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Diode-pumped Tm : Sc_2SiO_5 laser ($\lambda = 1.98$ μm)

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***Abstract*.** **Lasing at a wavelength of 1.98 μm is obtained for the first time in a diode-pumped ($\lambda = 792$ μm) active element made of a Tm^{3+} : Sc_2SiO_5 crystal grown by the Czochralski method. The laser slope efficiency reached 18.7 % at the output power up to 520 mW.**

***Keywords*:** *Tm^{3+} : Sc_2SiO_5 crystal, lasing, diode pumping.*

1. Introduction

The diode-pumped lasers based on Tm-containing crystalline active elements are characterised by a high average power of the output radiation in the wavelength region of ~ 2 μm at a high (40 % – 50 %) laser efficiency [1]. Crystals for laser elements must, first of all, have a high cross section of the induced transition in Tm ions and a good thermal conductivity. Since the lasing scheme is quasi-three-level, it is desirable to have a large splitting of the ground-state laser level. These lasers are most often based on YAG, YAP, and YLF crystals. At present, the search for new efficient crystalline matrices for Tm lasers has been continued.

As early as in 1961, Toropov and Vasil'eva studied for the first time the phase diagram of the $SC_2O_3 - SiO_2$ system and proposed the biaxial Sc_2SiO_5 (SSO) crystal as a matrix for active elements [2]. In this system, they observed two crystalline phases, Sc_2SiO_5 and $Sc_2Si_2O_7$ with melting temperatures of 1950 and 1850 °C, respectively. Paper [2] also presents the physical characteristics of the Sc_2SiO_5 crystal (density 3.49 g cm^{-3} and refractive indices $n_g = 1.850$ and $n_p = 1.835$).

Results on the growth of rare-earth orthosilicates were published two decades later [3]. The authors of [3] measured the melting temperatures of the Sc_2SiO_5 crystal (1930 °C) and its refractive indices ($n_g = 1.870$, $n_m = 1.838$, $n_p = 1.835$). The main problems in the growth of 60 – 80-mm-long Ln_2SiO crystals 20 mm in diameter by the Czochralski method from a cylindrical iridium crucible ⌀5 × 5 cm in size were described in [4].

The authors of [5] have grown a Tm : Sc_2SiO_5 (Tm : SSO) crystal with a Tm^{3+} concentration of ~ 4 %, which belongs to the group of oxide crystals with a monoclinic structure, and studied the specific features of the crystallographic structure of this crystal, its spectral characteristics, and the ground-state splitting, which reached ~ 691 cm^{-1}. Based on these studies and taking into account the relatively high thermal conductivity (7.5 W m^{-1} K^{-1}), it was suggested that the Tm : SSO crystal is promising for obtaining efficient 2-μm lasing under diode pumping at $\lambda = 791$ nm.

2. Experimental

We grew Tm : SSO crystals (60 mm long with the cross section 10 × 14 mm) by the Czochralski method from an iridium crucible ⌀4 × 4 cm. As a seed, we used an iridium wire 1 mm in diameter. The growth rate was 2 mm h^{-1}, the rotation rate was 20 rev min^{-1}, the process occurred in nitrogen atmosphere with 0.5 vol % of oxygen. To minimise the content of oxygen vacancies in the crystal lattice, the boule was annealed in air at a temperature of 1200 °C for 10 h. The concentration of Tm^{3+} ions was ~ 5 at % in the melt and about 3.6 at % in the upper part of the crystal boule.

In experiments, we used laser elements in the form of a cube with 3-mm edges and uncoated plane-parallel faces. The optical axis of the laser coincided with the crystallographic orientation $\langle -714 \rangle$ of the active element.

Lasing in a lamp-pumped Nd^{3+} : SSO crystal was previously obtained in [6]. The spectral properties of these crystals under lamp pumping were studied in [7].

In the present work, we obtained and studied for the first time lasing in a Tm : SSO crystal diode-pumped at a wavelength of 792 nm. The absorption spectrum of the crystal is shown in Fig. 1. The measurements were performed using a Shimadzu UV-3600 spectrophotometer. It should be noted that the spectrum measured by us significantly differs from the spectrum published in [5], in which the absorption coefficient was observed to considerably increase with shortening the wavelength in the range of 1000 – 300 nm. This additional absorption, which was assumed to be caused by colour centres contained in the crystal, was absent in our case, which points to a better optical quality of our crystals.

