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Thermo-optic effects in Ho:KY$(WO_4)_2$ thin-disk lasers

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Abstract: Thin (~250 µm) crystalline layers of monoclinic Ho^{3+}-doped KY$(WO_4)_2$ grown by the liquid phase epitaxy method on (010)-oriented undoped KY$(WO_4)_2$ substrates are promising for the development of thin-disk lasers at ~2.1 µm. Using a single-bounce pump geometry, 3 at.% and 5 at.% Ho:KY$(WO_4)_2$ thin-disk lasers delivering output powers of >1 W at 2056 nm and 2073 nm are demonstrated. The laser performance, beam quality and thermo-optic aberrations of such lasers are strongly affected by the Ho^{3+} doping concentration. For the 3 at.% Ho^{3+}-doped thin-disk, the thermal lens is negative (the sensitivity factors for the two principal meridional planes, $M_{A(B)}$, are −1.7 and –0.7 m^{-1}/W) and astigmatic. For higher Ho^{3+} doping (5-10 at.%), the effect of upconversion and end-bulging of the disk enhances the thermo-optic aberrations leading to a deteriorated laser performance.

OCIS codes: (140.3380) Laser materials; (140.3580) Lasers, solid-state; (140.3070) Infrared and far-infrared lasers; (140.6810) Thermal effects.

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1. Introduction

The thin-disk laser concept consists of a disk-shaped active element with a thickness smaller than the pump and laser spot sizes attached to a cooling holder in contact with the disk rear face for unidirectional heat flow [1]. It is promising for power-scalable and efficient laser sources operating in the continuous-wave (CW) and mode-locked (ML) regimes [2]. Despite the wide spread of Yb^{3+} thin-disk lasers emitting at ~1 μm and using various Yb^{3+}-doped laser crystals [3], the information about such lasers at ~2 μm is scarce [4,5] due to more strict requirements to spectroscopic and thermal properties of potential gain materials and less commercialized pump systems. Such an eye-safe emission is of interest for environmental sensing, spectroscopy and medical applications and can be achieved, e.g., with trivalent Holmium (Ho^{3+}) due to the $^5I_7 \rightarrow {}^5I_8$ transition.

To date, only few Ho thin-disk lasers were developed based on Ho:YAG with multiple pump bounces (up to 12, e.g. 24 passes of the pump) [5–8]. J. Speiser *et al.* reported on a CW 2 at.% Ho:YAG thin-disk laser (thickness: 400 μm) pumped by a Tm fiber laser at 1908 nm and utilizing 12 bounces of the pump [5]. This laser generated 15 W at ~2090 nm with a slope efficiency η of ~37%. Tuning between ~2075 and 2105 nm was also demonstrated [5]. M. Schellhorn studied a very similar Ho:YAG thin-disk with a Tm:YLF laser as a pump source and 12 bounces of the pump leading to the generation of 9.4 W of CW output at ~2090 nm with a slope efficiency reaching ~50% (with respect to the absorbed pump power) [6]. G. Renz used a 2.5 at.% Ho:YAG thin-disk (thickness: 300 μm) and a stack of InP laser diodes in combination with a commercial 12 bounce pump module to generate 22 W with η ~27% [7].

Very recently, J. Zhang *et al.* reported on a Kerr-lens mode-locked Ho:YAG thin-disk laser (doping: 2.5 at.% Ho, thickness: 200 μm) delivering 270 fs-long pulses at a repetition rate of 77 MHz with an average output power of 28 W [8,9]. This laser was pumped by two Tm fiber lasers at 1908 nm using a 12 bounce pump module. By soliton self-compression in a silica glass fiber, the pulse duration has been further shortened down to 15 fs [8]. All the above examples suffer from a very complex pump scheme of 12 bounces of the pump.

