Highly efficient Yb\textsuperscript{3+}-doped channel waveguide laser at 981 nm

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Abstract: Channel waveguide lasers operating at 981 nm are demonstrated in KY\textsubscript{1−x}Gd\textsubscript{x}Lu\textsubscript{y}(WO\textsubscript{4})\textsubscript{2}:Yb\textsuperscript{3+} waveguides grown by liquid phase epitaxy onto undoped KY(WO\textsubscript{4})\textsubscript{2} substrates and microstructured by Ar\textsuperscript{+} beam etching. Under pumping at 934 nm of samples with different waveguide geometry and outcoupling degree, a record-high slope efficiency of 76% versus absorbed pump power and a record-high output power of 650 mW for rare-earth-ion-doped microstructured channel waveguide lasers is achieved. The laser performance is compared to that of the same devices when pumping at 981 nm and lasing near 1025 nm.

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OCIS codes: (230.7380) Waveguides, channeled; (140.3615) Lasers, ytterbium.

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1. Introduction

The central line of absorption and emission between two crystal-field multiplets is the transition involving the lowest Stark level of each multiplet. Due to the large Boltzmann population of this Stark level and the selection rules that apply to the individual crystal-field transitions, the central line is often the transition with the largest effective absorption and emission cross-section. As the example investigated here, Fig. 1 shows (a) the energy level scheme, indicating the relevant transitions, and (b) the absorption and emission spectra of KY(WO4)2:Yb3+ with the dominant central line at 981 nm.

![Fig. 1. (a) Yb3+ 2F5/2 and 2F7/2 crystal-field multiplets with Stark-level energies in KY(WO4)2 and transitions from the lowest, highly populated Stark level of each multiplet. (b) Emission and absorption cross-section spectra of KY0.40Gd0.433Lu0.150Yb0.017(WO4)2 (sample A). Indicated are the pump and laser wavelengths at which the laser operates.](image)

While an ideal four-level laser which terminates in a short-lived excited-state multiplet would naturally operate on the crystal-field transition that provides the largest emission cross-section, hence the lowest laser threshold, typical laser transitions which terminate in the ground-state multiplet, such as the Nd3+ 0.9 µm, Yb3+ 1 µm, Er3+ 1.5 µm, Tm3+ 1.9 µm, Ho3+ 2.1 µm, and Dy3+ 3 µm transitions, usually operate at longer wavelengths to avoid the strong reabsorption at the central line from the ground state. However, with increasing outcoupling
degree, i.e., decreasing total reflectivity $R_{\text{out}}$ provided by the cavity mirrors, the laser shifts to shorter wavelengths and can ultimately oscillate on the central line [2]. This shift of laser wavelength can be examined by comparing the threshold excitation densities $N_2$ of the upper multiplet (level 2) for the competing laser transitions from its Stark levels $i$ with Boltzmann factors $b_{2i}$ to the different Stark levels $j$ of the lower multiplet (level 1) with Boltzmann factors $b_{1j}$ via solving the round-trip equation for the intra-cavity photon number in ground-state lasers under the condition that the gain equals the losses:

$$ (1 - 2\alpha\ell)R_{\text{out}} \exp\left(2\ell\Gamma\left[ b_{2i} N_2 - b_{1j} (N_1 - N_2) \left| \sigma_{2i\rightarrow j} \right| \right] \right) = 1 $$

$$ \Rightarrow N_2 = \frac{-\ln\left(1 - 2\alpha\ell\right) R_{\text{out}} / (2\ell\Gamma\left| \sigma_{2i\rightarrow j} \right|) + b_{1j} N_1}{(b_{2i} + b_{1j})} \quad \text{(1)} $$

The parameters occurring in Eq. (1) are explained in Table 1. In our case, relevant are only the four transitions from the lowest Stark level $i = 1$ of the upper multiplet (red arrows in Fig. 1) because of its large Boltzmann factor of $b_{21} = 0.748$.