The active element was pumped at a wavelength corresponding to the absorption line of the $^3H_4 - {}^3H_6$ laser transition. As a pump source, we used a fibre-coupled diode laser emitting unpolarised radiation at a wavelength of 792 nm. The fibre core diameter was 116 μm; the pump spot diameter in the active element was varied from 70 to 140 μm with the use of interchangeable objectives.

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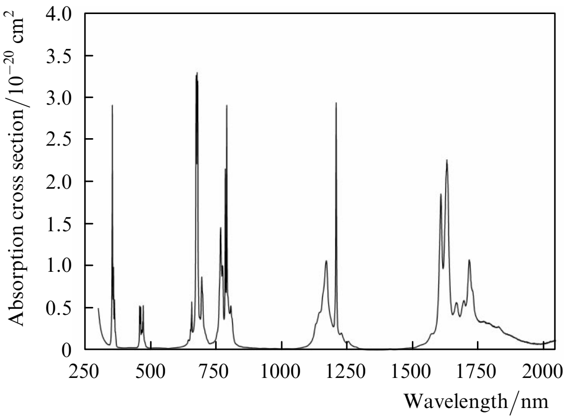

Figure 1. Absorption spectrum of the Tm : SSO crystal (Tm concentration 4 at %, $T = 300$ K).

Figure 2 shows the luminescence spectrum of the crystal and the wavelength dependences of the crystal absorption coefficient and of the output mirror transmittance. Lasing occurs in the region bounded by a rectangle. The position of this region is determined by the joint effect of all the three curves, the effect of the output mirror in our case being dominant.

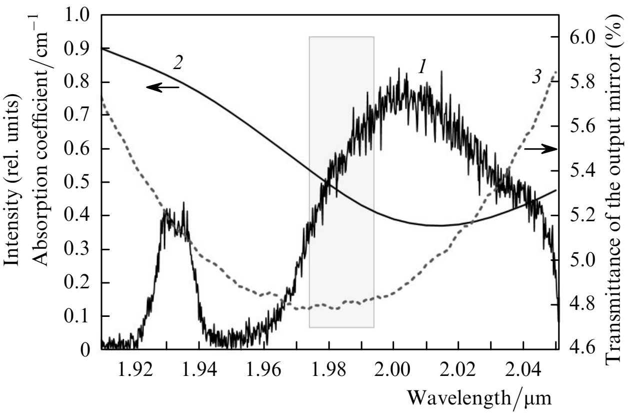

Figure 2. Luminescence spectrum of the crystal in the region of 2 μm (*1*), absorption cross section of the crystal (*2*), and transmittance of the output mirror (*3*). The rectangle encloses the wavelength region of lasing.

The active element was mounted via the side faces in a copper heatsink, whose temperature was kept at 10 or 20 °C, and placed into a cavity formed by a plane dichroic input mirror with 100 %-reflectance (through which pump radiation was coupled into the cavity) and a partly transparent concave spherical output mirror with the radius of curvature of 50 mm. In the experiments, the length of the cavity (~ 50 mm) was varied near its stability limit to match the pump spot diameter with the cross section of the fundamental cavity mode.

Lasing was obtained at a wavelength close to 1.98 μm. The laser radiation spectra at different pump powers are shown in Fig. 3. The measurements were performed using an MDR-204 monochromator. With increasing the pump power, the width of the laser spectrum, which consisted of one – two bands, increased from 20 to 30 nm. Note that the laser emission spectrum has a relatively large width and a rather flat peak, which distinguishes it from the emission spectra of other thulium lasers, for example, a Tm : YAG laser [8]. This specific feature of the Tm : SSO laser emission points to the possibility of obtaining mode-locked laser pulses shorter than the pulses of other two-micron thulium lasers.

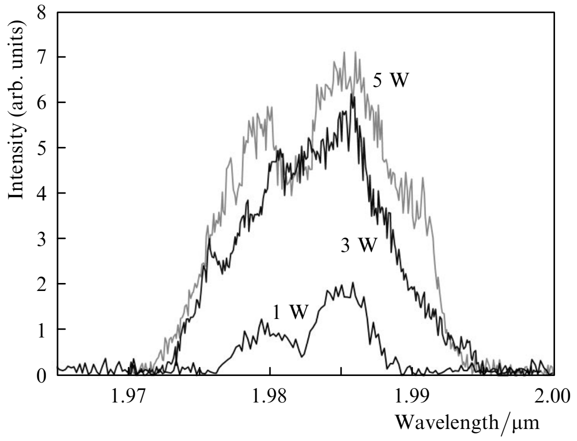

Figure 3. Spectra of laser radiation at different pump powers.