Besides YAG, another family of materials very suitable for Ho^{3+} doping are the monoclinic double tungstates (MDTs), with a chemical formula KRE(WO_4)$_2$ (RE = Gd, Y, or Lu) [10]. In the MDT lattice, the Ho^{3+} ions replace the RE^{3+} ones in a single site (C_2 symmetry, VIII-fold O^{2-} coordination). In particular, KY(WO_4)$_2$ (shortly KYW) seems to be the best host material for Ho^{3+} doping among the MDT due to the closeness of ionic radii of Y^{3+} (1.019 Å) and Ho^{3+} (1.015 Å). High Ho^{3+} doping concentrations accompanied with a weak luminescence quenching due to the long Y^{3+}-Y^{3+} interatomic distances (4.06-6.04 Å) are feasible [11]. From the point of view of spectroscopy, Ho:KYW crystals are attractive due to the high absorption, σ_{abs}, and stimulated-emission, σ_{SE}, cross-sections for polarized light (a maximum σ_{SE} ~2.6 × 10^{-20} cm^2 at 2056 nm for light polarized along the N_m optical indicatrix axis of these biaxial crystals, for comparison Ho:YAG: σ_{SE} ~1.6 × 10^{-20} cm^2 at 2090 nm), as well as relatively long lifetime of the upper laser level ($^5I_7$) of about 4.8 ms [11]. Anisotropic Ho^{3+}-doped MDTs can offer an "athermal" behavior for certain crystal cuts potentially leading to almost negligible thermo-optic aberrations being weaker than those in Ho:YAG. Ho^{3+}-doped MDTs in general and Ho:KYW in particular provided efficient lasing under in-band-pumping, e.g., by Thulium (Tm^{3+}) ion-doped lasers [12].

In the present work, we study the effect of Ho^{3+}-doping on the performance of Ho:KYW thin-disk lasers with a simple single-bounce (double pass) pumping scheme facilitated by the advantageous spectroscopic properties of Ho^{3+} in KYW. To prepare the thin-disk laser elements, we used the liquid phase epitaxy (LPE) method to grow thin layers of Ho^{3+}-doped KYW on undoped KYW substrates [13]. The thin-disk laser performance of Tm-doped KLuW/KLuW epitaxies was previously studied by part of the authors in [14]. With 2 pump bounces, such a thin-disk laser generated 5.9 W at 1855 nm with η ~47%.

2. Experimental

The thin-disks were based on Ho^{3+}-doped KYW layers grown on 1-mm-thick undoped KYW substrates by the LPE method from the flux using potassium ditungstate ($K_2W_2O_7$) as a solvent, Fig. 1(a). The substrate itself was grown by the Top-Seeded Solution-Growth (TSSG) Slow-Cooling method and oriented with the crystallographic [010] or ***b***-axis normal to its face. The crack- and inclusion-free active layers ($KY_{1-x}Ho_x(WO_4)_2$) were doped with x = 3, 5, 7 or 10 at.% Ho^{3+}. The 0.8...1 mm-thick as-grown layers were polished down to a thickness t of 250 ± 20 μm. The substrate face was antireflection (AR)-coated and the face with the epitaxial layer was high-reflection (HR)-coated for 1.8-2.1 μm. The latter was soldered to a Cu heat-sink, see Fig. 1(b), which was water-cooled to 12 °C. The light propagation for the thin-disk laser element was along the ***b***-axis (|| N_p optical indicatrix axis).

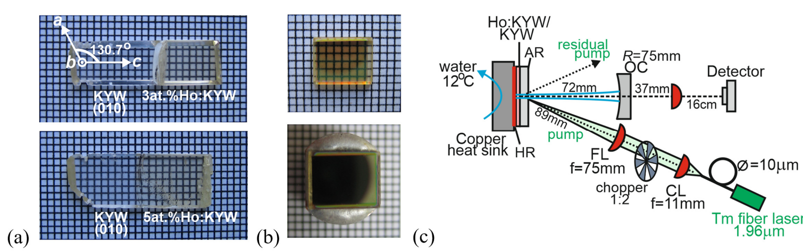

Fig. 1. (a) Photograph of the as-grown 3 and 5 at.% Ho:KYW/KYW epitaxies, their orientation with respect to the crystallographic axes (***a***, ***b***, ***c***); (b) cut, polished, and AR/HR coated 3 at.% Ho-doped sample (top image) soldered to a Cu heat-sink (bottom image); (c) thin-disk laser set-up: CL – collimating lens, FL –focusing lens, HR and AR – high-reflection and antireflection coatings, respectively, OC – output coupler.

