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Efficient lasing in Yb:$(YLa)_2O_3$ ceramics

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Abstract. **A high-optical-quality sample of $Yb_{0.1}Y_{1.7}La_{0.2}O_3$ ceramics is prepared using a recently developed technique of self-propagating high-temperature synthesis of rare-earth-doped yttrium oxide nanopowder from acetate–nitrates of metals. Its optical and spectral characteristics are studied, and quasi-cw lasing at a wavelength of 1033 nm is achieved with a power of 7 W and a slope efficiency of 25%.**

Keywords: *laser ceramics, yttrium oxide, lanthanides, disk laser.*

1. Introduction

In recent years, the average powers of highly efficient solid-state lasers have become much higher. The materials used for active elements (AEs) of such systems must satisfy severe requirements since the heat generated in these elements due to a high average power leads to parasitic thermal effects (thermal lens and thermally induced birefringence) and, above some threshold, may destroy the AE. The thermal effects, in turn, decrease the laser beam quality and limit a further increase in the laser power.

For generation and amplification of short pulses, the luminescence spectrum of active ions in a material must be sufficiently broad, while the material itself (in order to reduce nonlinear effects) must be suitable for fabrication of large-aperture active elements with a high optical quality. As a result, the lasers based on such traditional crystaline media as YLF, YAG, etc., almost have reached the average power limit. Among promising materials for AEs of highly efficient lasers are rare-earth sesquioxides with cubic symmetry R_2O_3 (R = Sc, Y, Lu, etc.) doped with Yb^{3+} ions. The use of these ions, which have no absorption from the excited state, cross relaxation and concentration quenching, makes it possible, in the case of laser pumping, to decrease the heat generation due to the quantum defect by three times with respect to Nd^{3+} ions [1, 2]. The rare-earth sesquioxides are characterised by a high heat conductivity [3–6], as well as by better thermooptical properties responsible for thermal lens and thermally induced depolarisation [7, 8] and by a broader amplification spectrum [9, 10] than that of the widely used $Yb^{3+}:Y_3Al_5O_{12}$ (Yb:YAG) crystal. Lasers based on sesquioxides demonstrate both high-power cw radiation with a high slope efficiency (P = 670 W, $\eta_{\rm slope}$ = 80% for $Yb^{3+}:Sc_2O_3$ [11]; 264 W, 70% for $Yb^{3+}:Sc_2O_3$ [5]; and 70 W, 70% for $Yb^{3+}:Y_2O_3$ [12]) and short mode-locked pulses (P = 7 W at τ_p = 142 fs, 25 W at 185 fs [13], and 1.09 W at 71 fs [14] for $Yb^{3+}:Lu_2O_3$ [14]; 840 mW at 81 fs for $Yb^{3+}Sc_2O_3$ [14]; 7.4 W at 547 fs [12] and 540 mW at 68 fs [15] for $Yb^{3+}:Y_2O_3$). Note that the main results are achieved with the use of single-crystalline AEs, while high average and peak powers of ceramic AEs were achieved only in work [12].

To obtain radiation with high average and peak powers, it is promising to use disk laser technology [16]. Most of the above-mentioned results are obtained using disk geometry of AEs. In particular, 5.3 kW of average power with a good beam quality was extracted from one disk AE in [17].

An important circumstance is the possibility of scaling of AEs. Scaling of elements of sesquioxide single crystals runs into some problems related to their high melting temperatures and existence of phase transitions, which strongly affects the maximum possible size and optical quality of AEs. At the same time, modern technologies make it possible to fabricate elements from various materials, including sesquioxides, with apertures considerably exceeding the maximum possible apertures for single crystals and with the same high optical quality. Development of the fabrication technology of laser-quality ceramics from promising optical materials, as well as of the accompanying technology for designing disk lasers, is important for solving the problem of obtaining laser radiation with simultaneously high average and peak powers.

The aim of the present work is to demonstrate significant progress in the development of domestic laser-quality Y_2O_3 ceramics doped with Yb^{3+} ions. Using the self-propagating high-temperature synthesis (SHS) [18] with the previously found optimal parameters [19], researchers of the Institute of Chemistry of High-Purity Substances, Russian Academy of Sciences, prepared a ceramic sample. Its quality was experimentally studied and efficient lasing in the disk AE was obtained.

