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Two-micron lasing in diode-pumped $Tm:Y_2O_3$ ceramics

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Abstract. **The results of investigation of the spectral, luminescent and lasing properties of $Tm:Y_2O_3$ ceramics are presented. Lasing in Y_2O_3 ceramics is obtained at wavelengths of 1.95 and 2.05 μm. The maximum output laser power at these wavelengths was 2.4 and 0.3 W, respectively.**

Keywords: *laser ceramics, $Tm:Y_2O_3$, diode pumping, two-micron laser radiation.*

1. Introduction

Two-micron laser radiation is of interest for biomedical applications, monitoring of some gases (CO, CO_2, NH_3, CH_4) and scientific research. Lasing in the spectral range 1.9–2.0 μm was obtained under diode pumping in various Tm^{3+}-doped active media ($Y_3Al_5O_{12}$, $YLiF_4$, $YAlO_3$, YVO_4) [1, 2]. The same media doped with Ho^{3+} ions allowed one to achieve laser radiation near 2.1 μm. To pump holmium lasers, one uses lasers with a wavelength of about 1.9 μm, while media with thulium ions can be efficiently pumped by widespread diode arrays emitting in the region of 0.8 μm.

The latter circumstance has raised interest in studying the laser properties of Tm^{3+}-doped Y_2O_3, Lu_2O_3 and Sc_2O_3 sesquioxide crystals and laser ceramics [3], because the luminescence spectrum of these materials for the $^3F_4 \rightarrow {}^3H_6$ transition of Tm^{3+} ions is shifted to longer wavelengths in comparison with other laser media and the lasers based on Tm^{3+}-doped sesquioxides can emit in the region of 2.1 μm under pumping by diode lasers with a wavelength of ~0.8 μm. For example, a diode-pumped solid-state laser based on $Tm:Sc_2O_3$ operates at the wavelength $\lambda = 2116$ nm with an output power of 26 W. In addition, it was shown that the wavelength of this laser can be tuned from 1975 to 2168 nm [4].

One more important advantage of Y_2O_3, Lu_2O_3 and Sc_2O_3 sesquioxides is their thermomechanical characteristics, which are better than those of $Y_3Al_5O_{12}$ (YAG) crystal [5]. However, the complicated growth of sesquioxide crystals of satisfactory optical quality with required sizes restricts the development of commercially available lasers based on these crystals. Therefore, extensive studies are currently focused on producing laser ceramics based on sesquioxides doped with rare-earth ions. In particular, the authors of [6] studied the spectral, luminescent and laser properties of $Tm:Lu_2O_3$ ceramics and obtained cw lasing at a wavelength of 2066 nm with an output power of 26 W.

It should be noted that the laser properties of $Tm:Y_2O_3$ crystals and ceramics are insufficiently studied to date. Quasi-cw operation of a laser based on $Tm:Y_2O_3$ crystal with an output power of 290 mW was achieved in [7] under pumping by a $Ti:Al_2O_3$ laser. In [8], it was shown that the $Tm:Y_2O_3$ crystal can emit laser radiation within a range of 1930–2090 nm. The maximum output laser power at a wavelength of 1.95 μm was 87 mW at a slope efficiency of 16%. The laser properties of a planar waveguide based on $Tm:Y_2O_3$ are described in [9]. The laser wavelength was about 1.95 μm, and the output power did not exceed 35 mW. In work [10], it was shown that, using $Tm:Y_2O_3$ crystals of good optical quality, it is possible to convert the radiation of a $Ti:Al_2O_3$ laser into two-micron laser radiation with a power up to 100 mW with a slope efficiency of 49%.

Concerning $Tm:Y_2O_3$ ceramics, there exists a paper devoted to studying only its spectroscopic characteristics [11]. We do not know publications on the laser characteristics of $Tm:Y_2O_3$ ceramics. In the present work, we present the results of investigations of the spectral, luminescent and lasing properties of diode-pumped $Tm:Y_2O_3$ (1.7 at % Tm^{3+}) ceramics.

2. Experimental samples and methods

The samples of $Tm:Y_2O_3$ (1.7 at % Tm^{3+}) in the form of pellets ∅8×1.7 mm in size (Fig. 1) were synthesised by solid-phase reaction sintering in vacuum at the V.A. Kotel'nikov Institute of Radio Engineering and Electronics, Fryazino Branch.

