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Continuous-wave 80-W lasing in Yb : YAG ceramics

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Abstract. **We report on continuous-wave lasing at a wavelength of 1030 nm with a maximum power of 80 W and a slope efficiency of 26% in a thin disk element made of domestic ytterbium-doped yttrium–aluminium–garnet ceramics [$(Yb_{0.05}Y_{0.95})_3Al_5O_{12}$]. The studied ceramic sample was fabricated by solid-phase sintering of a mixture of $(Yb_{0.05}Y_{0.95})_2O_3$ and Al_2O_3 nanopowders synthesised by laser ablation. The measured laser characteristics in cw and repetitively pulsed regimes are presented.**

Keywords: *Yb : YAG ceramics, yttrium–aluminium garnet, laser oscillation.*

1. Introduction

Development of solid-state lasers with high average and peak powers is one of the promising directions of laser engineering. This is related to a wide application of these light sources in industry (welding, cutting, drilling, and processing of materials and 3D printing of complex objects) and for various scientific and medical purposes. The average power of these lasers is restricted, in particular, by thermal effects appearing in active laser elements due to Stokes losses, absorption of radiation by impurities or defects in the material, various nonlinear thermal effects, etc. Heat release in optical elements drastically affects the mode composition of radiation and lasing and amplification efficiency. To reduce the influence of thermal effects and achieve higher powers, one uses diode pumping at wavelengths corresponding to the active-ion absorption spectrum, active ions with low Stokes losses (low quantum defect), materials with optimal thermooptical and mechanical characteristics allowing one to minimise thermal effects with the other conditions being the same, and specific geometries and methods of cooling of the active element to decrease its average temperature.

One of the widely used methods to achieve laser radiation with a high average power is to use disk active elements based on ytterbium-doped yttrium or lutetium aluminates with garnet crystal structure [$Yb_{3x}Y(Lu)_{3-3x}Al_5O_{12}$ and Yb : Y(Lu)AG] [1, 2]. This is possible because these materials have good spectral, optical, and mechanical properties and are technologically simple and rather well studied. In addition, the Yb^{3+} ion has a three-level energy diagram and a low quantum defect, which leads to a relatively low heat release in the process of lasing, as well as rather large absorption and amplification cross sections and an emission spectrum sufficiently broad for generation of subpicosecond pulses. To date, a disk laser with 44 passes of pump radiation at $\lambda = 940$ nm has been developed based on one active element made of $Yb^{3+}:Y_3Al_5O_{12}$ single crystal, which emits high-quality radiation with an average power of ~10 kW and an efficiency exceeding 50% [1].

At the same time, special attention in recent years has been drawn to development of high-power solid-state lasers with ceramic active elements, which is explained by some advantages of ceramics over single crystals of the same composition. Ceramic active elements can have larger sizes, they are easily produced, have lower energy consumption and cost, and allow introduction of a higher concentration of active centres with a gradient distribution [3, 4]. In this connection, it should be mentioned that the authors of [5, 6] succeeded to achieve a higher than 5-kW output power of disk lasers based on $Yb^{3+}:Y_3Al_5O_{12}$ and $Yb^{3+}:Lu_3Al_5O_{12}$ ceramics.

In Russia, ceramic active elements of high optical quality are produced in several institutes, including V.A. Kotel'nikov Institute of Radioengineering and Electronics (Fryazino Branch), Russian Academy of Sciences (Fryazino) [7]; G.G. Devyatykh Institute of Chemistry of High-Purity Substances, Russian Academy of Sciences (Nizhny Novgorod) [8, 9]; A.M. Prokhorov General Physics Institute, Russian Academy of Sciences (Moscow) [10, 11]; and Institute of Electrophysics, Ural Branch, Russian Academy of Sciences (Ekaterinburg) [12, 13]. A specific feature of the present work, which continues studies of the laser characteristics of thin-disk Yb : YAG ceramics [13], consists mainly in the use of a diamond heat sink for more efficient cooling of the active medium, which allowed us to increase the output laser power by an order of magnitude due to an increase in the pump spot diameter.

