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Spectral and lasing characteristics of 1 % Ho : YAG ceramics under intracavity pumping

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Abstract. **High-transparency 1 % Ho : YAG ceramics with the transmission coefficient of 82 % in the IR range at the sample thickness of 1 mm are synthesised from a mixture of the Ho : Y_2O_3 and Al_2O_3 nanopowders obtained by the laser method. Results of investigations of spectral and lasing characteristics of 1 % Ho : YAG ceramics under intracavity pumping by radiation of a 5 % Tm : KLuW disk element are presented. Based on spectral intensity analysis of generation in the 1.8 – 2.1 μm range and on cavity parameters, the estimated lasing slope efficiency for 1 % Ho : YAG ceramics is about 40 %.**

Keywords: *ceramic lasers, thin disks, diode pumping, two-micron spectral range.*

1. Introduction

Two-micron lasers are of particular interest for a series of applications including remote sensing of atmosphere [1, 2], ranging [3], environment monitoring [4, 5] and pumping of optical parametric converters [6 – 8]. Employment of highly transparent laser ceramics as active elements substantially broadens possibilities of such laser systems first of all due to a higher specific energy extraction and enhanced generation efficiency [9, 10]. In [11 – 13], lasing characteristics of Ho : YAG ceramics have been studied under pumping to the absorption maximum at a wavelength of 1.907 μm. The laser output power of 20 W and the slope efficiency of above 60 % have been obtained, which is very close to similar parameters for single-crystal active elements [8, 14]. In the present work, the results of experimental study of spectral and lasing characteristics of 1 % Ho : YAG ceramics under intracavity pumping are presented for the first time. Using the obtained results, the slope efficiency of ceramic sample under study was estimated.

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2. Experiment

2.1. Fabrication of ceramics

Coarse commercial powders Ho_2O_3, Y_2O_3 and Al_2O_3 with the purity of at least 99.99% were chosen for producing laser targets of two compositions (Ho^{3+} : Y_2O_3 and Al_2O_3) with their following evaporation by radiation of a CO_2 laser. Nanoparticles with an average size of 15 nm were produced by vapour condensation in air flow. The technology of laser synthesis of oxide nanopowders is more thoroughly described in [15].

Then, nanopowders of Ho^{3+} : Y_2O_3 and Al_2O_3 oxides were mixed in a proportion (Ho + Y) : Al = 3 : 5 for 48 h with zirconium oxide balls in ethanol. At the mixing stage, tetraethylorthosilicate (TEOS) was used as a sintering additive in the quantity of 0.5 mass percent. The mass ratio of nanopowder, balls and ethanol was 1 : 4 : 8, respectively. Then, the mixture was subjected to evaporation in a vacuum rotational evaporator and was annealed in air at a temperature of 600 °C for 3 h to remove organic impurities. Agglomeration of nanopowders was not observed.

The dry annealed mixture of nanopowders was used to form pellets with a relative density of 20 % with the following annealing in an atmosphere oven at a temperature of 1200 °C for 3 h. Then, the pellets were milled by balls made of zirconium oxide for 48 h, dried and annealed.

Compaction of the obtained powder into disks with a diameter of 15 mm and a thickness of 2 – 4 mm was performed by the method of dry uniaxial static pressing at a pressure of 200 MPa. The density of 1 % Ho : YAG was 2.18 g cm^{-3}, which corresponded to the relative density of 47.9 %. Then, the compacts were sintered in a vacuum furnace at a temperature of 1780 °C for 20 h. After that the ceramic samples were subjected to air annealing in order to partially remove mechanical stresses and fill the oxygen vacancies. At a final stage the samples were mechanically polished.

This technology has been previously used to produce laser Nd : YAG ceramics and has been thoroughly discussed in Refs [16, 17].

2.2. Study of lasing properties of ceramics

A photograph of the sintered 1 % Ho : YAG ceramics after atmospheric annealing and polishing is shown in Fig. 1. By using an optical OLYMPUS BX51TRF-5 microscope we have estimated the average grain sizes and the volume fraction of scattering centres which were 14 μm and 30 ppm, respectively.

