Quantum Electronics **44** (11) 989 – 992 (2014)

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LASERS

PACS numbers: 42.55.Rz; 42.60.Lh; 42.70.Hj
DOI: 10.1070/QE2014v044n11ABEH015513

Efficient 2-μm laser oscillation of 5%Tm^{3+} : $KLu(WO_4)_2$ disks and 5%Tm^{3+} : $KLu(WO_4)_2$/$KLu(WO_4)_2$ composite structures

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Abstract. **The spectral and lasing characteristics of active disk elements made of double potassium – lutetium tungstates 5%Tm : KLuW and 5%Tm : KLuW/KLuW composite structures are comparatively studied. Laser power of about 5 W in the cw regime at a wavelength of 1.85 μm was achieved in a composite sample with the active layer thickness of 250 μm. Under quasi-cw pumping, the slope efficiency of all the studied samples exceeded 50%. It is experimentally shown that the internal stresses in the composite structures strongly affect the spectral characteristics of the laser radiation.**

Keywords: *double potassium rare-earth tungstates, composite crystals, thin disks, diode pumping, thulium lasers, two-micron spectral region.*

1. Introduction

The crystals of double potassium rare-earth tungstates doped with trivalent thulium ions are promising laser materials for compact highly efficient sources of coherent two-micron (1.8 – 2.0 μm) radiation [1 – 5]. The results of investigations of the spectroscopic and lasing characteristics of Tm^{3+}: $KY(WO_4)_2$ and Tmm^{3+} : $KLu(WOO_4)_2$ crystals (hereinafter, Tm : KYW and Tm : KLuW) are presented in works [6 – 8]. The main advantages of these crystals are the large cross sections ($\sigma > 10^{-20}$ cm^2) of stimulated transitions in the spectral regions of pumping (~0.8 μm) and lasing (~1.94 μm) and a high slope efficiency (~50%). At the same time, the thermal conductivity ($k \sim 3$ W m^{-1} deg^{-1}) and the mechanical hardness (VH ~ 400) [9] of double tungstate crystals are comparatively low, because of which, to increase the output laser power, it is necessary to use special configurations of active elements in order to decrease thermomechanical stresses in the region of pumping. For example, the use of (5% – 15%) Tm:KLuW/KLuW epitaxial structures, which consist of an undoped (pure) substrate and an active crystalline layer doped with trivalent thulium ions, led to an increase in the specific power to 1.2 kW cm^{-2} [10] due to both partial heat removal through the crystalline substrate and an increase in the mechanical strength, because the substrate thickness exceeded the thickness of the active layer approximately by an order of magnitude.

A similar approach can also be used for composite structures, i.e., for a rigid construction consisting of two similar crystals with different compositions. As a rule, the components of these structures are connected via optical contact due to the mutual diffusion of subsurface layers of the contacting materials at high temperatures and pressures [11, 12]. Among the advantages of composite structures is the possibility of their orientation along any direction, while epitaxial structures can be grown only along particular directions determined by the growth planes. In the present work, we comparatively study the parameters and lasing spectra of 5%Tm : KLuW active disk elements and 5%Tm : KLuW/KLuW composite structures with the active layer thickness of 250 and 450 μm.

2. Experiment

The single crystals of double potassium – lutetium tungstates 5%Tm : KLuW and KLuW were grown by the low-gradient Czochralski method in the Institute of Inorganic Chemistry, Siberian Branch of the Russian Academy of Sciences [13]. To make composite elements, from both single crystals we cut and polished identical plane-parallel plates with dimensions 7.0 × 8.0 × 3.0 mm, whose faces were oriented with an accuracy of 0.5° along the optical indicatrix axes $N_{\rm m}$, $N_{\rm g}$, and $N_{\rm p}$, respectively. The plates were connected by optical contact and annealed in vacuum at a temperature of 850 °C during 48 h. As a result, we obtained a mechanically non-detachable structure of two crystals – 5%Tm : KLuW and KLuW – with a strength as good as the strength of the crystal itself. In particular, no one of the composite structures was destroyed in the optical contact region under action of mechanical or thermal stresses.

Two faces of the obtained composite structures were plane-parallel ground and polished so that the thickness of the 5%Tm : KLuW crystal layer (*b*-cut) was equal to 250 μm in one case and 450 μm in the other. The total thickness of the composite elements, taking into account the fixed substrate thickness of 2.50 mm, was 2.75 and 2.95 mm, respectively. At the same stage, we prepared two plane-parallel polished 5%Tm : KLuW plates 250 and 450 μm thick, such that the normal to their surfaces also coincided with the crystallographic axis b ($N_{\rm p}$).

