follows from the measurement results (Fig. 2), the heat release factor may be negative at doping levels up to 7%, but it is always positive at higher doping levels. This means that the additional nonlinear heat release is insignificant (smaller than the heat release due to the quantum defect with λ = 940 nm) at a doping level no higher than 7%. Thus, the additional heat release imposes the main limitation on the doping level in an Yb:YAG disk AE: it should not exceed 7%.

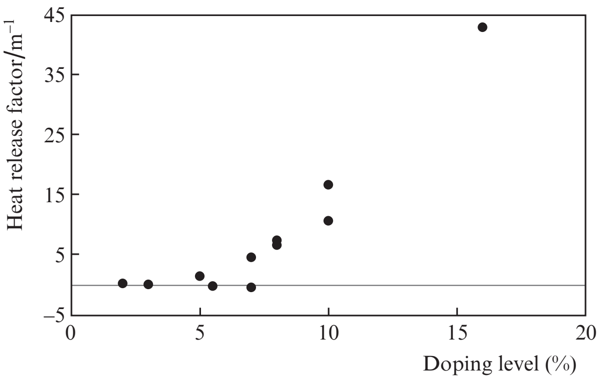

Figure 2. Dependence of the heat release factor at λ = 1030 nm on the doping level in Yb:YAG crystal.

We assume absorption to be efficient if no less than 95% pump radiation is absorbed in the AE. Then, with allowance for the doping level of 7%, the absorption cross section in the Yb:YAG crystal at λ = 940 nm, and the pump reflectance from the rear (mirror) disk surface, the distance passed by the pump beam in the active medium must be 2.5 mm. However, this thickness of disk element is too large [6] to provide efficient heat removal. Therefore, the pump radiation should be transmitted several times through the AE; this multipass geometry is implemented in most of disk lasers. The optimal disk AE thickness was calculated numerically [12, 13], simultaneously taking into account the AE heating, the amplification of radiation in it, the ASE effect, and the pump radiation absorption.

Figure 3 shows the results of numerical calculation of the maximum allowable average absorbed intensity of pump radiation (and its absorption efficiency) and the gain at λ = 1030 nm as functions of the disk thickness d. The calculation was performed on the assumption that the maximum surface temperature of the disk AE does not exceed 200 °C and that the heat exchange coefficient between the AE and thermally stabilised heat sink is 10 W K^{-1} cm^{-2}. It can be seen that the pump absorption efficiency increases with an increase in the disk thickness, and the necessary number of its reflections (V passes) from the AE mirror surface is reduced. However, an excessive increase in the disk thickness reduces the gain because of the decrease in the inversion density in the medium and narrows the dynamic range of allowable average absorbed pump radiation intensity, which leads, in particular, to a sharp decrease in the optical-to-optical laser efficiency (ratio of laser and pump radiation powers). A decrease in thickness d causes a significant increase in the allowable pump radiation intensity; however, it is accompanied by a large increase in the required number of V passes through the AE, which not always can be implemented technically. In addition, in the case of thin AE, the gain decreases because of the ASE effect [3]. One should also remember that thermally induced phase distortions of radiation increase with a rise in the disk thickness. Then one can state that the optimal disk AE thickness in the amplification mode is close to 0.4 mm. When an AE is used in a cw laser, the gain value is not so important as for the amplification mode, because the AE inversion density does not change after reaching the lasing threshold. In this case, the thickness d can be reduced to 0.2–0.3 mm in order to widen the range of allowable absorbed pump intensities and reduce the thermally induced distortions.

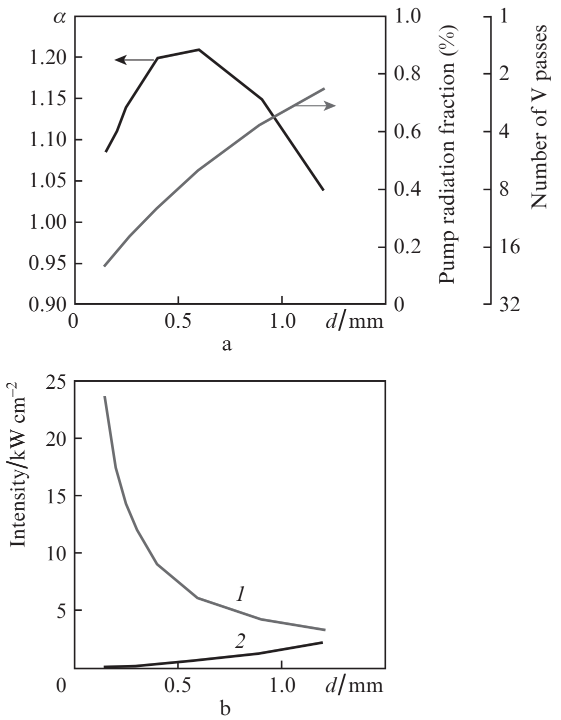

Figure 3. Dependences of several parameters on the disk AE thickness d: (a) the weak-signal gain α and fraction of pump radiation absorbed per reflection from the AE mirror surface (additional scale indicating the number of V passes of pump radiation that is necessary for its efficient (i.e., more than 95%) absorption) and (b) the maximum allowable average absorbed pump intensity (*1*) and threshold average absorbed radiation intensity (*2*) necessary for amplification.