The absorption spectra were recorded by a PerkinElmer Lambda 950 double-beam spectrophotometer. We used a

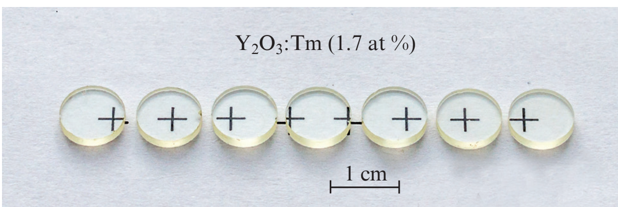

Figure 1. Photograph of $Tm:Y_2O_3$ (C_{Tm} = 1.7 at %) ceramic samples.

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halogen lamp as a radiation source and a PbS photoresistor as a detector of IR emission. Luminescence was recorded using a Horiba FHR 1000 spectrophotometer and excited by a laser diode with a wavelength of 808 nm and a power of about 2 W. The lifetime of the upper laser level $^3F_4$ of Tm^{3+} ions was estimated by luminescence decay curves. The $Tm:Y_2O_3$ ceramic samples for laser experiments were cut in the form of rectangular parallelepipeds with dimensions of 1.5× 1.5×5 mm; their faces were antireflection coated for a wavelength of ~2 μm. The active elements were wrapped in indium foil and clamped in a copper holder.

For thermal stabilisation of active elements, we used a water-cooled Peltier element; the temperature was kept constant at 18 °C. The active elements were pumped by a Dilas Compact diode laser system (LD) with a wavelength of about 809 nm and a maximum output power of 60 W. Two-micron laser radiation was detected using a PDA20H Thorlabs PbSe photoresistor and a Tektronix TDS 2022C oscilloscope. The pump radiation was cut off by a dielectric mirror with a corresponding spectral dependence of the transmission coefficient. The laser power was measured by an 11PMK-30H-H5 (Standa) thermoelectric power meter, while the laser spectra were recorded by a Horiba FHR1000 spectrophotometer.

3. Spectral and luminescent characteristics of $Tm:Y_2O_3$ ceramics

The absorption spectrum of $Tm:Y_2O_3$ ceramic samples is shown in Fig. 2. The existence of a smooth decline of the transmission curve in the range 400–800 nm indicates that the samples contain submicron pores. Nevertheless, as is seen from Fig. 2, the ceramics transmission in the near IR region exceeds 70%, and the optical quality, at least in this region, can be considered as satisfactory because the wavelength considerably exceeds the size of pores and the scattering from pores makes no significant contribution to the losses.

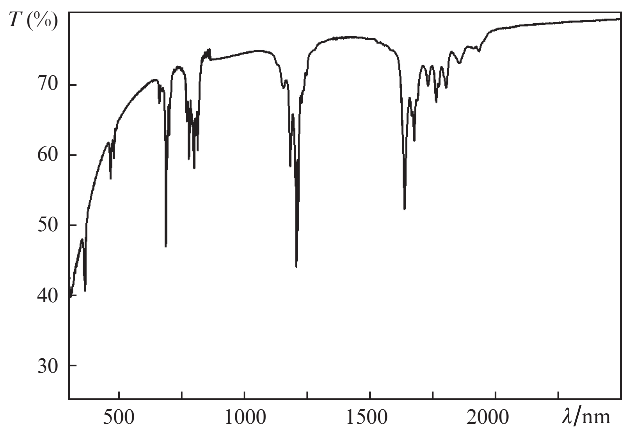

Figure 2. Panoramic transmission spectrum of $Tm:Y_2O_3$ (C_{Tm} = 1.7 at %) ceramics.

Figure 3 shows the spectral dependence of the absorption coefficient of $Tm:Y_2O_3$ ceramics at the $^3H_6 \rightarrow ^3F_4$ transition; the pump wavelength (809 nm) is indicated by an arrow.