The results of our investigations of the laser power under different excitation conditions are shown in Fig. 4.

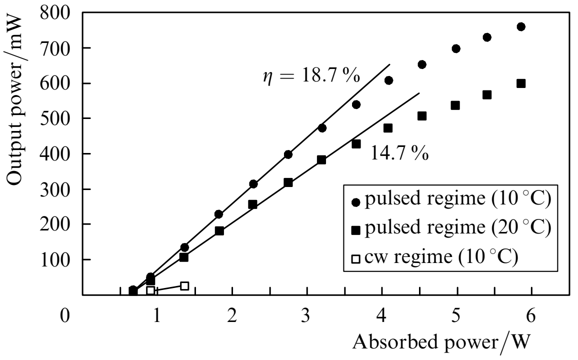

Figure 4. Dependences of the laser output power on the absorbed pump power for different pumping regimes.

The highest laser efficiency (15.3 %) at the slope efficiency $\eta = 18.7$ % and an average output power of 140 mW (pulse power ~ 500 mW) were obtained under the following conditions. The active element, whose temperature was kept at 10 °C, was pumped in a quasi-cw regime with an duty cycle of 1 : 4 and a pulse duration up to 20 ms. To reduce thermooptical distortions, we placed a plane-parallel plate with dimensions $\varnothing 5 \times 1$ mm made of an undoped YAG crystal in optical contact with one of the working faces of the active element.

It should be noted that the efficiency of the diode-pumped Tm : SSO laser in our experiments (Fig. 4) is considerably lower than the typical efficiency of lasers based on other thulium-containing active elements [1, 8]. The pronounced difference in the efficiency in the cw and pulsed regimes can be explained by the appearance of short-lived colour centres. In addition, the active element contains multiple scattering inhomogeneities visible with the naked eye in the laser mode volume, which introduce additional intracavity losses. According to our estimates based on the absorption spectra (Fig. 1) and direct measurements of the transmittance of the generated radiation, these losses reach a value of 1 % – 2 % per pass. In addition, there exist losses due to heating of the crystal in the pump channel. Thus, to increase the efficiency of the Tm : SSO laser, it is necessary to study the effect of the crystal growth conditions on the existence of stable and short-lived colour centres, as well as on the optical quality of the crystal.

Lasing in the Tm : SSO crystal was also obtained under cw pumping (Fig. 4), but the laser efficiency in this case was considerably lower. With increasing pump power, the laser power at first increases up to ~ 27 mW and then, after saturation, decreases up to the termination of lasing at the pump power of 1.7 W. The study of the decrease in the laser power with time showed that, from the instant of pump switching on, the laser power decreases for several seconds and then levels off. This allows us to suggest that the main reason for the decrease in the laser efficiency is an increase in the intracavity losses due to the absorption in the active element with increasing temperature.

Figure 5 presents the time dependences of the laser output power. At a rather intense pumping, the laser output power begins to decrease as early as several tens of milliseconds after pump switching on (Fig. 5a). This explains the above-mentioned difficulties with the realisation of a cw regime of the Tm : SSO laser. The laser radiation recorded with a better time resolution (Fig. 5b) clearly reveals its spike structure typical for thulium lasers.

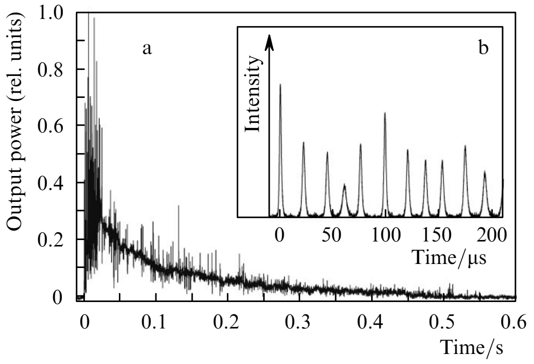

Figure 5. Time dependence of the laser output power at a high-power pulsed pumping (a) and the spike structure of the laser emission (b).

3. Conclusions

We have grown by the Czochralski method a Tm^{3+}: Sc_2SiO_5 crystal and obtained for the first time 1.98-μm lasing in this crystal in the pulsed (duty cycle 1 : 4) and cw regimes under diode pumping. The optical and slope laser efficiencies under pulsed pumping were 15.3 % and 18.7 %, respectively, with the average and pulsed output powers of 140 and 520 mW. The maximum pulsed power was 780 mW at the active element temperature of 10 °C. A further increase in the laser efficiency can be achieved by improving the growth technology of Tm : SSO crystals in order to improve their optical quality.

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