2. Synthesis of the ceramic sample

The studied sample of Yb : YAG laser ceramics was made at the Institute of Electrophysics, Ural Branch, Russian Academy of Sciences (Ekaterinburg) by solid-phase sintering of nanopowders with additional annealing of the oxide mixture before compaction. Nanosized $Yb_{0.1}Y_{1.9}O_3$ and Al_2O_3 particles synthesised by laser ablation [14, 15] were used as initial materials. The obtained nanopowders were calcined in air at a temperature of 900–1200 °C for 3 h to transform the metastable structure of particles into the main cubic phase

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and achieve the exact stoichiometric ratio $Yb_{0.15}Y_{2.85}Al_5O_{12}$ upon weighing. The oxide nanopowders were mixed in ethanol with addition of 0.5 wt % of tetraethoxysilane as a sintering additive. The obtained mixture was dried using a rotary vacuum evaporator, calcined in air at a temperature of 1200 °C for 3 h to eliminate organic compounds and achieve partial phase transformation of the structure of particles into the garnet structure, and then compacted at a pressure of 200 MPa into a cylindrical sample with a diameter of 14 mm and a thickness of 3 – 4 mm. The compact was sintered at a temperature of 1780 °C for 20 h at a residual gas pressure of $\sim 10^{-3}$ Pa. After sintering, the ceramic sample was bleached by annealing in air at 1300 °C for 10 h and polished using diamond pastes with different grain sizes.

Figure 1 shows the transmission spectra of the synthesised Yb : YAG ceramic sample 2 mm thick, which were measured using a Shimadzu UV-1700 spectrophotometer immediately after sintering and after bleaching annealing. In the long-wavelength range (860 – 1070 nm), both spectra show identical structured absorption bands formed by Yb^{3+} ions. In the visible and UV region, the spectrum of unannealed ceramics shows three broad absorption bands at $\lambda = 640$, 385, and 280 nm caused by the presence of divalent ytterbium ions in the crystal lattice [16]. These bands completely disappear after the bleaching annealing of the sample in air, which simultaneously leads to the appearance of an additional band at $\lambda = 450$ nm and a bend at 340 nm, which are obviously caused by the presence of a small amount of Ce^{3+} ions [17]. The theoretical transmission curve for YAG (dot-and-dash curve) is calculated by known values of the refractive index. The transmittance of the synthesised ceramics after the bleaching annealing reaches 82.6% in the near-IR region, which is approximately 1 % lower than the theoretical value.

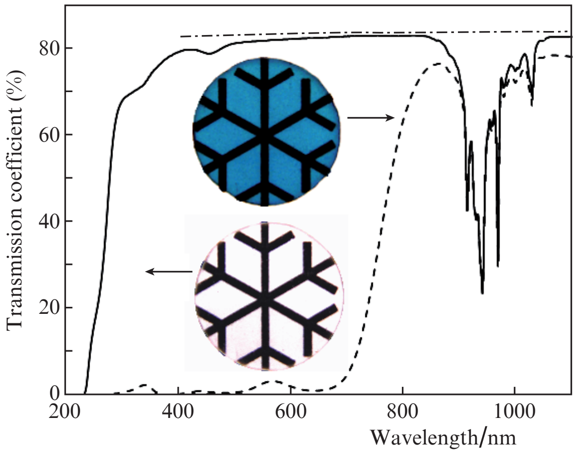

Figure 1. Transmission spectra and photographs of an Yb : YAG ceramic sample (top) before and (bottom) after bleaching annealing. The dot-and-dash curve corresponds to the YAG theoretical transmission.

3. Laser oscillation

To perform laser experiments and achieve disk laser operation, we decreased the ceramic sample thickness to 300 μm. The faces of the sample were coated with dielectric films [an antireflection coating on one face and a reflecting coating on the other face for the laser (1030 nm) and pump (940 nm) wavelengths]. The fabricated active element was mounted on a diamond heat sink placed in a water-cooled laser head [18]. The laser head was inserted in a laser cavity formed by the rear face of the active element and two dielectric mirrors, namely, a spherical mirror (radius of curvature 120 cm) with a reflectivity of ~100% at $\lambda = 1030$ nm and a plane output mirror. The reflectivity of the output mirror at $\lambda = 1030$ nm was 90%. A Laserline LDM 2000 fibre-coupled diode laser emitting at $\lambda = 940$ nm was used as a pump source. The scheme provided 10 V-shaped passes of pump radiation through the cavity. Lasing at $\lambda = 1030$ nm was obtained both in repetitively pulsed (pump pulse duration 3 ms, pulse repetition rate 10 Hz) and cw regimes with the pump spot diameters of 3.5 and 5 mm. The temperature of the active element in the region of the pump spot was recorded during lasing. As the temperature reached 120 °C, we stopped increasing the pump power to avoid detachment of the active element from the heat sink and its subsequent destruction. The active element temperature in the repetitively pulsed regime did not change in the entire pump power range. The experimental results are presented in Fig. 2.