The plano-concave laser cavity was composed by the flat HR mirror deposited on the substrate face of the disk and a concave output coupler (OC) with a radius of curvature RoC of 75 mm and a transmission T_{OC} of 1.5%, 3% or 5% at 1.82-2.07 μm, see Fig. 1(c). The pump source was a fiber Bragg grating (FBG) stabilized thulium-doped fiber laser (model IFL15, LISA laser products) emitting up to 12.5 W at 1960 nm (full width at half maximum: 1.5 nm). Its unpolarized output (beam quality parameter, M^2 ~1) was collimated and focused onto the laser element with a pair of AR-coated CaF_2 lenses (focal lengths: f_{CL} = 11 mm, f_{FL} = 75 mm) providing a pump spot size $2w_p$ of 300 ± 10 μm. Thus, the condition $2w_p > t$ for the thin-disk laser was satisfied. The total pump absorption (single-bounce = double-pass), was measured by monitoring the residual pump. It was 14% for the 3 at.% and 33% for the 5 at.% Ho^{3+}-doped epitaxies. Optionally, the pump beam was modulated with a mechanical chopper (duty cycle: 1:2, frequency: 20 Hz).

3. Results and discussion

3.1 Laser performance

Laser operation was achieved with the 3 and 5 at.% Ho-doped KYW thin-disks in true CW as well as in the quasi-CW regime. In all cases, the laser output was linearly polarized ($\boldsymbol{E} \parallel N_m$) according to the anisotropy of the gain [11]. The corresponding input-output dependences are shown in Fig. 2(a,b). The best performance was observed for T_{OC} = 3%.

In the quasi-CW mode, the 3 at.% Ho:KYW thin-disk laser generated a peak output power of 1.10 W at 2057 nm with a slope efficiency η of 66% (with respect to the absorbed pump power, P_{abs}). The laser threshold was at P_{abs} = 0.14 W. The 5 at.% Ho:KYW thin-disk laser provided an increased output power of 1.31 W (due to its higher absorption) at 2058 nm and 2073 nm albeit at a reduced slope efficiency, η = 34%, and an increased laser threshold, P_{abs} = 0.40 W. The inferior characteristics are attributed to the stronger thermo-optic aberrations and higher upconversion losses associated with stronger heat load at higher Ho^{3+} doping. However, neither fracture of the disks nor thermal roll-over of the output dependence were observed up to at least P_{abs} = 4.20 W.

In the CW regime, the difference in the output performance was more pronounced: the 3 at.% Ho:KYW thin-disk laser generated 1.01 W with η = 60% whereas the maximum output from the 5 at.% Ho:KYW thin-disk laser was only 0.24 W with η = 15%. In the latter case, laser operation ceased at P_{abs} ~2.1 W. The slope efficiency for the CW 3 at.% Ho:KYW thin-disk laser was higher than the one for Ho:YAG [6].

The typical emission spectra of both lasers are shown in Fig. 2(c). The spectra contain multiple lines due to the etalon effects in the disk. For the 3 at.% Ho:KYW thin-disk laser, the emission wavelength was weakly dependent on the OC. However, for the 5 at.% Ho-doped one, the emission was at 2072-2076 nm for T_{OC} = 1.5%, two emission bands were observed for T_{OC} = 3% and again only one band at 2056-2059 nm for T_{OC} = 5%. This spectral shift is due to the quasi-three-level nature of the Ho^{3+} laser [11] while the effect of Ho^{3+} concentration is due to the increasing reabsorption losses.

