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Holmium thin-disk laser based on Ho:KY(WO$_4$)$_2$ / KY(WO$_4$)$_2$ epitaxy with 60% slope efficiency and simplified pump geometry

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We report on the first Holmium (Ho^{3+}) monoclinic double tungstate thin-disk laser. It is based on a 250 μm-thick 3 at. % Ho:KY(WO$_4$)$_2$ active layer grown on a (010)-oriented KY(WO$_4$)$_2$ substrate. When pumped by a Tm-fiber laser at 1960 nm with a single-bounce (single double-pass) pump geometry, the continuous-wave Ho:KY(WO$_4$)$_2$ thin-disk laser generated 1.01 W at 2057 nm corresponding to a slope efficiency η of 60% and a laser threshold of only 0.15 W. Implementing a double-bounce (second double-pass) for the pump, the output of this laser was scaled to 1.57 W with η = 55%. The maximum stimulated-emission cross-section σ_{SE} of the Ho^{3+} ions in the epitaxial layer reaches 2.5×10^{-20} cm^2 at 2056.5 nm for $E \parallel N_m$. The Ho:KY(WO$_4$)$_2$ epitaxial structures are promising for multi-watt mode-locked thin-disk lasers at ~2.06 μm.

OCIS codes: *(140.3380) Laser materials; (140.3580) Lasers, solid-state; (300.0300) Spectroscopy; (140.3070) Infrared and far-infrared lasers.*

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Holmium (Ho^{3+}) ions (electronic configuration [Xe]4f^{10}) are well-known for the development of lasers emitting above 2 μm due to the $^5I_7 \rightarrow {}^5I_8$ transition. The eye-safe emission of Ho lasers is used in remote sensing [1], laser materials processing and laser surgery and it is of interest for pumping of mid-IR optical parametric oscillators (OPOs) [2]. The most efficient way to excite the Ho^{3+} ions is their resonant (in-band) pumping to the $^5I_7$ upper laser level, e.g. by Thulium (Tm^{3+}) lasers emitting at <2 μm [3,4]. Such a pump scheme offers high Stokes efficiency and suppressed upconversion losses (e.g., as compared with the Tm^{3+},Ho^{3+}-codoping scheme [5]) leading to weak heat loading and high laser efficiency [6].

The thin-disk laser concept is attractive for both continuous-wave (CW) and pulsed (mode-locked, ML) operation [7,8]. Such a laser is based on a disk-shaped active element with a thickness smaller than the size of the laser beam. One surface of the disk is attached to the heat sink providing unidirectional heat flow and, appropriately coated, serves as a cavity mirror [9,10]. Thin-disk lasers offer reduced thermo-optic effects and high potential for power scaling. Moreover, high slope efficiencies have been demonstrated [11]. In addition, they are attractive for ML lasers due to the diffraction-limited beam and the reduction of the nonlinear effects in the active medium [8,12,13].

CW and ML thin-disk lasers have been extensively studied at ~1 μm utilizing Yb^{3+} ions in hosts such as YAG [7], Lu_2O_3 [11], $KY(WO_4)_2$ [12], $CaGdAlO_4$ [14], etc. Concerning, the 2 μm spectral range, the research focused mostly on Tm^{3+} ions in YAG, Lu_2O_3 or $LiLuF_4$ [7,15-17]. So far, Ho thin-disk lasers have been realized only with Ho:YAG [18-20]. In [19], a 2 at.% Ho:YAG thin-disk operated with a rather complex pump geometry consisting of 24 pump passes or 12 bounces (as typical for Yb:YAG thin-disks) using a Tm:YLF laser as pump source, generating 9.4 W in CW at ~2090 nm with a slope efficiency η of ~50% (with respect to the absorbed pump power). Even higher output power, 22 W with η ~27% was achieved in a similar mutipass-pumped Ho:YAG laser [20] using an InP diode.