Then, the polished surfaces of the disks and composite structures (from the side of the 5%Tm : KLuW active layer) were coated with a dichroic layer reflecting the pumping (800 – 810 nm) and laser (1850 – 1950 nm) radiation, so that the range-averaged residual transmission did not exceed

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Received 9 April 2014
Kvantovaya Elektronika **44** (11) 989 – 992 (2014)
Translated by M.N. Basieva

0.2%. The dielectric mirror was additionally coated by a copper layer for soldering with a chromium underlayer; the total thickness of the metal layers was ~3 μm, and the mirror reflection coefficient increased up to 99.9%. The other face of the samples (facing the output mirror) was coated by a dichroic antireflection layer for the same pumping and lasing spectral regions with a residual reflection of ~0.1%. At the final stage, the disks and composites were soldered to copper heat sinks with dimensions of 9 × 9 × 12 mm using a low-temperature indium solder. The photographs of the active elements are presented in the inset to Fig. 1.

The active elements were pumped by the collimated radiation of two diode arrays with the total optical power up to 50 W at a wavelength of 806 nm. The collimation system enabled us to focus the radiation of arrays into an approximately round spot 0.95 mm in diameter. The power supply allowed the diode arrays to operate in both repetitively pulsed (pump pulse duration 7 ms, pulse repetition rate 20 Hz, off-duty-ratio 14%) and cw regimes. All lasing experiments were performed with a short linear cavity with the physical length $L = 20$ mm, which was formed by a spherical output mirror and a rear plane mirror deposited on the active element (from the side of the heat sink). The transmission coefficient of the concave output mirror with a curvature radius of 40 mm was 7% in the spectral range 1850–1950 nm. The optical scheme elements were mounted on a common base, whose temperature was stabilised by Peltier modules ($T = 25 \pm 0.5\,°\mathrm{C}$). The experimental module design was almost the same as in work [8] (see Fig. 2 in [8]), but without a retroreflector, i.e., we used a two-pass pumping scheme. The absorbed pump power in all the cases was determined as a difference between the passed and incident powers; the optical powers of the light beams (pumping and lasing) were recorded using an MDR-204 monochromator, an FR-185 photoresistor, and a Unipan-233 selective nanovoltmeter as a preamplifier; the spectral resolution was ~0.5 nm (FWHM).

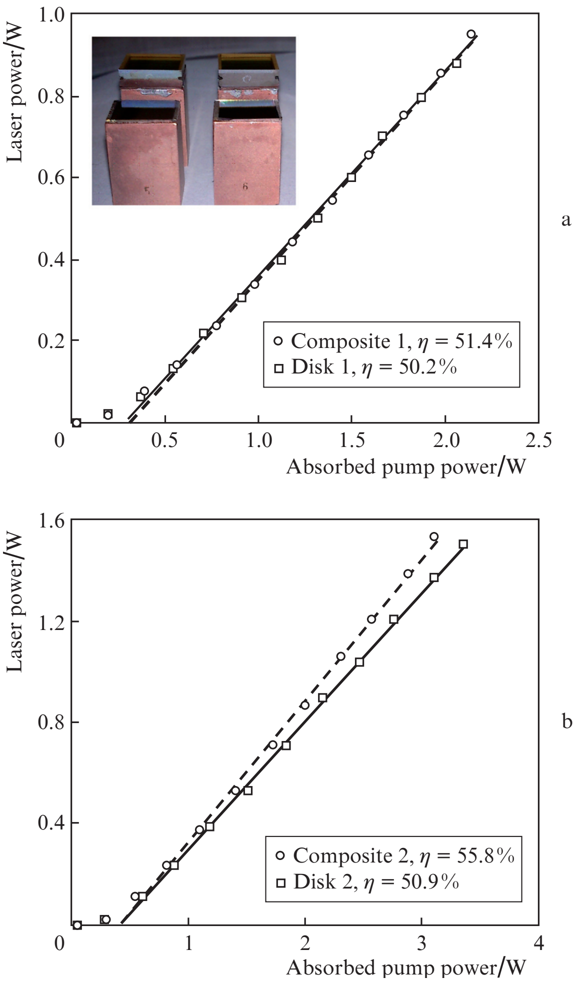

Figure 1. Dependences of the output power of lasers with active elements in the form of 5%Tm : KLuW disks and 5%Tm : KLuW/KLuW composites on the absorbed pump power at the 5%Tm : KLuW active layer thickness of 250 (a) and 450 μm (b). The inset shows the disk (foreground) and composite (background) active elements; η is the slope efficiency.