Another important condition for disk laser operation is to mount the laser on a water-cooled high thermal conductivity heat sink with a minimum thermal resistance. We investigated the thermal contact between a disk AE and a polycrystalline diamond heat sink, which was implemented applying two different techniques: (i) crystal soldering [14] and (ii) a new method based on ultrathin gluing of disk AE with polished polycrystalline diamond surface using photopolymer glue VERFIX B665-0. The main drawback of soldering is the thermal effect, which leads to deformations of the thin disk element after cooling and, therefore, gives rise to additional beam phase distortions. In addition, soldering may cause spoilage, which manifests itself as inhomogeneous thermal resistance and leads to occurrence of superheated AE regions during disk laser head operation. The second method of thermal contact formation is based on the use of polymer glue for the heat-exchange layer. Its thermal conductivity is low in comparison with that of indium solder. However, due to the high-quality polishing of polycrystalline diamond heat sink and high glue fluidity, the glue layer can be made as thin as few tenths of micrometer. Thus, one can reduce its thermal resistance to a negligible value and provide good homogeneity of the contact with the controlled phase profile of disk AE mirror surface. Figure 4 shows dependences of the maximum surface temperature of disk AE for the contacts formed using either indium solder or an ultrathin polymer glue layer. Measurements were performed using an IR camera for identical 220-μm-thick disk AEs. It can be seen that the maximum surface temperatures of disk AE are the same for both mounting techniques throughout the entire measurement range.

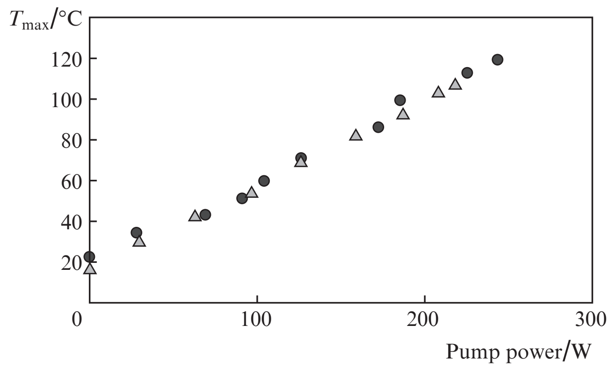

Figure 4. Dependences of the maximum surface temperature of disk AEs on the absorbed pump power when forming a thermal contact using (△) indium solder and (●) polymer glue.

3. Lasing

Based on the investigations and developments described in the previous section, we fabricated laser heads with Yb:YAG disk AEs having a doping level of 7%, thickness of 220 μm, and diameters ranging from 10 to 15 mm. The laser radiation losses on the antireflective and mirror surfaces were, respectively, 0.2% and less than 0.1%. To examine the lasing efficiency, we investigated AEs made of materials from different manufacturers. Up to 16 pump radiation passes were provided in disk laser heads; according to Fig. 2, this number of passes is sufficient for efficient pump absorption both in the presence and absence of lasing. Lasing was performed in a stable cavity [15] (Fig. 5a) with an output mirror having a transmittance $\tau = 10\%$ for $\lambda = 1030$ nm (the optimal τ value was preliminarily chosen in experiments). The curvature radius of the spherical

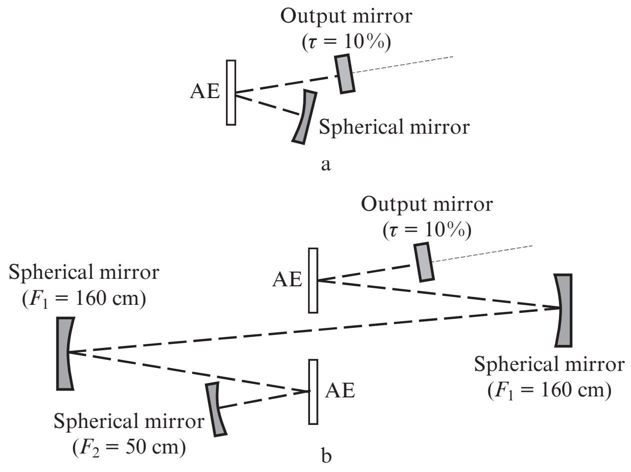

Figure 5. Schematics of a V-shaped cavity with (a) one and (b) two disk AEs.

mirror was 120 cm at a cavity length of 40 cm, which provided a diameter of 0.9 mm for the fundamental transverse mode on the AE, with a pump beam diameter of 5 mm. As a result, multimode lasing was observed. The experimental data are presented in Fig. 6. One can see that the lasing threshold and slope lasing efficiency are close for different disk elements. However, at a high pump power, there are distinctions related to the difference in the optical and laser qualities of the material in use. A radiation power of 600 W at a slope efficiency of 60% and optical efficiency of 50% was obtained for the best samples; this value is close to the best world results. The pump intensity was ~6 kW cm^{-2}. A further increase of both the output laser power and pump intensity in experiments was limited by the available pump power: 1250 W.