2. Active element fabrication

Powders for sintering $Yb_{0.1}Y_{1.7}La_{0.2}O_3$ ceramics were synthesised by the SHS method using acetate-nitrate metal complexes [19]. As initial materials, yttrium oxide (99.99%), lanthanum oxide (99.99%), ytterbium oxide (99.99%), nitric acid (99.9999%) and acetic acid (99.9999%) were used. The SHS method is optimal for synthesis of nanopowders because the initial components (acetic and nitric acids and water) can be

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easily purified by traditional methods and obtained nanopowders are weakly agglomerated (agglomerates disintegrate upon pressing) and do not require removal of additive agents (for example, the mother solution, as is required in precipitation methods). The powders were not additionally treated (milled or granulated). Although these procedures may improve compressibility of powders and increase the compact homogeneity, it is more important to retain the high purity of powders. Milling media, solvents, and plasticisers cause additional contamination and considerably decrease the sinterability of yttrium oxide nanopowders.

To make compacts, the powders were uniaxially pressed with a pressure of 500 MPa into disks 15 mm in diameter and 2 mm thick. Since the thickness-to-diameter ratio of the samples is much smaller than unity, the pressing conditions are close to isostatic, which allows one to obtain rather high density distribution homogeneity in compacts.

Sintering was performed in a vacuum furnace (SNVE 1.3.1) with tungsten heaters (residual pressure ~ 10^{-3} Pa) and a heat shield. At the first stage, the samples were heated with a rate of 10 K $\min^{-1}$ to 1850 °C. Then, the temperature for 5 min was decreased to 1800 °C and the samples were kept at this temperature for 2 h. After this, the temperature was decreased to room temperature with the same rate of 10 K $\min^{-1}$. This sintering regime ensures a higher quality of optical elements than sintering at a fixed temperature.

After sintering and treatment, the diameter and thickness of the sample were 11.5 and 0.7 mm, respectively; the obtained AE was polished from two sides. The transmission and scattering of the sample were measured by the method described in [19] using a collimated laser source (wavelength 1075 nm, power 10 mW) and an Ophir PD300 power meter. The laser beam propagated through the studied sample, and the passed signal power was measured immediately behind the sample (at a distance shorter than 5 mm) and at a distance of 5 m from it. The radiation power in the absence of the sample was measured at the same points. The transmission and scattering of the studied sample at $\lambda = 1075$ nm were estimated based on the experimental data. The transmission was 82.6%, which, within the experimental accuracy, coincides with the theoretical value for this material and corresponds to absorption losses lower than 0.01 cm^{-1}. The scattering was 1.8%, which corresponds to scattering losses of 0.26 cm^{-1}. For comparison, the scattering losses in the best of the samples in [19] were 4.78 cm^{-1}, i.e., higher by a factor of 18. To obtain lasing, the AE faces were coated by dichroic dielectric layers for wavelengths $\lambda_p = 940$ nm and $\lambda_{gen} = 1030$ nm. One face of the AE was coated by a reflecting layer, and the other face was antireflection coated.

3. Study of lasing properties

The optical scheme of the developed laser is shown in Fig. 1. A fibre-coupled Laserline LDM 2000 diode module emitting at $\lambda_p = 940$ nm was used as a pump source. Its radiation was focused on the studied sample by a spherical mirror (*3*) into a spot 2 mm in diameter and, after one V-pass through the sample, was deflected to a beam dump; the absorber pump power in one V-pass was about 50%. The disk element was mounted on a water-cooled copper heat sink using thermal grease and placed into a cavity formed by two mirrors [spherical mirror (*5*) with a curvature radius of 30 mm and a reflectivity of ~100% at $\lambda_{gen} = 1030$ nm and plane output mirror (*6*) with a reflectivity of 96% at the same wavelength] and the specular back surface of the AE. The length of one cavity shoulder was 40 mm.

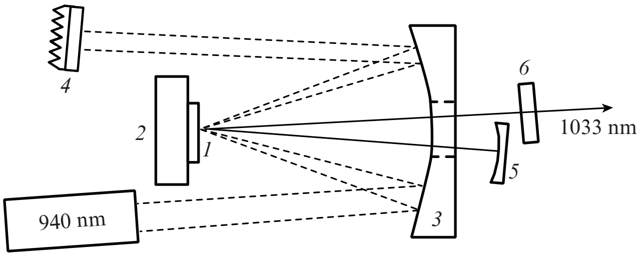

Figure 1. Laser scheme: (*1*) laser ceramic sample; (*2*) copper heat sink; (*3*) spherical mirror (R = 100% at $\lambda_p = 940$ nm); (*4*) dump; (*5*) spherical mirror (R = 100% at $\lambda_{gen} = 1030$ nm); (*6*) plane output mirror (R = 96% at $\lambda_{gen} = 1030$ nm).