The spectral dependence of the stimulated $^3F_4 \rightarrow ^3H_6$ transition cross section was plotted using the luminescence spectrum of this transition in Y_2O_3 ceramics and the Fuchtbauer–Ladenburg formula

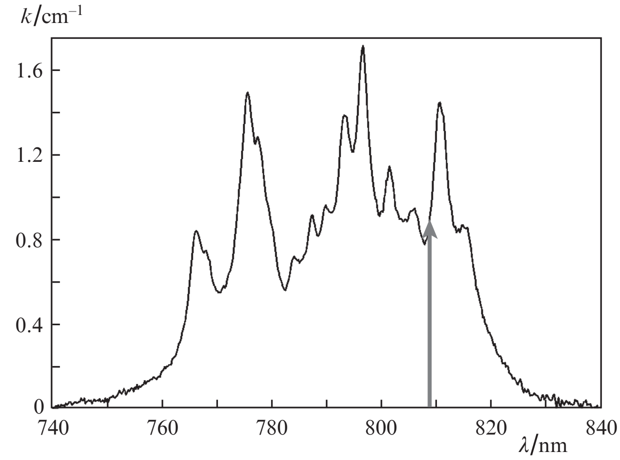

Figure 3. Spectral dependence of the absorption coefficient of $Tm:Y_2O_3$ (C_{Tm} = 1.7 at %) ceramics at the $^3H_6 \rightarrow ^3F_4$ transition of Tm^{3+} ions.

$$\sigma_{em}(\lambda) = \frac{\lambda^5 I(\lambda)}{8\pi c \tau_r n^2 \int I(\lambda)\lambda d\lambda} \quad (1)$$

where τ_r is the radiative lifetime of the excited level, n is the refractive index of the material, λ is the transition wavelength, and I is the luminescence intensity in relative units.

The radiative lifetime of the $^3F_4$ level of Tm ions in Y_2O_3 ceramics was determined from the luminescence decay time to be τ_r = 4.5 ms. In our opinion, this value is probably overestimated due to reabsorption, because of which, to determine the dependence $\sigma_{em}(\lambda)$ by formula (1), we used τ_r = 3.5 ms estimated by the Kravets formula (see [12]).

The spectral dependences of Tm^{3+} absorption ($^3H_6 \rightarrow ^3F_4$) and luminescence ($^3F_4 \rightarrow ^3H_6$) cross sections are presented in Fig. 4. Knowing the dependences $\sigma_{em}(\lambda)$ and $\sigma_{abs}(\lambda)$, one can determine the spectral dependence of the gain cross section of the active medium at this laser transition and find that lasing in $Tm:Y_2O_3$ ceramics can be achieved in the range 1900–2100 nm.

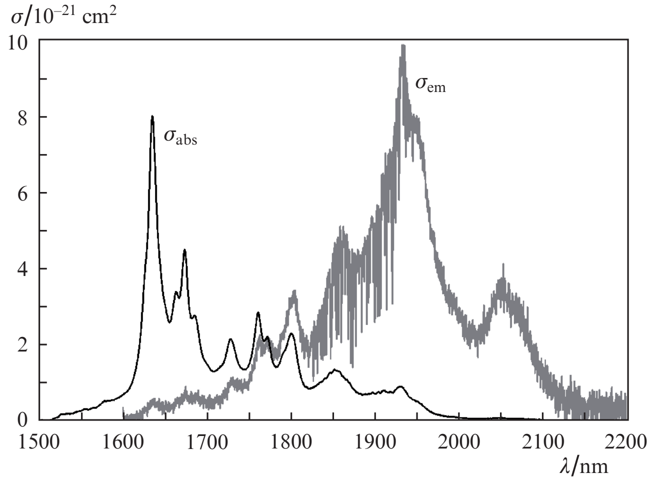

Figure 4. Spectral dependences of the cross sections of the absorption and luminescence $^3F_4 \rightarrow ^3H_6$ transition of Tm^{3+} ions in Y_2O_3 ceramics.

4. Laser experiment

In the experiment, the pump radiation was focused in the active element into a spot with a diameter of 400 μm using a four-lens objective. The active element absorbed 53% of pump power per pass. To achieve lasing at the wavelength λ = 1.95 μm (Fig. 5a), the laser cavity was formed by spherical mirror (*1*) with a curvature radius of 300 mm and plane mirror (*2*) with the transmission coefficient T = 7% at the laser wavelength.