3. Results and discussion

The lasing characteristics of 5%Tm : KLuW disks and 5%Tm : KLuW/KLuW composites for a quasi-cw pumping regime (off-duty ratio 14%) are presented in Fig. 1 and Table 1. According to the measurements, the slope efficiency for the composites is slightly higher than that for disk elements, which is obviously related to a lower overheating of the structure in the pumped region due to additional heat removal through the substrate. At the same time, the slope efficiency for all the studied samples exceeds 50%, which well agrees with the slope efficiency for single crystals [1, 2, 9] and epitaxial structures [8, 10].

The spectra of lasers with 5%Tm : KLuW disk active elements and composite structures in the case of quasi-cw pumping at the maximum output power are shown in Fig. 2. The spectrum of lasers with disk elements 250 μm thick was almost identical to the spectra of epitaxial structures [8–10] and consisted of several individual non-equidistant peaks with a spectral width of ~ 1 nm each. In turn, the laser spectrum of the composite active element with the active layer thickness of 250 μm was almost continuous (Fig. 2a) with the bandwidth exceeding 200 nm (1750–2000 nm). To clarify the reasons for this difference in the spectra, the composite was unsoldered from the heat sink base and sawed into approximately identical fragments, which were then again soldered to the heat sunk bases. After this procedure, the lasing threshold remained the same, while the slope efficiency slightly decreased but was still higher than 50%. At the same time, the laser spectrum considerably changed and became almost identical to the spectra of lasers with active elements in the form of disks and epitaxial structures (see inset in Fig. 2a).

Table 1. Laser parameters for disk and composite active elements with a 5%Tm : KLuW active layer in the case of quasi-cw pumping (pulse duration 7 ms, pulse repetition period 50 ms, off-duty ratio 14%).

Sample	Active layer thickness/μm	Slope efficiency (%)	Optical efficiency (%)	Threshold power/W
Composite 1	250	51.4	44.6	0.31
Disk 1	250	50.2	43.1	0.29
Composite 2	450	55.8	49.1	0.39
Disk 2	450	50.9	44.9	0.41

In our opinion, this situation is explained by the internal stresses appearing in the composite structure during cooling after diffusion bonding due to some difference between the linear expansion coefficients of the doped and pure crystal layers, which causes the change in the laser spectrum. The sawing of the composite structure partially or completely removes these stresses, because of which the laser spectra of

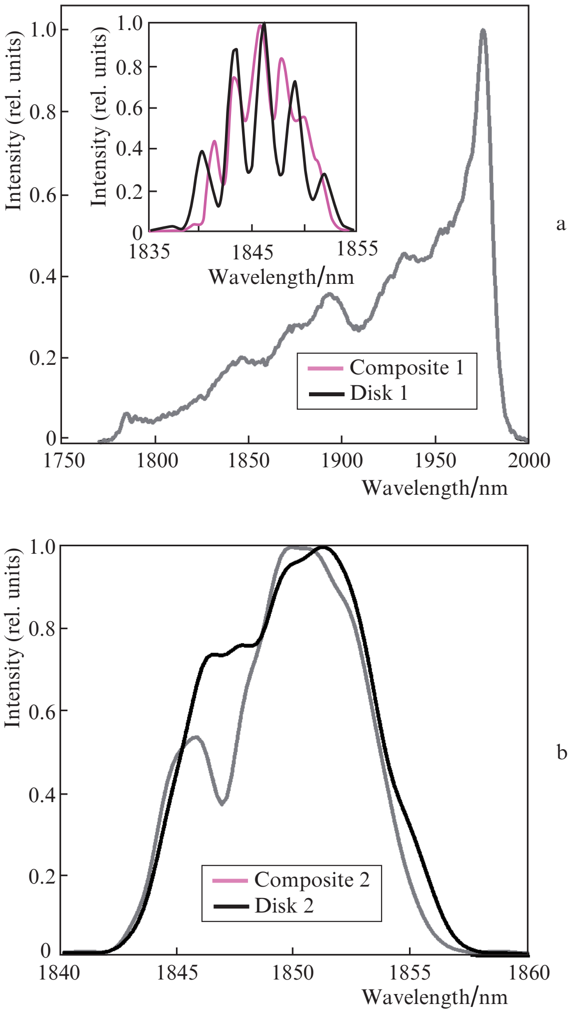

Figure 2. Emission spectra of lasers with active elements in the form of 5%Tm : KLuW disk and 5%Tm : KLuW/KLuW composite with the active layer thickness 250 (a) and 450 μm (b). The inset shows the laser spectra for the disk element and the composite element after its sawing.

composites and disks become almost identical. This supposition is also confirmed by the fact that the laser spectra in the case of a composite with the active layer 450 μm thick are not continuous. Most probably, these stresses are concentrated in a comparatively thin transition layer and, in the case of a thick active layer, only slightly affect the laser spectra. From this it follows that the spectral shape in the free-running mode is determined both by the parameters of the composite structure and by the technology of its fabrication; this may be of interest in the development of superbroadband laser systems, including femtosecond two-micron lasers.