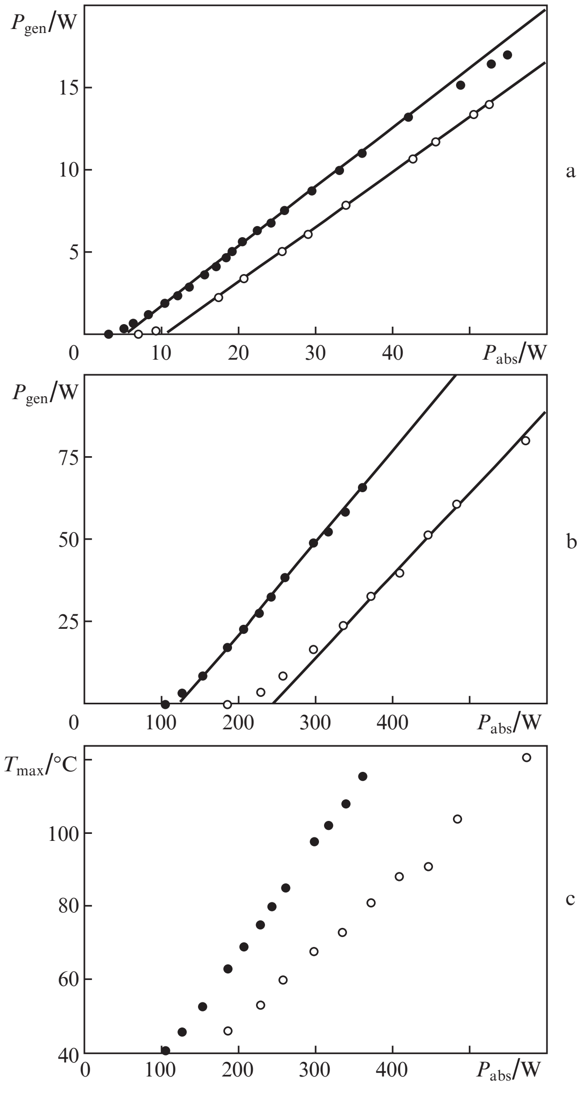

Figure 2. Dependences of the output laser power in (a) repetitively pulsed and (b) cw regimes, as well as (c) of the maximum active element temperature in the cw regime, on the average absorbed pump power at pump spot diameters of (•) 3.5 and (○) 5 mm.

The lasing slope efficiency in the repetitively pulsed regime, when the thermal effect can be neglected, was 36 and 33.5% for the pump spot diameters of 3.5 and 5 mm, respectively. In the cw regime, the slope efficiency was 28% and 26% and the maximum average powers reached 66 and 80 W, respectively. These powers are an order of magnitude higher than the powers obtained by us in [11]. This was achieved as a result of the 1.75–2.5-fold increase in the pump spot diameter, which did not cause degradation of the laser characteristics due to the ceramics homogeneity and the more efficient cooling of the active element owing to the use of diamond as a heat-sink material. Thus, the developed methods of fabrication of Yb : YAG ceramics and its mounting on a diamond heat sink make it possible to scale up the active elements of disk lasers and achieve higher output average powers, which is important for practical and scientific applications.

Thus, we have studied the laser characteristics of domestic Yb : YAG ceramics fabricated by solid-phase reactive sintering of nanopowders synthesised by laser ablation with additional calcination of the oxide mixture before compaction. The transmittance of the sample 2 mm thick reached 82.6% in the near-IR region, which is only 1% lower than the theoretical value. Continuous-wave lasing of domestic ceramics at a wavelength of 1030 nm with a power of 80 W and a slope efficiency of 26% has been demonstrated for the first time owing to the use of a diamond heat sink and an increase in the pump spot diameter to 5 mm.

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