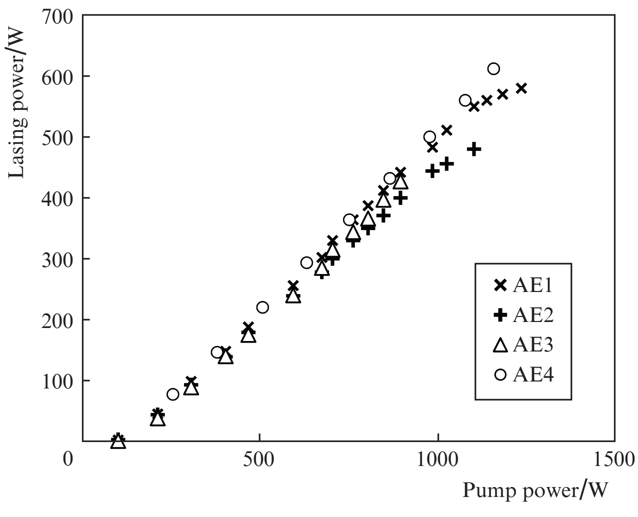

Figure 6. Dependences of the lasing power on the pump power in Yb:YAG disk elements from different manufacturers.

To increase the lasing power, we developed a laser cavity with two disk laser heads, each pumped by 1200-W radiation. The experiment was performed with samples AE1 and AE2 (Fig. 6). A schematic of the cavity is shown in Fig. 5b. The optimal transmittance of the output mirror was 10%. The spherical mirror had curvature radii F_1 = 160 cm and F_2 =

50 cm. At a cavity length of 358 cm, the fundamental mode diameter on the AE was 0.7 mm at a pump beam diameter of 5 mm. The AE surface temperature was additionally measured using an IR camera. The measurement results are presented in Fig. 7. A radiation power of 1 kW was obtained; the slope efficiency for this configuration was somewhat reduced (to 50%), which is explained by the more complex optical scheme of the cavity. Note also that the AE surface temperature ranged from 150 to 190 °C and did not limit lasing efficiency. These laser heads allow for further increase in the laser power by increasing the pump power, both with a beam diameter of 5 mm, used in our experiment, and at its scaling up to 10 mm. This approach will make it possible to obtain a lasing power of several kilowatts without any loss of efficiency.

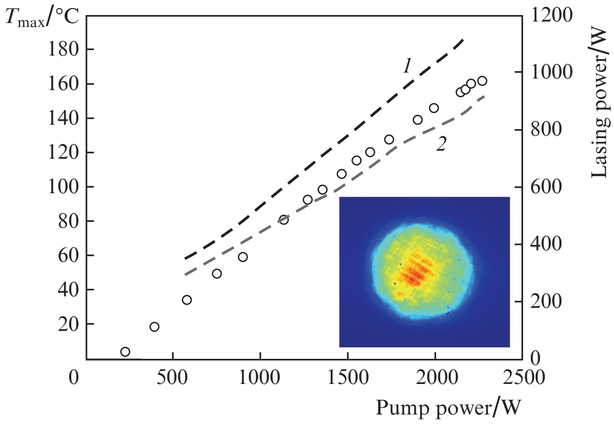

Figure 7. Dependences of the (○) lasing power in a cavity with two disk laser heads and the maximum surface temperatures of (*1*) AE1 and (*2*) AE2 on the total pump power. The inset shows a photograph of the output beam cross section at a lasing power of 800 W.

4. Conclusions

A disk laser head for implementing a lasing power of several kilowatts was developed and optimised, and a lasing power of ~1 kW at an optical efficiency of 50% was experimentally obtained. The slope lasing efficiency with one disk laser head amounted to 60% at an output laser power of 600 W. When designing a laser head, we investigated the effect of additional nonlinear heat release in heavily doped samples and developed a method for mounting disk AEs with the aid of an ultrathin photopolymer glue layer. The AE thickness and the number of pump radiation passes through the AE were optimised by joint numerical solution of the heat conduction equation and balance equations with allowance for the ASE effect. It was shown that the optimal doping level in the Yb:YAG crystal is ~7%. In this case, the AE thickness should be no more than 0.4 mm to provide efficient cooling of the AE bulk and no less than 0.2 mm to weaken the ASE effect and avoid excessive complication of the optical pumping scheme.

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