Monoclinic double tungstates (MDTs), $KRE(WO_4)_2$ where RE = Gd, Y or Lu (shortly KREW), are suitable hosts for Ho^{3+} doping [21]. They offer the possibility to be doped with relatively high Ho^{3+} concentrations suitable for efficient lasing (up to 5 at.%) [21], high transition cross-sections in polarized light and long lifetime of the $^5I_7$ upper laser level (~4.2 ms) [22,23]. These characteristics make the Ho^{3+}-doped MDTs very promising for thin-disk lasers with ultimately reduced number of pump passes. Efficient bulk in-band-pumped Ho^{3+} MDT lasers were reported [6,21]. Among the MDTs, KYW is very suitable for Ho^{3+} doping due to the closeness of the ionic radii of VIII-fold coordinated Y^{3+} (1.019 Å) and Ho^{3+} (1.015 Å) leading to a negligible lattice distortion [22].

Thin epitaxial layers of high optical quality MDTs can be grown despite the low symmetry of this material. Such a concept was used to demonstrate the first Tm MDT thin-disk lasers [24,25]. A 250 μm-thick 5 at.%Tm:KLuW / KLuW thin-disk laser pumped by an AlGaAs laser diode with only 2 pump bounces (i.e. a simple retro-reflection) generated 5.9 W at 1855 nm with η = 47% [25].

In the present work, we report an efficient Ho MDT thin-disk laser using a Ho:KYW / KYW epitaxial structure.

The undoped KYW substrate was cut from a bulk crystal grown by the Top-Seeded Solution Growth (TSSG) method and oriented with the crystallographic ***b***-axis normal to its face. It was 1 mm-thick. The crack- and inclusion-free active layer, a 3 at.% Ho:KYW ($N_{Ho} = 2.16\times10^{20}$ cm^{-3}), was grown by the liquid phase epitaxy (LPE) method, see Fig. 1(a). It was polished down to 250±10 μm thickness. The face with the substrate was antireflection (AR) coated for 1.8-2.1 μm (for both the pump and laser wavelengths) while the face containing the Ho:KYW epitaxial layer was coated for high reflection (HR) at 1.8-2.1 μm. It was further soldered to a Cu heat-sink, see Fig. 1(b), which was water-cooled to 12 °C. The laser element was oriented for light propagation along the ***b***-axis (***b*** || N_p optical indicatrix axis).

At first, we studied the spectroscopic properties of the epitaxial layer. The absorption, σ_{abs}, and stimulated-emission, σ_{SE}, cross-sections for the $^5I_7 \rightarrow {}^5I_8$ transition of Ho^{3+} ions are shown in Fig. 2(a) for light polarization with ***E*** || N_m. The maximum $\sigma_{abs} = 2.3\times10^{-20}$ cm^2 at 1961.6 nm (the full width at half maximum, FWHM is 8.7 nm). The maximum σ_{SE} reached 2.5×10^{-20} cm^2 at 2056.5 nm (calculated with the reciprocity method). The Ho:KYW layer exhibited broadband (1.88-2.1 μm) luminescence, Fig. 2(a).

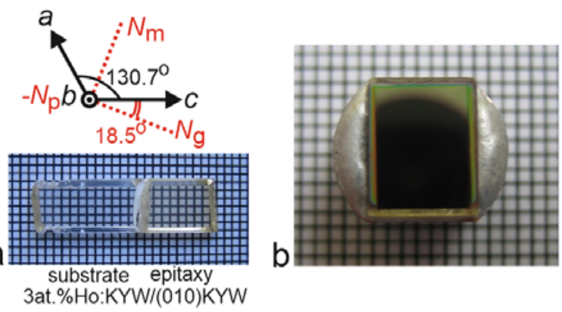

Fig. 1. (a) Photograph of the as-grown 3 at. % Ho:KYW/KYW epitaxy and orientation of the crystallographic (***a***, ***b***, ***c***) and the orthogonal optical indicatrix axes (N_p, N_m, N_g); (b) cut, polished, and AR/HR coated sample soldered on a Cu heat-sink (top view).

The Ho^{3+} ions represent a quasi-three-level laser scheme. To predict the laser wavelength, the gain cross-sections, $\sigma_{gain} = \beta\sigma_{SE} - (1-\beta)\sigma_{abs}$, were calculated, Fig. 2(b). Here, β is the inversion ratio. For small $\beta < 0.25$, a maximum gain at ~2076 nm is observed and for higher β, a different maximum gain at ~2056 nm dominates. The determined spectroscopic data agree with those for bulk Ho:KYW [22] confirming high quality of the epitaxial layer.