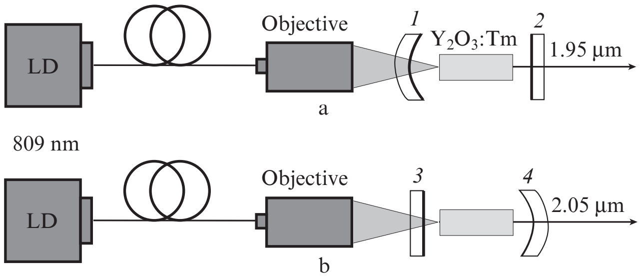

Figure 5. Optical scheme of a Tm : Y_2O_3 ceramic laser emitting at a wavelength of (a) 1.95 and (b) 2.05 μm.

The emission spectrum at the $^3F_4 \rightarrow {}^3H_6$ transition of Tm^{3+} ions in the Tm : Y_2O_3 ceramics is presented in Fig. 6. The maximum output laser power at a wavelength of 1.95 μm was 2.4 W.

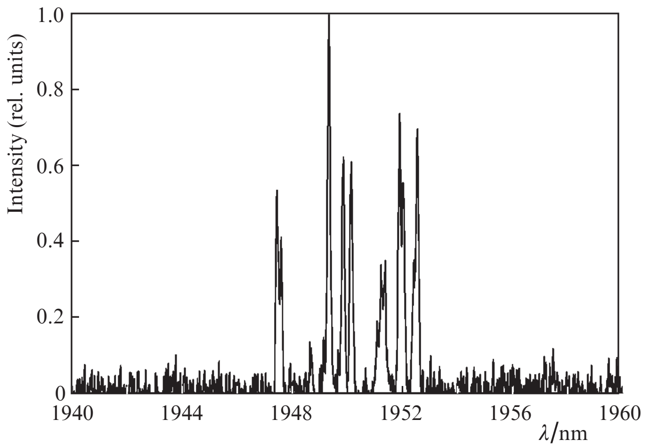

Figure 6. Spectrum of a Tm : Y_2O_3 ceramic laser operating at a wavelength of 1.95 μm.

The dependence of the output laser power at 1.95 μm on the power absorbed in the active element is shown in Fig. 7. The threshold absorbed pump power was 3 W at the slope efficiency η = 11%.

To achieve laser radiation at a longer wavelength, we used a spectrally selective cavity (see Fig. 5b). The plain mirror (3) of the cavity had a high (R > 99%) reflection coefficient in the spectral range 1.9–2.1 μm (T < 0.5 %), while the spherical mirror (*4*) with a curvature radius of 150 mm had a transmittance T exceeding 30% at the wavelength λ = 1.95 μm and about 3% in the wavelength range λ = 2.0–2.1 μm. Thus, the laser spectrum presented in Fig. 8 was determined by the spectral dependences of the stimulated emission gain in the active element and by the transmission of the output cavity mirror.

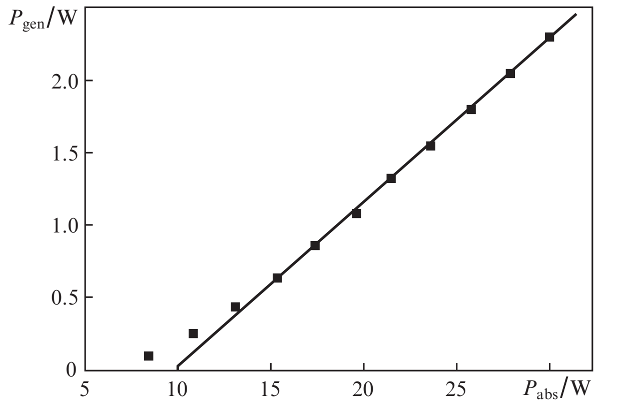

Figure 7. Dependence of the output power of a Tm : Y_2O_3 ceramic laser at a wavelength of 1.95 μm on the absorbed pump power.