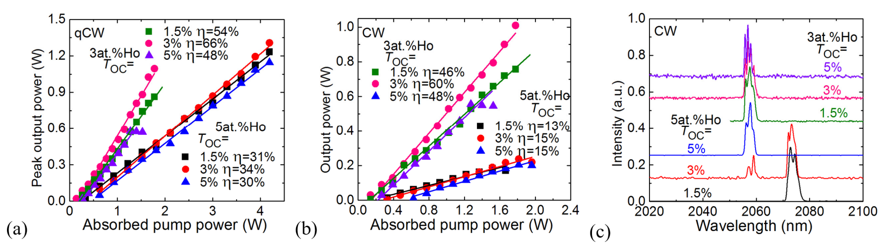

Fig. 2. (a,b) Input-output dependences for the 3 and 5 at.% Ho:KYW thin-disk lasers in quasi-CW (qCW, duty cycle 1:2) (a) and CW (b) operation modes (*symbols*: experimental data, *lines*: fits for the calculation of the slope efficiency η); (c) typical laser emission spectra for the Ho:KYW thin-disk lasers for various OCs (CW regime, P_{abs} ~1.7 W). The laser polarization is $\boldsymbol{E} \parallel N_m$.

3.2 Thermo-optic effects

To characterize the thermo-optic effects in the Ho:KYW thin-disk lasers, we studied the variation of the spatial intensity profile of the laser beam with P_{abs}, Fig. 3(a,b). A pyrocamera SPIRICON PY-III-C-B located at 20 cm from the OC and an AR-coated 50 mm CaF_2 focusing lens were used for recording the beam profiles.

For the 3 at.% Ho:KYW thin-disk laser, the beam was nearly circular at the threshold. For higher P_{abs}, it expanded and became elliptic, Fig. 3(a). Similarly to the bulk MDTs the active media are cut along the ***b***-axis. The orientation of the major and minor semiaxes of the elliptic beam (A and B, respectively) was related to the anisotropy of the thermal expansion of the KYW host crystal [15], namely A $\parallel$ X'_3 and B $\parallel$ X'_1 where

X'$_i$ (i = 1, 2, 3) are the principal axes of the eigen-frame of the thermal expansion tensor α_{mn} [16]. In this way, the elliptic laser beam was rotated with respect to the polarization direction ($\boldsymbol{E} \parallel N_m$) at an angle X'$_1$^$N_m$ ~30° [16]. For the 3 at. % Ho:KYW laser and P_{abs} = 1.78 W, Fig. 3(a), the measured beam ellipticity $e = w_L(B)/w_L(A)$ was 0.64 and the measured beam quality factors were $M^2_A = 3$ and $M^2_B = 1.6$.

For the 5 at.% Ho:KYW thin-disk laser, the beam was already slightly distorted even at the laser threshold. With the increase of P_{abs}, it was confined and became extended along the vertical direction so that the A and B semiaxes were oriented along the vertical and horizontal directions, respectively, Fig. 3(b). It was not possible to associate them with the X'$_i$ axes which might indicate a strong effect of the pump geometry. The beam ellipticity e was 0.60 and $M^2_A = 1.5$, $M^2_B = 1.4$ (at P_{abs} = 1.75 W). For P_{abs} > 1.9 W, a multimode output was observed.

In the quasi-CW pumped regime the distortions of the beam profiles were reduced, Fig. 3(c). As a consequence the 5 at.% Ho:KYW thin-disk laser could be operated up to much higher pump levels.

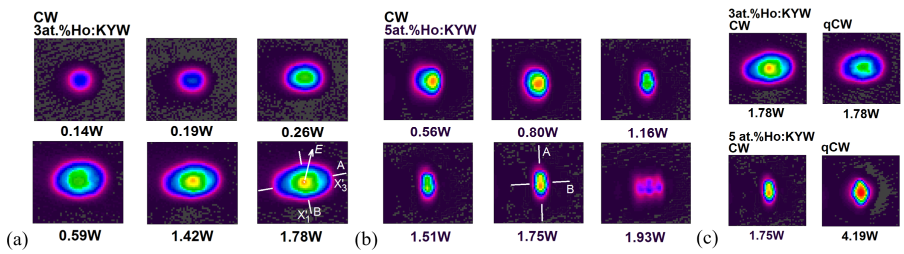

Fig. 3. (a,b) Spatial profiles of the output laser beam for the 3 at.% Ho:KYW (a) and 5 at.% Ho:KYW (b) thin-disk lasers measured at different P_{abs} as indicated by the numbers below the figures (CW regime, T_{OC} = 1.5%); (c) comparison of the spatial profiles of the output laser beam for the 3 and 5 at.% Ho:KYW thin-disk lasers in the CW and quasi-CW (qCW) regimes.