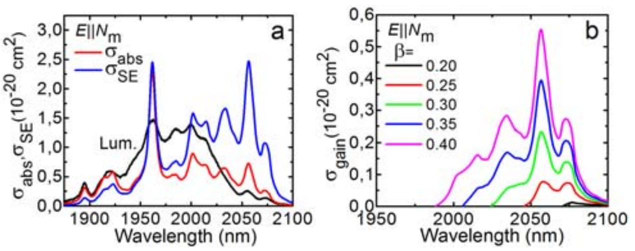

Fig. 2. Spectroscopy of the 3 at.% Ho:KYW/KYW epitaxy: (a) absorption, σ_{abs}, and stimulated-emission (SE) cross-section, σ_{SE}, spectra, *black line* - luminescence spectrum; (b) gain cross-section, $\sigma_{gain} = \beta\sigma_{SE} - (1-\beta)\sigma_{abs}$, spectra for various inversion ratios $\beta = N_2(^5I_7)/N_{Ho}$ ($^5I_7 \rightarrow {}^5I_8$ transition of Ho^{3+} ions, light polarization ***E*** || N_m)

The scheme of the thin-disk laser is shown in Fig. 3. The pump source was a Tm-fiber laser (model IFL15, LISA Laser Products, OHG) emitting up to 12.5 W at 1960 nm (FWHM = 1.5 nm). Its unpolarized output (M^2 ~1) was collimated and focused into the laser element with a pair of AR-coated spherical CaF_2 lenses (f_{CL} = 11 mm, f_{FL} = 75 mm) providing a pump spot size $2w_P$ of 300±10 μm. The angle of incidence of the pump beam was about 10°. The total pump absorption (single-bounce), was measured by monitoring the residual pump, *Abs* = 14%. This agrees with the small-signal absorption calculated from the spectroscopic data, ~15% (the polarization-averaged absorption cross-section is $\langle\sigma_{abs}\rangle$ = 1.54×10^{-20} cm^2). Optionally, a double-bounce of the pump beam was realized with a HR concave mirror (radius of curvature, *R* = 100 mm), Fig. 3, resulting in a total absorption of *Abs* = 25%. The pump beam was also optionally modulated with a mechanical chopper (duty cycle: 1:2, i.e. reducing the average power to ½, frequency: 20 Hz) inserted between the two pump lenses (CL and FL). The plano-concave thin-disk laser cavity consisted of a flat HR mirror deposited on the disk surface and a concave output coupler (OC) with a radius of curvature R_{OC} of 75 mm and a transmission T_{OC} of 0.5%, 1.5%, 3%, 5% or 10% at 1.82-2.07 μm. The laser generated a linearly polarized output (***E*** || N_m) and the polarization was naturally-selected by the gain anisotropy.

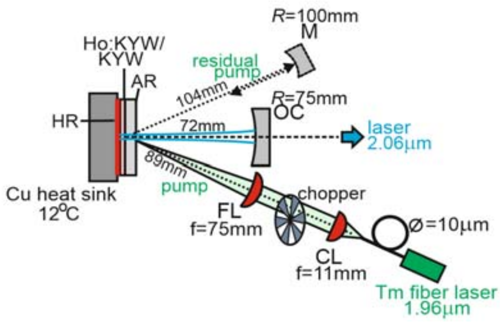

Fig. 3. Thin-disk Ho:KYW laser: (a) laser set-up, CL and FL – collimating and focusing lenses, respectively, HR and AR – high-reflective and antireflection coatings, respectively, OC – output coupler.