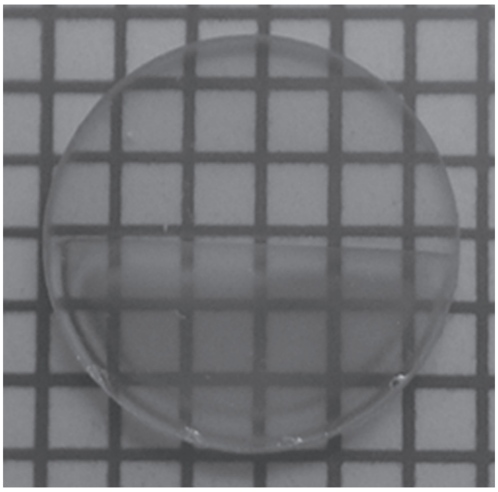

Figure 1. Photograph of 1% Ho : YAG ceramics with a partial antireflection coating.

Lasing characteristics were studied in sample No. 1083 of 1% Ho : YAG ceramics with the size of ∅11 × 1 mm; the corresponding transmission spectrum is shown in Fig. 2. Since the optical density of the sample is relatively low even at maximal absorption (the absorption at a wavelength of 1907 nm is about 15%), the sample was pumped by the intracavity scheme shown in the inset in Fig. 2. The cavity was formed by a highly reflecting mirror on a surface of a 250-μm-thick crystal of double potassium–lutetium tungstate 5% Tm : KLuW [18] and a partially transmitting mirror ($T_{\text{out}} = 0.6\%$ in the range 1.85–2.1 μm) deposited on the external surface of the ceramics. All optical surfaces inside the cavity had antireflection coatings in the spectral range of 1.85–2.1 μm (with the residual losses on each surface of at most 0.1% in the range 1.85 μm and ~0.5% in the range 2.1 μm). The lens made of fused KI silica with a focal length of 18 mm was placed at equal distances from the ceramics and disk element, and the physical cavity length was 50 mm. The active disk element (5% Tm : KLuW) was pumped by collimated radiation from two arrays of laser diodes (at a wavelength $\lambda_{\text{p}} = 806$ nm) as in [19]; the diameter of the pump beam was 0.95 mm. For reducing thermal fluxes all measurements were performed in a quasi-cw regime with the duty factor of 14%, the duration of current pulses of diode pumping was 7 ms at a pulse repetition rate of 50 ms. The absorbed power of diode pumping was always determined as the difference between passed and incident powers, and the optical powers of light beams (pumping, generation) were detected by an Ophir L30A power meter. Lasing spectra were measured with an MDR-24 monochromator, FR-185 photoresistor and selective Unipan-233 nanovoltmeter employed as a pre-amplifier; the spectral resolution was ~0.5 nm.

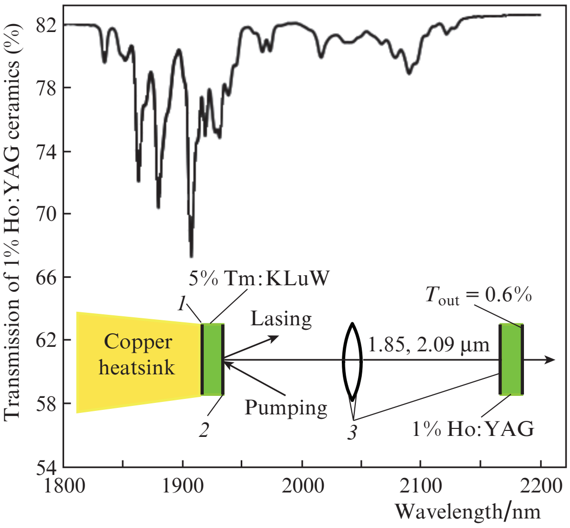

Figure 2. Transmission spectrum of the sample of optical 1% Ho : YAG ceramics with a thickness of 1.0 mm. The inset shows the schematic diagram of the experiment: (*1*) highly reflecting dichroic mirror with the reflection coefficient $R > 99.9\%$ in the range 1.85–2.1 μm and at $\lambda = 0.8$ μm; (*2*, *3*) antireflection coatings in the region specified.

