Quantum Electronics **50** (8) 727–729 (2020)

https://doi.org/10.1070/QEL17349

Lasing characteristics of $ZrO_2-Y_2O_3-Ho_2O_3$ crystals pumped by a $Tm:LiYF_4$ laser

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Abstract. **Two-micron lasing is obtained on the $^5I_7 \rightarrow {}^5I_8$ transition of Ho^{3+} ions in $ZrO_2-Y_2O_3-Ho_2O_3$ crystals upon resonance pumping into the $^5I_7$ level of these ions by a pulsed laser based on a $Tm:LiYF_4$ crystal. The efficiency of conversion of pump radiation incident on the crystal to laser radiation and the slope lasing efficiency at a pulse duration of 8 ms and a pulse repetition rate of 10 Hz were 25% and 28%, respectively.**

Keywords: *thulium laser, two-micron spectral region, $ZrO_2-Y_2O_3-Ho_2O_3$ crystal.*

1. Introduction

Significant interest in the development of two-micron solid-state lasers is explained by their wide application in medical devices, lidars, devices for monitoring various gases, and as pump sources for lasers emitting in the range of 4–5 μm. Today, there exist a large number of works on two-micron lasers based on Tm^{3+}- and Ho^{3+}-doped crystals and ceramics operating in different regimes [1–15].

In [13–15], we reported about obtaining two-micron laser radiation at the $^5I_7 \rightarrow {}^5I_8$ transition of Ho^{3+} ions in $ZrO_2-Y_2O_3-Ho_2O_3$ crystals upon pumping into the $^5I_7$ level of these ions by a cw $Tm:LiYF_4$ laser [13, 14] and a thulium fibre laser [15].

The crystal-field (Stark) splitting of manifolds of rare-earth (RE) ions in RE-doped $ZrO_2-Y_2O_3-R_2O_3$ (R is a rare-earth ion) crystals, sesquioxides, and ceramics (Y_2O_3, Lu_2O_3, Sc_2O_3) is larger than in other oxide materials (for example, in $Y_3Al_5O_{12}$) [14]. In particular, the luminescence range of the $^5I_7 \rightarrow {}^3I_8$ transition of Ho^{3+} ions in $ZrO_2-Y_2O_3-Ho_2O_3$ crystals is 1800–2300 nm, which allowed us to obtain lasing at the longest wavelength among crystalline media doped with Ho^{3+} ions and to achieve wavelength tuning in the range 2056–2168 nm [14]. In [15], using a cw thulium fibre laser as a pump source, we obtained *Q*-switched two-micron lasing in $ZrO_2-Y_2O_3-Ho_2O_3$ crystals with pulse durations of 140 and 310 ns at pulse repetition rates of 1 and 10 kHz, respectively.

It should be noted that the low thermal conductivity of stabilised zirconia crystals restricts their application as active elements of high-power solid-state lasers. The instantaneous laser power can be increased by using pulsed pumping, which makes it possible to considerably decrease the thermal load on the crystal. Therefore, it is of interest to study the lasing characteristics of $ZrO_2-Y_2O_3-Ho_2O_3$ crystals upon resonance pumping into the $^5I_7$ level of Ho^{3+} ions by a pulsed solid-state laser based on the $Tm:LiYF_4$ crystal.

2. Results

The studied $ZrO_2-Y_2O_3$(13.6 mol%)$-Ho_2O_3$(0.4 mol%) crystals (hereafter, Ho:YSZ) were grown by direct high-frequency heating in a cold container in a Kristall-407 crystal-growth furnace (crucible diameter 130 mm, crucible lowering rate 10 mm h^{-1}). The lasing experiments were performed on active elements cut from the grown crystals in the form of rectangular parallelepipeds with a size of 3 × 3 × 18 mm.