| Quantity | Parameter | Value |
|----------|-----------|-------|
| Dopant concentration | $N_d$ | $1.08 \times 10^{20} \text{ cm}^{-3}$ |
| Excitation density | $N_2$ | see Fig. 2 |
| Mode overlap with active waveguide geometry | $\Gamma$ | 0.82 |
| Waveguide length | $\lambda$ | 0.66 cm |
| Propagation loss | $\alpha$ | 0.34 dB/cm |
| Mirror reflectivity | $R_{\text{out}}$ | see Fig. 2 |
| Boltzmann factors $b_{2i}$ and $b_{1j}$ of Stark levels 1 and 1 in upper and lower laser level, respectively, at 300 K | $b_{21}$ | 0.748 |
| | $b_{11}$ | 0.605 |
| | $b_{12}$ | 0.269 |
| | $b_{13}$ | 0.086 |
| | $b_{14}$ | 0.040 |
| | $\sigma_{2i\rightarrow j}$ from Fig. 1(b) | $\sigma_{21\rightarrow 14} \times b_{21}$ | $0.05 \times 10^{-17} \text{ cm}^2$ |
| | | $\sigma_{21\rightarrow 13} \times b_{21}$ | $0.29 \times 10^{-17} \text{ cm}^2$ |
| | | $\sigma_{21\rightarrow 12} \times b_{21}$ | $0.50 \times 10^{-17} \text{ cm}^2$ |
| | | $\sigma_{21\rightarrow 11} \times b_{21}$ | $1.34 \times 10^{-17} \text{ cm}^2$ |

2. Threshold analysis and resulting laser wavelength

The potassium double tungstates KY(WO$_4$)$_2$, KGd(WO$_4$)$_2$, and KLu(WO$_4$)$_2$ [3] are attractive laser materials due to the extremely large transition cross-sections of Yb$^{3+}$ ions doped into these hosts. Planar [4, 5] and channel [6] waveguide lasers were demonstrated in KY(WO$_4$)$_2$:Yb$^{3+}$. Co-doping with Gd$^{3+}$ and Lu$^{3+}$ ions [7] simultaneously allows for lattice matching with the undoped substrate, increased refractive index for tighter light confinement, and variation of Yb$^{3+}$ concentration between 0% and 53% [8], which so far has resulted in slope efficiencies of 82.3% versus absorbed power in Yb$^{3+}$-doped planar waveguide lasers [9] and 72% (71%) versus absorbed (launched) power in channel waveguide lasers [10].

The absorption and emission cross-sections in KY$_{1-x-y-z}$Gd$_x$Lum$_y$Yb$_z$(WO$_4$)$_2$ composite layers were derived [8] as weighted averages of the spectra measured in the compounds KY(WO$_4$)$_2$:Yb$^{3+}$ [1], KGd(WO$_4$)$_2$:Yb$^{3+}$ [11], KLu(WO$_4$)$_2$:Yb$^{3+}$ [12], and stoichiometric KYb(WO$_4$)$_2$ [13]. For KY(WO$_4$)$_2$:Yb$^{3+}$ the emission spectrum presented in [1] was calculated incorrectly from the measured absorption spectrum and, therefore, had to be recalculated [8]. The threshold analysis for the two investigated KY$_{1-x-y-z}$Gd$_x$Lum$_y$Yb$_z$(WO$_4$)$_2$ channel waveguides according to Eq. (1) based on the convoluted spectra confirmed the observed laser threshold behavior.

For transitions with small cross-sections, the first term in the numerator of Eq. (1) becomes relevant and the threshold increases drastically with decreasing $R_{\text{out}}$, while for the
central line with its large cross-section the threshold is only weakly influenced by $R_{\text{out}}$. For the four emission transitions of KY(WO$_4$)$_2$:Yb$^{3+}$ indicated by the red arrows in Fig. 1(a), the corresponding threshold excitation densities $N_2$, estimated from Eq. (1) and the values given in Table 1, change in such way that the laser wavelength shifts from 1025 nm at high $R_{\text{out}}$ to the central line at 981 nm for low $R_{\text{out}}$ (Fig. 2). Nevertheless, only by intense pumping at shorter wavelengths one can achieve the high excitation densities of ~50% required to operate a laser at the central line (Fig. 2), as has been observed experimentally in KY(WO$_4$)$_2$:Yb$^{3+}$ bulk crystals [14].