The observed distortions of the output beam were modeled within the ray transfer matrix formalism (ABCD law) assuming a thin astigmatic thermal lens (TL) located in the active layer and are characterized by the optical (refractive) power of D_A (D_B) [15]. The results are shown in Fig. 4(a). For the designed cavity, according to the ABCD modelling, a negative (defocusing) lens will lead to the beam expansion in the far-field and a positive (focusing) lens – to a beam compression. For the 3 at.% Ho:KYW thin-disk laser, a purely negative TL (e.g., with $D_{A(B)} < 0$ for both principal meridional planes containing the A and B directions [17]) was determined with the so-called sensitivity factors ($M_{A(B)} = dD_{A(B)}/dP_{abs}$) of $M_A = -1.7$ and $M_B = -0.6$ m^{-1}/W. The astigmatism degree $S/M = |M_A - M_B|/|M_A|$ is then 59%.

For the plane stress approximation suitable for laser disks [17], the sensitivity factors of an astigmatic TL can be represented as $M_{A(B)} = [\eta_h/(\pi\kappa w_p^2)] \times \varDelta_{A(B)}$, where η_h is the fractional heat loading estimated as $\eta_h \approx 1 - \eta_{St} = 1 - \lambda_p/\lambda_L$, κ is the thermal conductivity, and $\varDelta_{A(B)}$ is the "generalized" thermo-optic coefficient (TOC), namely $\varDelta_{A(B)} = dn/dT + P_{PEA(B)} + (1 + \nu^*_{A(B)})(n - 1)\alpha$ [17]. Here, the three terms stand for the temperature dependence of the refractive index (expressed by TOC, dn/dT), the photo-elastic effect P_{PE}, and the macroscopic bulging of the surface of the laser disk ($\nu^*_{A(B)}$ is the "generalized' Poisson ratio and n is the refractive index).

The TOC of KYW is negative at ~2 μm, $dn_m/dT = -8.9 \times 10^{-6}$ K^{-1} [18]. However, the photo-elastic term and the end-bulging one are known to be positive for ***b***-cut MDT laser elements [15] and thus a positive $\varDelta_{A(B)}$ is typically observed for at least one principal meridional plane (typically, along the X'$_1$-axis). For the ***b***-cut 3 at.% Ho:KYW/KYW thin-disk, the substrate acting as an undoped cap efficiently diminishes the end-bulging and thus a negative TL is observed for both principal meridional planes, as expressed by the calculated $\varDelta_A = -6.5$ and $\varDelta_B = -2.3 \times 10^{-6}$ K^{-1}.

In contrast, for the 5 at.% Ho-doped thin-disk, the beam compression (Fig. 3(b)) and even laser ceasing for P_{abs} ~2.1 W (CW regime) can be explained only by the action of a

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strong positive TL. The corresponding sensitivity factors are estimated to be $M_B = 5.2$ and $M_A = 0.5$ m^{-1}/W. We attribute this to a strongly localized heat load leading to an increased disk bulging which acts as a positive lens counteracting the negative dn/dT. The disk bulging is facilitated by the inclination of the pump beam (angle of incidence: ~10°) and the strongly anisotropic thermal expansion in the disk plane (e.g., the crystallographic ***a-c*** plane of KYW) [16]. The positive TL leads to the cavity instability and to the observed termination of the laser operation. Moreover, we believe that the same effect prevented laser operation of the 7 and 10 at.% Ho:KYW thin disks.