The optical scheme of the pulsed Ho:YSZ laser is presented in Fig. 1. The Ho:YSZ active element was pumped by a pulsed $Tm:LiYF_4$ laser, which, in turn, was pumped by pulses of high-power laser diode arrays. The $Tm:LiYF_4$ pump laser operated at wavelength λ_p 1910 nm, while its pulse duration was varied in the course of experiments, namely, it was 2, 4, 6, and 8 ms at a pulse repetition rate of 10 Hz. These durations were chosen because it was interesting to study the energy characteristics of pulsed lasing at pump pulse durations smaller or comparable with the lifetime of the $^5I_7$ level of Ho^{3+} ions, which was determined in [13] to be 14.7 ms. The maximum pump pulse duration (8 ms) was chosen to avoid breakdown of the $Tm:LiYF_4$ laser active element.

Figure 2 shows the spectral dependences of the absorption and stimulated emission cross sections ($^5I_8 \rightarrow {}^5I_7$ and $^5I_7 \rightarrow {}^5I_8$

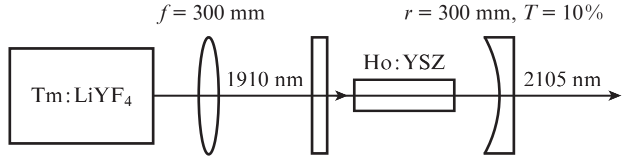

Figure 1. Optical scheme of a laser based on a Ho:YSZ crystal pumped by a pulsed $Tm:LiYF_4$ laser.

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Received 14 April 2020
Kvantovaya Elektronika **50** (8) 727–729 (2020)
Translated by M.N. Basieva

transitions, respectively) of Ho^{3+} ions in Ho : YSZ crystals, which were plotted from the experimental absorption and luminescence spectra of these transitions in our previous works [13, 14]. One can see from the absorption spectrum of this crystal (transition $^5I_8 \rightarrow {}^5I_7$ of Ho^{3+}) that the wavelength 1910 nm is optimal for pumping.

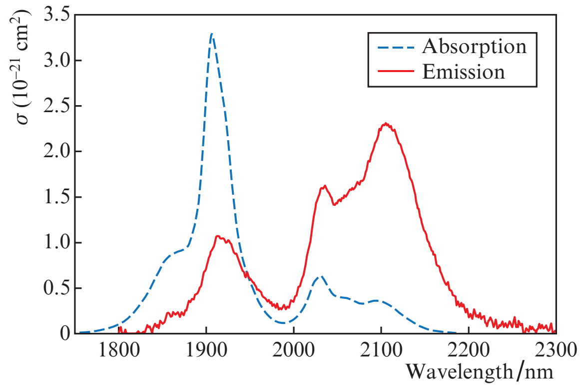

Figure 2. Spectral dependences of the absorption and stimulated emission cross sections ($^5I_8 \rightarrow {}^5I_7$ and $^5I_7 \rightarrow {}^5I_8$ transitions, respectively) of Ho^{3+} ions in Ho : YSZ crystals at T = 300 K [13, 14]].

The faces of the Ho : YSZ active element were not antireflection coated, because of which the active element was inclined at a small angle with respect to the pump beam to prevent its reflection back to the pump laser. For efficient heat removal, the active element was wrapped into indium foil and mounted in a copper holder, whose temperature during the experiment was T = 13 °C. The beam of the pulsed Tm : $LiYF_4$ pump laser was focused into the active element by a lens with the focal length f = 300 mm. The pump beam waist diameter in the active element was d = 0.6 mm.

The laser cavity was formed by a plane input mirror and a spherical output mirror. The plane input mirror had a high transmission coefficient at the pump wavelength HT = 98 % (λ_p = 1910 nm) and a high reflection coefficient at the lasing wavelength HR = 99.9 % (λ_g = 2105 nm). The radius of curvature of the spherical output mirror was r = 300 mm. The output mirror transmission T_m at λ_g was 10 %, and the reflection coefficient R at λ_p was 90 %, which ensures a double pass of pump radiation through the Ho : YSZ active laser crystal. The Ho : YSZ laser characteristics were measured using a dichroic mirror with T_m = 98 % at λ_g and R = 99.9 % at λ_p to cut off the pump radiation.