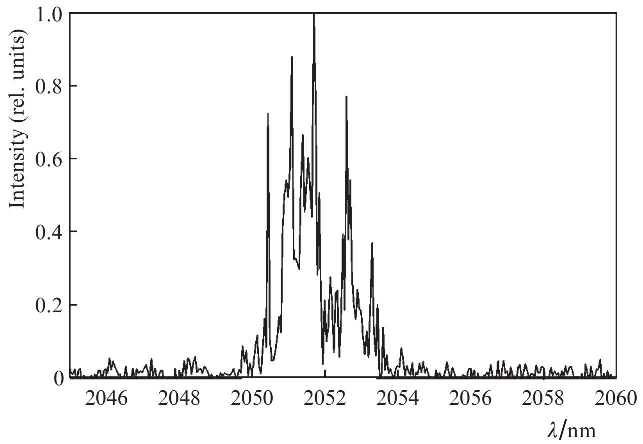

Figure 8. Spectrum of a Tm : Y_2O_3 laser operating at a wavelength of 2.05 μm.

The maximum output power (300 mW) was achieved at the minimum cavity length (15 mm). Figure 9 presents the dependence of the output laser power at λ = 2.05 μm on the absorbed pump power.

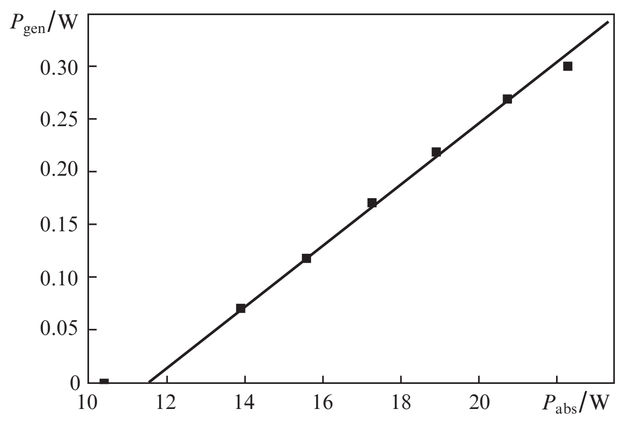

Figure 9. Dependence of the output power of a Tm : Y_2O_3 ceramic laser at a wavelength of 2.05 μm on the absorbed pump power.

5. Conclusions

Thus, as a result of our studies of $Tm:Y_2O_3$ (1.7 at %) ceramics, we obtained two-micron lasing at the $^3F_4 \rightarrow {}^3H_6$ transition of Tm^{3+} ions under semiconductor laser pumping with a maximum output power of 2.4 W at a wavelength of 1.85 μm and 300 mW at a wavelength of 2.05 μm. We believe that improvement of the optical quality of $Tm:Y_2O_3$ ceramics used as an active medium of the laser, as well as optimisation of the dopant concentration, will allow one to achieve higher output laser powers and slope efficiencies.

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References

1. Walsh B.M. *Laser Phys*., **19**, 855 (2009).
2. Ohta K., Obara M. *J. Appl. Phys*., **73**, 3149 (1995).
3. Scholle K., Lamrini S., Koopmann Ph., et al. *Frontiers in Guided Wave Optics and Optoelectronics* (Croatia: Intech, 2010) p. 471.
4. Koopmann P., Lamrini S., Scholle K., et al. *Advanced Solid-State Photonics. OSA Technical Digest Series* (Washington, 2011) paper ATuA5.
5. Jasbinder S., Kim W., Villalobos G., et al. *Ceram. Laser Mater*., **5**, 258 (2012).
6. Antipov O.L., Novikov A.A., Zakharov N.G., Zinoviev A.P. *Opt. Mater. Express*, **2**, 183 (2012).
7. Diening A., Dicks B.-M., Heumann E., et. al. *Advanced Solid-State Lasers*, **10**, 194 (1997).
8. Fornasiero L., Berner N., Dicks B.-M., et. al. *Advanced Solid-State Lasers*, **26**, 450 (1999).
9. Szela J.W., Sloyan K.A., Parsonage T.L., et. al. *Opt. Express*, **21**, 12460 (2013).
10. Ermeneux F.S., Sun Y., Cone R.L. *Advanced Solid-State Lasers*, **26**, 497 (1999).
11. Qing Yi, Taiju Tsuboi, Shengming Zhou. *Chin. Opt. Lett*., **10**, 091602-1 (2012).
12. El'yashevich M.A. *Atomnaya i molekulyarnaya spektroskopiya* (Atomic and Molecular Spectroscopy) (Moscow: Gos. izd. fiz.-mat. lit., 1962).