The optical beam quality parameter M^2 was determined by the sharp edge method according to the standard procedure [14]. The results of measurement at the maximum laser power upon quasi-cw pumping are presented in Fig. 3 (the x and y axes correspond to the optical indicatrix axes N_m and N_g). Approximation of the experimental data by parabolic dependences [14] for the used pump geometry and cavity parameters yields $M_x^2 = 10.0$ and $M_y^2 = 12.7$. We think that the comparatively large M^2 is caused by the fact that the pump spot diameter (0.95 mm) considerably exceeds the Gaussian beam diameter (~0.15 mm), because of which lasing occurs mainly in a multimode regime.

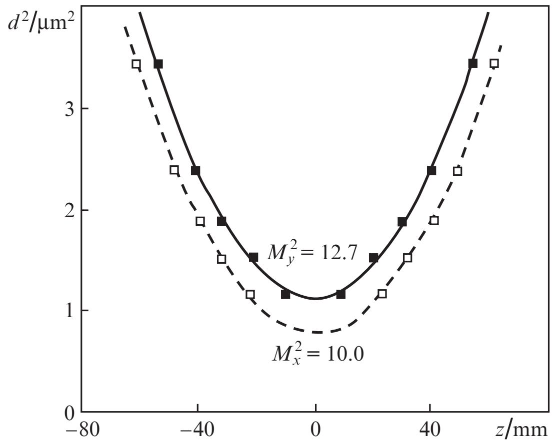

Figure 3. Dependences of the square of the laser beam diameter (disk active element) in the far-field zone on the distance to the lens focus (f = 150 mm) (points) and their approximations by parabolic dependences [14] (curves).

Figure 4 presents the results of laser experiments under the conditions of cw pumping. As was expected, the breakdown threshold (with respect to the absorbed pump power) of the composite structure is more than twofold higher than that for thin disks. At the same time, the slope lasing efficiency for composites (40.1%) turned out to be lower than for disks (46.2%), which can be caused by the existence of residual mechanical stresses in the composite structures in the region of contact between the crystals as was discussed above; however, this question is not yet completely clear and requires further investigations. Here, we can note that the maximum output energy density for the studied composite structure 5%Tm : KLuW/KLuW (630 W cm^{-2}) is approximately twofold lower than for the epitaxial structure of the same composition (1200 W cm^{-2}) and the same active layer thickness (250 μm). This also testifies to the existence of uncompensated mechanical stresses in the region of contact between the crystals.

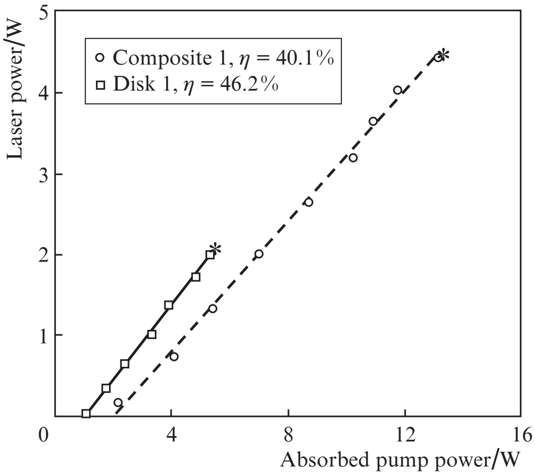

Figure 4. Dependence of the output power on the absorbed pump power in the cw regime for disk and composite elements with the active layer thickness 250 μm. The asterisks correspond to breakdown thresholds. η is the slope efficiency.

4. Conclusions

The performed investigations of the spectral and lasing characteristics of lasers with active elements in the form of 5%Tm : KLuW thin disks and 5%Tm : KLuW/KLuW composite structures demonstrated their high efficiency at an output power of 2–5 W. The geometric sizes of the composite structures allow us to expect further increase in the output power to ~50 W at wavelengths of 1.85–1.95 μm due to an increase in the pump spot diameter to 3–5 mm, which we are going to experimentally show in one of our subsequent studies. It is noteworthy that the laser wavelength 1.85 μm lies near the absorption maximum of Cr^{2+} : ZnSe crystals and can be used for their pumping when developing compact highly efficient tunable mid-IR lasers (~2.7–3.2 μm).

Acknowledgements. This work was supported by the Program of the Presidium of the Russian Academy of Sciences 'Fundamentals of Dual-Purpose Technologies for Homeland Security'.

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