![Fig. 2. Relative threshold excitation densities of the emission lines indicated by the red arrows in Fig. 1(a) in the investigated KY$_{0.40}$Gd$_{0.15}$Lu$_{0.15}$Yb$_{0.017}$(WO$_4$)$_2$ channel waveguide (sample A) as a function of $R_{\text{out}}$, estimated from Eq. (1) and the values given in Table 1.](image)

The attractiveness of lasing at the central line becomes apparent in integrated waveguides. Firstly, like in fiber lasers operating at this transition [15], the required high inversion can easily be achieved due to the strong pump-light confinement and, consequently, high pump intensity. Secondly, the large gain of up to 935 dB/cm obtained at 981 nm when strongly inverting highly Yb$^{3+}$-doped waveguides in a non-lasing situation [16] can establish threshold inversion in integrated resonators with low reflectivity, e.g. based on Bragg gratings [17] or cavities with Fresnel reflection from one [18] or two [19] waveguide end facets. Thirdly, while the propagation losses in integrated waveguides are typically high and contribute a significant fraction to the total cavity losses, the low $R_{\text{out}}$ required to operate the laser at the central line increases the fraction of useful cavity losses, thereby enhancing the slope efficiency. By exploiting the latter fact, in this work we demonstrate waveguide lasing with a slope efficiency of 76% versus absorbed pump power, which, to the best of our knowledge, represents the highest slope efficiency reported for any rare-earth-ion-doped microstructured channel waveguide laser to date. Combining such a central-line laser with the high-gain amplifier previously demonstrated [16] at this wavelength can provide a very attractive configuration for high-power (Watt-level) integrated optics.

3. Experimental

KY$_{1-x-y}$Gd$_x$L$_y$Y$_b$(WO$_4$)$_2$ layers were grown onto undoped, (010)-orientated, laser-grade polished KY(WO$_4$)$_2$ substrates of 1 cm$^2$ size by liquid phase epitaxy in a K$_2$W$_2$O$_7$ solvent [20] at temperatures of 920-923°C using the vertical dipping method. While the Yb$^{3+}$ concentration was chosen to optimize pump absorption and laser performance, the fractions $x$ and $y$ of Gd$^{3+}$ and Lu$^{3+}$ ions, respectively, were calculated according to the procedure outlined in Ref [8], to ensure lattice matching with the undoped KY(WO$_4$)$_2$ substrate. Subsequently,
the layer surface was polished parallel to the layer-substrate interface with a rms surface roughness of 1.5 nm. A KY$_{0.40}$Gd$_{0.43}$Lu$_{0.150}$Yb$_{0.017}$(WO$_4$)$_2$ layer (sample A) was polished to a thickness of 2.4 µm, while a KGd$_{0.490}$Lu$_{0.485}$Yb$_{0.025}$(WO$_4$)$_2$ layer (sample B) was polished to a thickness of 5 µm. Both layers were microstructured by standard lithography and Ar$^+$ beam etching [21] to obtain 7-µm-wide, 1.4-µm-deep ridge waveguides along the $N_g$ optical axis. To improve mode overlap with the active region, diminish propagation losses, and facilitate end-face polishing, both samples were overgrown by an undoped KY(WO$_4$)$_2$ cladding. The end faces of each sample were polished parallel to the $N_m$ optical axis, resulting in a waveguide length of 7.0 mm (re-polished from 7.5 mm after previous investigations [21]) and 6.6 mm [10] for sample A and B, respectively.

The waveguides were end-pumped by a continuous-wave Ti:Sapphire laser operating at ~934 nm with its polarization parallel to the $N_m$ optical axis. The pump laser was mechanically chopped with a 50% duty cycle at a frequency of 200 Hz. Pump light was coupled into the channel waveguide using a × 16 objective lens with a numerical aperture (N.A.) of 0.32. With a variable beam expander in the pump-beam line the pump mode was adapted to the slightly lower N.A. of the channel waveguides. By use of mode-solver software (Phoenix FieldDesigner [22]) a coupling efficiency of 88% and 82% (excluding Fresnel reflection) was calculated for the pump light, of which ~62% and ~80% was absorbed in sample A and B, respectively. The waveguide geometries and calculated [22] fundamental laser modes are presented in the insets of Fig. 3. Sample A additionally supports propagation of a weakly confined higher-order laser mode, while no higher-order modes were found by the mode-solver software for sample B. Considering the higher refractive index contrast and larger waveguide dimensions of sample B, this result is counter-intuitive, but is known from Petermann structures [23]. The cavity of sample A was formed by the 11% Fresnel reflection at the pumped waveguide end-facet and a mirror with 97% reflectivity at 981 nm butt-coupled to the other end-facet by fluorinated oil (Fluorinert FC-70), resulting in $R_{out} = 11\%$. The emitted laser light was collected from the pumped end via a beam splitter placed into the pump beam. A reflective grating was used to separate the laser emission from residual pump light. The cavity of sample B was formed by the Fresnel reflections from both waveguide end-facets, providing $R_{out} = 1.2\%$. Here, the emitted light was monitored only from the unpumped end in order to launch the maximum available pump power. The measured emitted power was multiplied by a factor of two to account for emission from the pumped end. This is a conservative estimation, since according to our rate-equation calculations counter-propagating laser light is more efficiently amplified than co-propagating laser light.