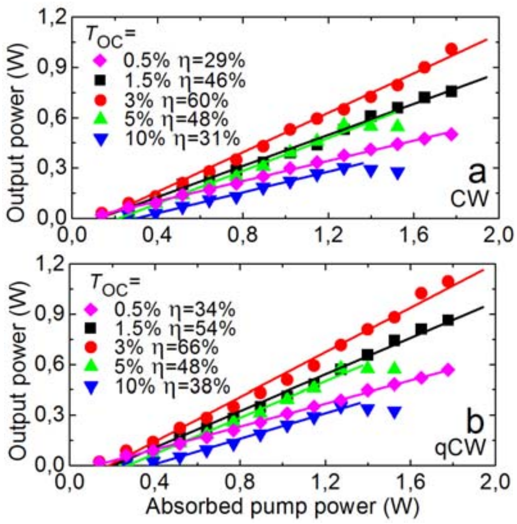

Fig. 4. Input-output dependences for the Ho:KYW thin-disk laser in CW (a) and quasi-CW (duty cycle 1:2) (b) operation modes: *symbols* are the experimental data, *lines* are fits for the determination of the slope efficiency *η* (single-bounce pumping).

The results on the true CW laser performance with a single bounce pumping are presented in Fig. 4(a). For T_{OC} = 3%, the maximum output power was 1.01 W at 2057 nm corresponding to a slope efficiency *η* of 60% (with respect to the absorbed pump power P_{abs}). The laser threshold was at P_{abs} = 0.15 W and the optical-to-optical efficiency η_{opt} with respect to the incident pump power was 8%. No thermal roll-over was observed when using this OCs. For higher T_{OC} = 5% and 10%, the laser performance deteriorated due to upconversion losses and, hence, an increased heat deposition, leading to lower *η* and thermal roll-over at P_{abs} > 1.28 W.

Using the chopper (in quasi-CW mode) with the optimum T_{OC} = 3%, the peak output power reached 1.10 W with an increased *η* = 66% (due to the relaxed heat problems), Fig. 4(b). Still, the used duty cycle (1:2) was not enough to improve the performance of the laser for T_{OC} >5%.

The typical emission spectra from the Ho:KYW thin-disk laser are shown in Fig. 5. For T_{OC} = 1.5% and higher, the laser emission extended from 2056 to 2059 nm while only for T_{OC} = 0.5%, the main emission shifted to 2072-2075 nm. This behavior agrees well with the gain spectra, cf. Fig. 2(b). The multi-peak spectra are due to the etalon effects in the KYW substrate.

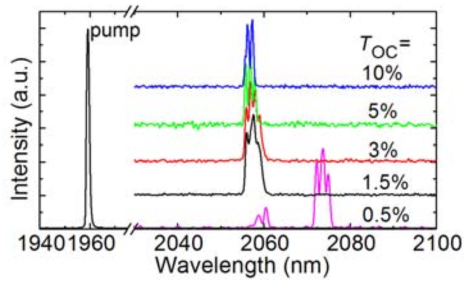

Fig. 5. Typical laser emission spectra for the Ho:KYW thin-disk laser for various OCs (CW mode, single bounce pumping, P_{abs} = 1.52 W). The emission spectrum of the Tm-fiber laser is shown for comparison.

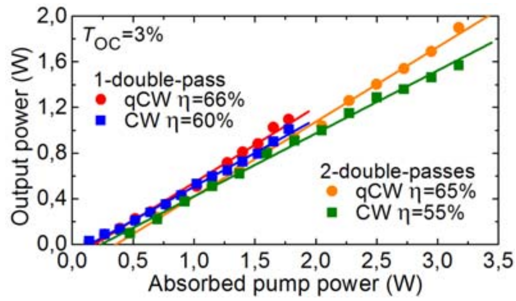

Fig. 6. Comparison of the output performance of the Ho:KYW thin-disk laser in CW and quasi-CW operation modes for 1 and 2 bounces of the pump: η is the slope efficiency, T_{OC} = 3%.

Further power scaling of the thin-disk laser was achieved by implementing a second bounce of the pump, see Fig. 6. For the optimum T_{OC} = 3%, the CW output power reached 1.57 W with η = 55% and η_{opt} = 12%. The output dependence was clearly linear; while the deterioration of the slope efficiency and increase of the laser threshold (P_{abs} = 0.34 W) as compared with the single-bounce scheme is attributed to worse mode-matching and stronger heat loading in the active medium. Indeed, for quasi-CW operation mode, the peak output power was as high as 1.90 W with η = 65%.