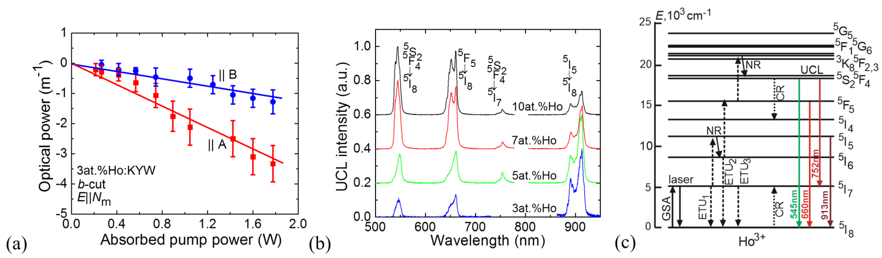

Fig. 4. (a) Optical power of the TL in the 3 at.% Ho:KYW thin disk along A(B) directions (*symbols*: experimental data, *lines*: Linear fits for the calculation of the sensitivity factors M); (b) upconversion luminescence (UCL) spectra of the 3 - 10 at.% Ho:KYW/KYW epitaxies, λ_{exc} = 1960 nm; (c) scheme of the energy levels of the Ho^{3+} ion showing relevant processes: GSA – ground-state absorption, ETU – energy-transfer upconversion, CR – cross-relaxation, NR – nonradiative relaxation.

ML of a thin-disk laser requires the lowest order transverse mode operation. In our case, the beam quality was limited by a relatively strong astigmatic thermal lens arising from (i) small pump spot size, (ii) asymmetric pump geometry and (iii) light propagation along the ***b*** (N_p) axis. As the M-factor of the thermal lens is proportional to $1/w_p^2$, an increase of the pump spot size will efficiently reduce the thermo-optic aberrations. Moreover, anisotropic MDTs offer an “athermal” behavior for certain directions of light propagation [16,18] (e.g., along the N_g axis), and both the unwanted negative sign of the thermal lens and its astigmatism can be neglected for “athermal”-cut laser elements [12].

The effect of Ho^{3+} concentration was also monitored by measuring the upconversion luminescence (UCL) spectra, Fig. 4(b). For low (3 at.% Ho) doping, the dominant emission is from the $^5I_5$ state (at ~913 nm), which is populated by the phonon-assisted energy-transfer upconversion (ETU) process ETU$_1$ ($^5I_7 + {}^5I_7 \rightarrow {}^5I_5 + {}^5I_8$) [19], Fig. 4(c). For higher Ho^{3+} doping, the dominant emissions occur from the higher-lying thermally coupled $^5S_2 + {}^5F_4$ states (at ~545 nm, to the $^5I_8$ ground-state, and at ~725 nm, to the $^5I_7$ excited-state) and from the $^5F_5$ state (at ~660 nm, to the ground-state) which are populated through different ETU and cross-relaxation (CR) processes whose efficiency is enhanced with the Ho^{3+} doping level, Fig. 4(b).

KYW has a maximum phonon energy $h\nu_{ph}$ of 905 cm^{-1} which is higher than that of YAG (~800 cm^{-1}). The shortest Y^{3+}-Y^{3+} distance for KYW (4.06 Å) is longer than that for YAG (3.67 Å). Thus, one can expect weaker upconversion for Ho:KYW. Focusing on KYW, Ho^{3+} doping with a concentration of >5 at.% seems to produce a relatively strong upconversion. Note that for Ho:YAG thin-disks [6], the Ho^{3+} doping is typically limited to about 2 at.% because of the same reason.

4. Conclusion

We demonstrated successful operation of Ho:KYW thin-disk lasers based on a Ho:KYW/KYW epitaxial structure grown by the LPE technology. The lasers are capable of delivering >1 W of output power at ~2056 or ~2073 nm with a slope efficiency as high as ~60% using a simple single-bounce pump geometry. Our study reveals the key role of the Ho^{3+} concentration on the output characteristics of such lasers (slope efficiency, beam profile and emission wavelength). The degradation of the laser output for >3 at.% Ho^{3+} doping is attributed to increasing thermo-optic distortions caused by disk bulging and a strong interaction of the Ho^{3+} ions leading to upconversion losses. Power scaling of these

Ho:KYW thin-disk lasers is feasible by optimizing the Ho^{3+} doping (1-3 at.%), simple pump retro-reflection with readjusted polarization for the second bounce, or alteration of the disk orientation (e.g., for light propagation along the N_g-axis). In the latter case, efficient laser operation with higher Ho^{3+} doping levels (5-7 at.%) can be expected.

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