In a quasi-cw regime under pumping by 3-ms pulses with a repetition rate of 32 ms, at the exit of the cavity we observed free-running radiation, whose power was measured with an Ophir 10A power meter. The luminescence spectrum in the absence of lasing was measured on a SOLAR TII S150-2 spectrometer. The fibre input of the spectrometer was positioned to the side of the pumped AE region at a distance of 2–3 mm. The luminescence spectrum is shown in Fig. 2a by the solid curve. Also, we measured the spectrum of laser radiation (Fig. 2a, dashed line), which was attenuated and directed to the fibre input of the spectrometer. The dependence of the

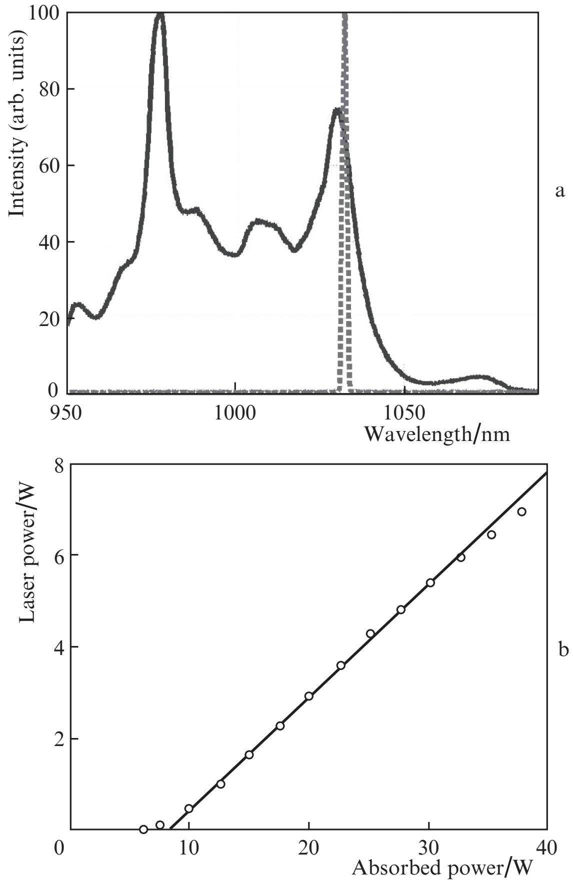

Figure 2. (a) Luminescence (solid curve) and lasing (dashed curve) spectra, as well as (b) dependence of the laser power on the absorbed pump power.

laser power on the absorbed pump power is shown in Fig. 2b. Lasing with the maximum at a wavelength of 1033 nm appeared when the absorbed pump power exceeded a threshold of 6.1 W. The slope efficiency was 25%. At an absorbed pump power of 39 W, the laser power in the quasi-cw regime was 7 W. Note that the output power almost did not change as the pump beam scanned the AE aperture, which testifies to a high homogeneity of the AE.

Measurements at higher pump powers were not performed because of a strong heating of the AE due to both its non-optimal geometry and inefficient cooling scheme. The demonstrated efficiency of the laser is limited not only by the crystal quality but also by the non-optimal cavity scheme. In particular, the output mirror transmission was not optimised.

In the future, we plan to optimise the AE thickness, use a multipass pump scheme, place the AE into a pump cavity designed for a disk AE [20] and obtain efficient cw lasing in $Yb_{0.1}Y_{1.7}La_{0.2}O_3$ ceramics.

4. Conclusions

The optimisation of SHS regimes, of the concentration of lanthanum oxide as a sintering additive, and of pressing and sintering conditions allowed us to develop a method of synthesis of $Yb_{0.1}Y_{1.7}La_{0.2}O_3$ ceramics with high optical quality and decreased optical scattering losses. The scattering losses were decreased from 4.78 [19] to 0.26 cm^{-1}, which testifies to a considerably better quality of the synthesised ceramics. At an absorbed pump power of 39 W at a wavelength of 940 nm, quasi-cw lasing at a wavelength of 1033 nm was obtained with a power of 7 W and a slope efficiency of 25%.

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