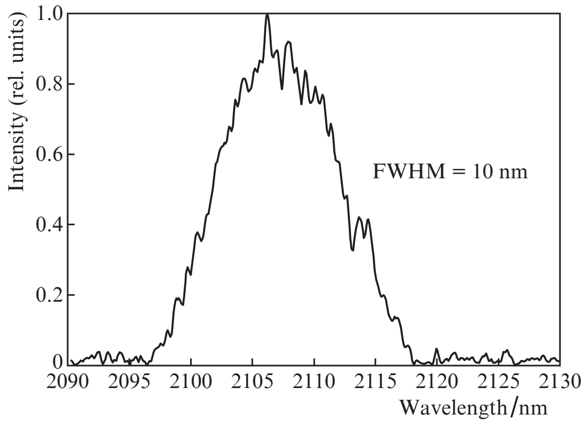

Figure 3. Ho : YSZ laser spectrum.

In the course of experiments, we achieved pulsed lasing in a Ho : YSZ crystal pumped by a Tm : $LiYF_4$ laser with pulse durations of 2, 4, 6, and 8 ms and a pulse repetition rate of 10 Hz. The laser wavelength was 2107 nm at the spectral width at half maximum $\Delta\lambda$ = 10 nm (Fig. 3).

Figure 4 shows the pulses of the Ho : YSZ laser and the Tm : $LiYF_4$ pump laser recorded using an SIP-100-250M-TO39-NG photodetector (Vigo System). One can see that radiation of both lasers has a typical spike structure.

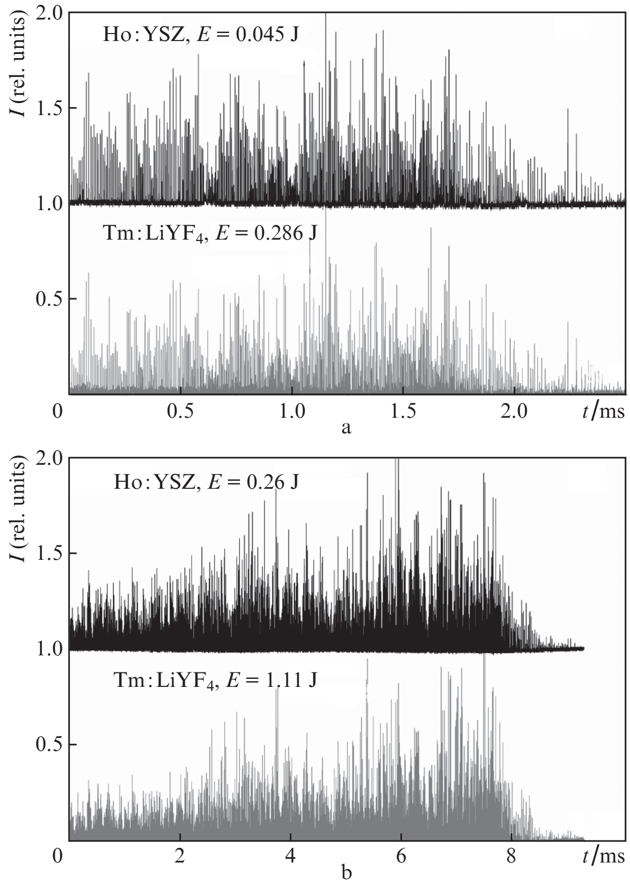

Figure 4. Pulses of Ho : YSZ and Tm : $LiYF_4$ lasers at pump pulse durations of (a) 2 and (b) 8 ms and a pulse repetition rate of 10 Hz.

The energy of the Ho : YSZ and Tm : $LiYF_4$ laser pulses was measured using a PE50BBDIF-C pyroelectric energy meter (Ophir). The dependences of the Ho : YSZ laser energy on the energy of the Tm : $LiYF_4$ pump laser at pump pulse durations τ_p = 2 and 8 ms are shown in Fig. 5.