3. Results and discussion

The dependence of the average output power of the laser on the average absorbed pump power for the cavity geometry described above is shown in Fig. 3. Curve (*1*) was obtained for the optical 1% Ho : YAG ceramics with dielectric coatings and characterises the radiation power with wavelengths of 1.85 and 2.09 μm. Curve (*4*) corresponds to the radiation power with $\lambda = 1.85$ μm (obtained by using a plane dielectric mirror with the transmittance of 0.6% instead of the ceramics). Curves (*2*) and (*3*) correspond to the powers at these wavelengths obtained by recalculating the relative intensities of the lasing spectra according to data from Fig. 4.

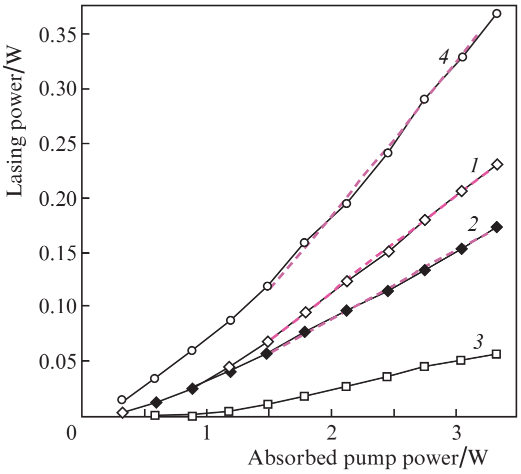

Figure 3. Output lasing power vs. absorbed pump power: (*1*) for the optical 1% Ho : YAG ceramics and radiation with $\lambda = 1.85$ and 2.09 μm; (*2*) and (*3*) for the same ceramics and radiation with $\lambda = 1.85$ and 2.09 μm, respectively, recalculated from curve (*1*) taking into account relative spectral intensities (see Fig. 4); (*4*) for the dielectric plane mirror (instead of the ceramics) with the transmission $T_{\text{out}} = 0.6\%$ at 1.85 μm. Dashed curves in (*1*), (*2*) and (*4*) are linear approximations of the corresponding dependences for calculating the slope efficiency η_{exp}.

Starting with a certain threshold pump power (~1 W according to Figs 3 and 4), there are two light fields excited simultaneously in the cavity, which correspond to the $^3F_4 \rightarrow {}^3H_6$ transition of Tm^{3+} ions in the KLuW matrix and the $^5I_7 \rightarrow {}^5I_8$ transition of Ho^{3+} ions in the YAG matrix. At a wavelength of 1.85 μm the absorption of 1% Ho : YAG ceramics

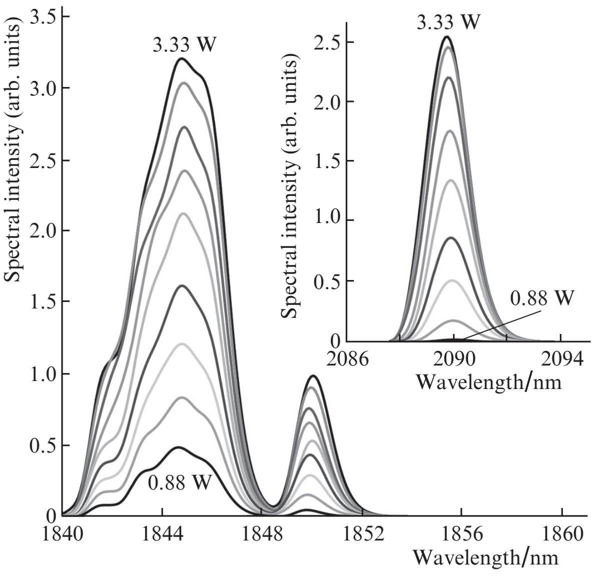

Figure 4. Spectral intensities of lasing at the absorbed pump power of 0.88, 1.19, 1.49, 1.79, 2.13, 2.45, 2.75, 3.05 and 3.33 W.

