Секция 3. ФИЗИЧЕСКИЕ, ФИЗИКО-МАТЕМАТИЧЕСКИЕ, МАТЕРИАЛОВЕДЧЕСКИЕ И ТЕХНОЛОГИЧЕСКИЕ ОСНОВЫ ПРИБОРОСТРОЕНИЯ

UDC 535.327

CW Tm:KLu(WO$_4$)$_2$ MICROCHIP LASER

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Thulium lasers attract interest as they operate around ~2 µm ($^3F_4 \rightarrow {}^3H_6$ transition) and this wavelength is desirable in medicine (due to the strong absorption of water) and remote sensing of CO$_2$ and water in the atmosphere. In addition, Tm^{3+} ions offer reduction of non-ratiative path due to efficient cross-relaxation processes resulting in luminescence quantum yield approaching 2. Among the Tm-doped gain materials, monoclinic potassium lutetium double tungstate Tm:KLu(WO$_4$)$_2$ combines good spectroscopic and thermal properties, as well as high available doping levels of Tm, that leads to realization of high-efficient continuous-wave, CW, and pulsed "bulk" lasers [1]. Power scaling has also been attempted in thin-disk and mini-slab geometries showing a great potential of this laser material using powerful diodes as a pump source. In the present paper, we report on CW microchip Tm:KLu(WO$_4$)$_2$ laser.

Monolithic microchip lasers consist of a laser crystal with two flat mirrors attached or directly deposited on the crystal surfaces. Such a device is attractive due to its compact and robust design that is insensitive to misalignment, as well as high efficiency due to absence of losses at the air/crystal interfaces. Sometimes, the microchip laser concept is extended to quasi-monolithic design with at least one plane mirror being in direct contact with the crystal. This option enables for insertion of some additional elements in the cavity, a saturable absorber for Q-switching or a Fabry-Perot etalon for single- frequency operation.

The mode stabilization in such a plano-plano laser cavity is provided by focusing thermal lens and the gain stabilization mechanism is also known. Thus, materials with negative dn/dT coefficients like Tm:KLu(WO$_4$)$_2$ are not suitable for microchip operation. Indeed, plano-plano cavity with internal negative lens is unstable. The peculiarity of Tm:KLu(WO$_4$)$_2$ is strong anisotropy of thermal and thermo-optic properties [2]. This in principle offers the possibility to observe purely positive lens for material with purely negative dn/dT values.

This conclusion is clear from figure 1, where we present measured values of optical power of the thermal lens D (inverse of the focal length, $D = 1/f$) in N_g-cut Tm:KLu(WO$_4$)$_2$ crystal vs. absorbed pump power P_{abs}. Here lines are linear fits of experimental points in order to determine sensitivity factors $M = =\mathrm{d}D/\mathrm{d}P_{abs}$ showing the change of refractive power due to 1 W variation of the pump level. Their values for both *pg* and *mg* principal meridional planes are relatively large and positive, +12.9 and +8.1 m^{-1}/W. The difference of M-factors for these planes is usually denoted as astigmatism degree S. Beam propagation along N_g axis possesses relatively low astigmatism of the thermal lens, S = 4.8 m^{-1}/W or S/M = 37% (so it is close to spherical).

Thus, beam propagation along N_g axis only partially satisfies the conditions of athermal compensation of the thermally-induced optical path difference in solid-state lasers, namely weak positive spherical thermal lens. However, this crystal cut is in principle suitable for microchip operation.

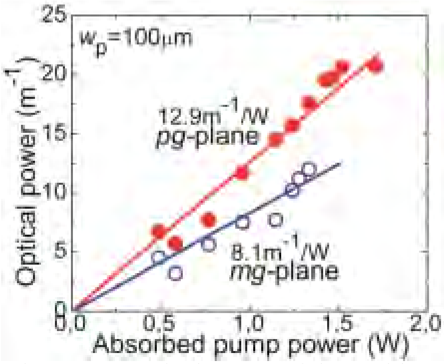

Figure 1 – Optical power of thermal lens for N_g-cut Tm:KLu(WO$_4$)$_2$ crystal

A plano-plano laser cavity was used for the microchip experiment. Pump mirror was antireflection-coated for ~805 nm (pump wavelength), providing also high reflection, R > 99.9%, at ~1950 nm (laser wavelength). Output coupler had a transmission T_{OC} = 3% at ~1950 nm. A fiber coupled AlGaAs diode was used as a pump source [200 µm core diameter, numerical aperture, N.A.=0.22] operating at 805 nm. We used lens assembly (1:1 imaging ratio) that enabled collimation and focusing of the pump beam into the crystal. The pump spot size in the crystal was w_p = 100 µm. The active medium was uncoated 3at. % Tm:KLu(WO$_4$)$_2$ crystal with dimensions ~2.5×3 ×3 mm^3 along the optical indicatrix axes, N_g, N_p and N_m, respectively. The crystal was mounted in a water-cooled Cu-holder set at 16ºC. The crystal was oriented for light propagation along the N_g axis. Indium foil was used to improve the thermal contact between the crystal and holder. The air gaps between the crystal and mirrors were < 1 mm, they did not affect the mode stabilization principle in the plano-plano cavity. The overall cavity length was ~4 mm. The scheme of microchip laser setup is depicted in figure 2.