The efficiency of conversion of the pump pulse energy incident on the crystal to the laser pulse energy at a pulse duration of 8 ms and a repetition rate of 10 Hz was η_0 = 25 % with a slope efficiency η_d = 28 %. The corresponding values at a pulse duration of 2 ms and the same repetition rate were 16 % and 22 %. At pump and lasing pulse durations of 4 and 6 ms, the slope efficiency was 24 % and 25 %, respectively. An increase in the Ho : YSZ laser efficiency with increasing the pump pulse duration is, in our opinion, caused by the follow-

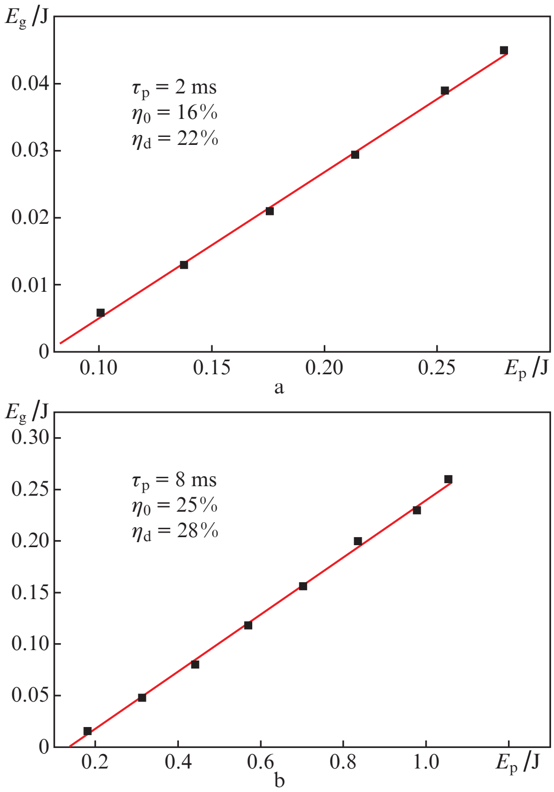

Figure 5. Dependences of the Ho : YSZ laser energy E_g on the pulsed Tm : $LiYF_4$ pump laser energy E_p at pulse durations of (a) 2 and (b) 8 ms and a pulse repetition rate of 10 Hz.

ing. First, there exists a delay of the laser pulse from the pump pulse, during which the inverse population in the active medium forms. Second, the average laser pulse power reaches a maximum for a time depending on the pump rate and the lifetime of Ho^{3+} ions at the upper laser level. Thus, the contribution of the laser pulse part with a lower average power to the total laser pulse energy is larger for short pulses, which leads to the observed dependence. Note that we did not consider the thermal lens effect because it is insignificant at the used pump laser parameters.

It is necessary to note that the presented energy dependences for the studied pump pulse durations and energies at the chosen pulse repetition rate were linear, which indicates the possibility of increasing both the pulse energy and the repetition rate by increasing the corresponding parameters of the pump laser. At pump energies E_p = 0.28 and 1.11 J and pulse durations τ_p = 2 and 8 ms (pulse repetition rate 10 Hz in both cases), the laser energy was 0.045 and 0.26 J, respectively.

Thus, in the present work we studied pulsed operation of a laser based on the crystal $ZrO_2–Y_2O_3$ (13.6 mol%)–Ho_2O_3 (0.4 mol%). At resonance pumping into the $^5I_7$ level of Ho^{3+} ions by a pulsed Tm : $LiYF_4$ laser, lasing at the $^5I_7 \rightarrow {}^5I_8$ transition was obtained with a wavelength λ_g = 2107 nm and pulse durations of 2, 4, 6, and 8 ms at a pulse repetition rate of 10 Hz. The maximum energy of 8-ms pulses at a repetition rate of 10 Hz was 0.26 J at a pump energy E_p = 1.11 J. The efficiency of conversion of the pump energy incident on the crystals into the laser radiation and the slope efficiency at a pulse duration of 8 ms and a pulse repetition rate of 10 Hz were 25% and 28%, respectively.

Acknowledgements. This work was supported by the Russian Foundation for Basic Research (Grant No. 18-29-20039).

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