(in two passes) is 3.0% in the regime of unsaturated absorption, and in the regime of lasing taking into account inversion ~20% [14] (see Figs 3, 4) the absorption is $T_{\rm abs} = 2.4\%$. Thus, the total losses in the cavity with 1% Ho:YAG ceramics are $T_{\rm tot} = T_{\rm abs} + T_{\rm out} + T_{\rm loss}$, where $T_{\rm loss}$ are parasitic losses inside the cavity (per single pass) to absorption and scattering reduced to the wavelength 1.85 μm. If the ceramics is substituted for the outcoupling mirror with the transmission $T_{\rm out}$, then absorption is absent, i.e., $T_{\rm abs} = 0$. According to general relations [20], the slope efficiency $\eta_{\rm exp}$ determined experimentally can be written in the form

$$\eta_{\rm exp} = \eta T_{\rm out}/(T_{\rm abs} + T_{\rm out} + T_{\rm loss}), \tag{1}$$

where η is the 'limiting' lasing slope efficiency for the ideal lossless cavity. By applying (1) to dependences (*4*) and (*2*) in Fig. 3 one obtains the relation

$$(0.6\% + T_{\rm loss})/(3.0\% + T_{\rm loss}) = 6.2\%/14.0\% = 0.44 \tag{2}$$

(here, 14.0% and 6.2% correspond to the lasing slope efficiencies for these dependences, respectively). Hence, relations (1) and (2) give a possibility to estimate the parameter $T_{\rm loss}$ which is ~1.2% at $\eta = 45\%$; this is in good agreement with results from [21, 22]. The estimate $T_{\rm loss} \approx 1.2\%$ also seems reasonable taking into account a large number of optical surfaces inside the cavity. According to these estimates, the light power absorbed by ceramics is five times greater than the output lasing power corresponding to curve (*2*) in Fig. 3.

On the other hand, the total losses at a wavelength of 2.09 μm on antireflection coatings are approximately 3% [from our estimates $T_{\rm loss}(2.09) = 3.0\% \pm 1\%$], i.e., the intracavity losses are almost five times greater than the transmission coefficient of the outcoupling mirror $T_{\rm out}(2.09) = 0.6\%$. Thus, by comparing curves (*2*) and (*3*) with (1) taken into account one can estimate the 'limiting' lasing slope efficiency for 1% Ho:YAG ceramics on the $^5I_7 \rightarrow {}^5I_8$ transition under intracavity pumping with respect to the absorbed power at a wavelength of 1.85 μm: $\eta = 40\% \pm 10\%$. This value is approximately twice the similar parameter for Ho:YAG crystals [8, 14], which may be related with possible structural microscopic defects in ceramics.

Note that in some papers, the lasing parameters of holmium crystals were studied under intracavity pumping by radiation of thulium lasers; in that case the lasing slope efficiency (with respect to the absorbed power of diode pumping) was from 20% [23] to ~40% [24]. In the present work for the 1% Ho:YAG ceramic sample under investigation this parameter was 2.6% [curve (*3*) in Fig. 3], which is explained, first of all, by the fact that intracavity losses are substantially higher than the transmission of the outcoupling mirror. Hence, for further enhancing the efficiency and output power of lasing, the cavity parameters should still be optimised.

4. Conclusions

In the present work, lasing characteristics of 1% Ho:YAG ceramics have been studied under intracavity pumping by the radiation of the 5% Tm:KLuW disk element at a wavelength of 1.85 μm. We have shown that the lasing slope efficiency at a wavelength of 2.09 μm relative to the pump power at λ = 1.85 μm is 40% ± 10%. The lasing efficiency and intracavity losses have been estimated. The suggested design of the cavity can be successfully used for producing multi-colour radiation sources in the two-micron spectral range.

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