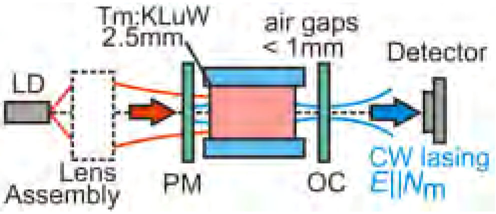

Figure 2 – The scheme of CW Tm:KLu(WO$_4$)$_2$ microchip laser: LD is laser diode, PM and OC are pump mirror and output coupler

Input-output dependence for Tm:KLu(WO$_4$)$_2$ quasi-monolithic microchip laser is presented in figure 3. Maximum output power achieved was 880 mW at an absorbed power of 3 W, laser threshold was 590 mW, and the slope efficiency with respect to absorbed power reached 45%. The optical-to-optical efficiency was 29%. We observed that above 2.5 W of absorbed power a kind of saturation of the output power appeared probably due to thermal loading in the crystal. The output beam was polarized parallel to N_m-axis that corresponds to highest gain in the Tm:KLu(WO$_4$)$_2$ crystal; it was spectrally centered at 1949 nm.

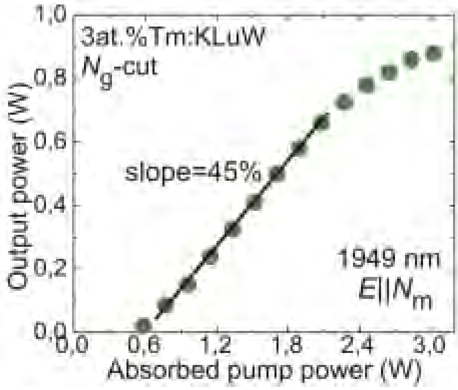

Figure 3 – Output-input dependence for Tm:KLu(WO$_4$)$_2$ microchip laser

The output beam profile was measured with a thermal imaging camera. Figure 4 shows the far-field intensity of the microchip laser indicating a TEM$_{00}$ mode characterized by a Gaussian distribution as well as the fits for the horizontal (|| N_m) and vertical (|| N_p) directions. In addition, 2D and 3D plots are presented. The measurement was carried out for the maximum available absorbed pump power (~3 W). The M^2 factor was measured to be M^2_x, M^2_y < 1.05. Good quality of the output laser beam (i.e., its circular shape and low ellipticity, as well as Gaussian profile and extremely low M^2 factor) are directly related to the low astigmatism of the thermal lens for N_g-cut Tm:KLu(WO$_4$)$_2$ crystal.

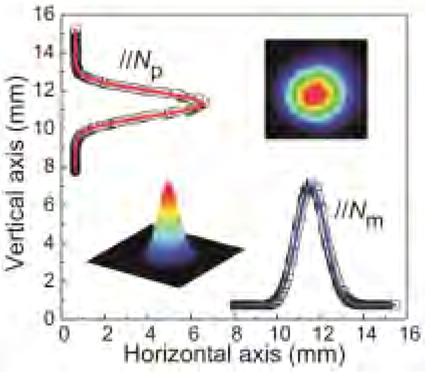

Figure 4 – Analysis of the laser mode quality for Tm:KLu(WO$_4$)$_2$ microchip laser

Previously, quasi- microchip lasing was realized with antireflection-coated 5at.%Tm:KY(WO$_4$)$_2$ crystal cut along the N_g-axis and T_{OC} = 3% [3]. CW output power of 650 mW was obtained with slope efficiency of 44%. Thus, the present paper demonstrates improvement of this result (in addition, the lasing was obtained for crystal without antireflection coating). Our conclusion about potential of N_g-cut double tungstates for microchip lasing is supported by recent results for 10at.% Yb:KY(WO$_4$)$_2$ and 7at. % Nd:KGd(WO$_4$)$_2$ crystals “sandwiched” into synthetic diamond with almost 1 W CW output [4].

In conclusion, the microchip concept was applied to Tm:KLu(WO$_4$)$_2$ laser crystal to demonstrate TEM$_{00}$-mode laser operation with maximum output power approaching 1 W at 1949 nm and demonstrate a slope efficiency as high as 45%. The key role of thermally-induced effects for the mode stabilization in the plano-plano cavity is explained. Further improvement will focus on perfect mode-matching between the pump and laser modes to increase the efficiency and output power of this laser as well as on optimization of the doping level and thickness of the active medium.

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