For comparison with the usual lasing situation, experiments were also performed by pumping at 981 nm. In this case mirrors were butt-coupled on both waveguide ends, resulting in $R_{out} = 77\%$ at 1028 nm (sample A) or $R_{out} = 30\%$ at 1023 nm (sample B).

4. Laser results

The measured laser performance at 981 nm, displayed as green triangles in Figs. 3(a) and 3(b), reveals slope efficiencies of 76% and 72% (green solid lines) versus absorbed pump power and maximum output powers of 77 mW and 650 mW for sample A and B, respectively. The pump threshold was 13 mW and 130 mW of absorbed pump power in case of sample A and B, respectively. The laser emission spectrum from sample B was analyzed by a spectrometer (Jobin-Yvon iHR550) with a resolution of 0.11 nm. The emission peak occurred at a wavelength of 981 nm with a width of 0.5 nm. In comparison, when pumping at 981 nm, lasing occurred at 1023–1028 nm with slope efficiencies of 62% and 72%. Since in these experiments the mirror reflectivities at the laser wavelength were chosen to be significantly higher, hence outcoupling losses were significantly smaller, lower pump thresholds of 5.5 mW and 30 mW resulted for samples A and B, respectively.
Despite the significantly larger reabsorption cross-section on the central line at 981 nm, equal or even higher slope efficiencies are obtained for lasing on this transition (Fig. 3, green triangles) compared to laser performance at longer wavelengths of 1023–1028 nm (Fig. 3, red squares). At first glance this may be counter-intuitive, because reabsorption reduces the efficiency of the laser process. However, there is a large difference in the applied outcoupling efficiency between laser operation at the central line and at longer wavelengths. The much larger outcoupling degree used at the central line laser operation increases the threshold inversion and available gain, thus compensating the accordingly decreased reabsorption losses, while simultaneously increasing the useful outcoupling losses. These effects explain the highly efficient laser operation of these laser devices at the central line. The fact that in sample B the slope efficiency is the same for both operational regimes could be explained by the conservative estimation of monitored laser output power at 981 nm, which was based on the assumption that equal power is emitted from both waveguide ends.

5. Summary

From the calculated emission cross-section spectra and chosen resonator outcoupling degrees, the output wavelength characteristics of Yb$^{3+}$-doped KY$_{1-x-y}$Gd$_x$Lu$_y$(WO$_4$)$_2$ channel waveguide lasers was analyzed, based on the laser round-trip equation. The large gain which is present on the central line at 981 nm in Yb$^{3+}$-doped potassium double tungstate channel waveguides under pumping at a shorter wavelength of 934 nm was exploited in open cavities based on Fresnel reflection at one or both waveguide end-facets. In this configuration the large outcoupling efficiency leads to a large population inversion and accordingly reduced reabsorption on the central line. Furthermore, it diminishes the adverse influence of the fairly large intra-cavity propagation loss in a channel waveguide, resulting in the demonstration of a high slope efficiency of 76% and a total extracted laser power of 650 mW. This approach promises high efficiencies also for other laser transitions in rare-earth ions.

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Fig. 3. Measured power characteristics (symbols) and fitted slope efficiencies (lines) of the waveguide lasers based on (a) sample A and (b) sample B for pumping at 934 nm and lasing at 981 nm (green) and comparison with pumping at 981 nm and lasing at 1023–1028 nm (red). The insets show the modeled fundamental-mode profiles in these structures.