The spatial beam profiles of the laser output from the thin-disk laser (CW mode, T_{OC} = 3%, single-bounce pumping) were captured with a pyrocamera SPIPICON PY-III-C-B at 20 cm from the OC using an AR-coated 50 mm CaF_2 focusing lens. The beam profiles are shown in Fig. 7 for low and high P_{abs}. At low absorbed pump power, the beam is nearly-circular. With the increase of the P_{abs}, it becomes elliptic. This indicates the astigmatism of the thermal lens [26] induced in the disk. The measured M^2 factor of the output laser beam was <1.2 (at the maximum P_{abs}).

In Fig. 7(b), A and B denote the major and minor semiaxes of the elliptic beam, respectively. Physically, these directions correspond to the principal meridional planes of the astigmatic thermal lens [27]. The orientation of these planes is linked to the anisotropy of the thermal expansion [26]. For a ***b***-cut Ho:KYW/KYW disk, there are two principal axes of the thermal expansion tensor in the disk plane, X'_1 and X'_3. They do not coincide with the optical indicatrix axes (the angle N_m^X'_1 = N_g^X'_3 = 30.9° for KYW [28]), see Fig. 7(a). According to Fig. 7(b), A || X'_3 and B || X'_1. It should be noted that the use of the epitaxial structure Ho:KYW / KYW for the thin-disk laser design is beneficial for suppressing the unwanted end-bulging of the disk [29], as the substrate acts as an undoped cap.

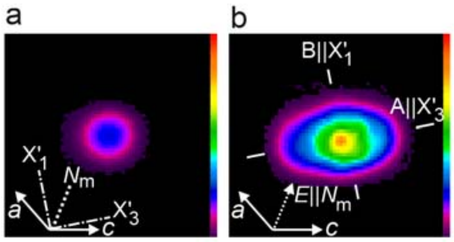

Fig. 7. Spatial profiles of the output laser beam from the Ho:KYW thin-disk laser measured at (a) low P_{abs} = 0.39 W and (b) high P_{abs} = 1.78 W (CW mode, single bounce pumping, T_{OC} = 3%). A and B – major and minor semiaxes of the elliptic laser beam; X_1' and X_3' – principal axes of the thermal expansion tensor of KYW, respectively.

The achieved maximum slope efficiency of the true CW Ho:KYW thin-disk laser (η = 60%) represents a record among all the Ho thin-disk lasers reported so far. However, it is lower than the Stokes efficiency, $\eta_{St} = \lambda_P/\lambda_L$ ~ 95% (λ_P and λ_L are the pump and laser wavelengths, respectively) and the maximum slope efficiency achieved in bulk in-band-pumped Ho MDT lasers (η = 88% for 3 at. % Ho:KLuW [30]). We attribute this difference to the non-optimum mode-matching due to the strongly anisotropic thermal lensing in a ***b***-cut laser disk and notable heat loading when using a relatively small pump beam ($2w_P$ = 300 μm). Power scaling and further improvement of the efficiency of the Ho:KYW thin-disk laser is expected by increasing the pump beam, optimization of the pump geometry and the Ho^{3+} doping concentration as well as Ho:KYW active layers grown on KYW substrates with different orientations.

In conclusion, we report on the first Holmium thin-disk laser based on monoclinic double tungstate crystals using an epitaxial composite consisting of a thin active Ho:KYW layer grown by the liquid phase epitaxy method on an undoped bulk KYW substrate. The thin-disk laser was pumped at 1960 nm by a Tm-fiber laser in a single double-pass and emitted at ~2057 nm. The output power was scaled up to the watt-level in the CW operation mode representing a record slope efficiency of η = 60%. The possibility of further power scaling is demonstrated with a double-bounce of the pump, leading to an almost 2-fold increase of the output power. Higher doping level with simultaneous reduction of the active layer thickness is expected to improve the results substantially. The presented Ho:KYW thin-disk laser can be considered as a proof-of-concept for the further development of highly-efficient multi-watt Ho MDT thin-disk lasers with a diffraction-limited laser output. Due to the broadband emission characteristics, the epitaxial Ho:KYW / KYW structures are attractive for mode-locked laser oscillators above 2 μm.

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