Highly Efficient Rare-earth-doped Waveguide Lasers

D. Geskus, K. van Dalfsen, F. Ay, S.M. García-Blanco, S. Aravazhi, and M. Pollnau

The potassium double tungstates $KGd(WO_4)_2$, $KY(WO_4)_2$, and $KLu(WO_4)_2$ are excellent candidates for solid-state lasers, see Ref. [1] and Refs. therein, because of their high refractive index of ~2.0-2.1, the large transition cross-sections of rare-earth (RE) ions doped into these hosts, the possibility to incorporate very large concentrations of RE^{3+} ions, reaching the stoichiometric structure $KRE(WO_4)_2$, a long inter-ionic distance of ~0.5 nm that allows for large doping concentrations without lifetime quenching, and a reasonably large thermal conductivity of ~3.3 W m^{-1} K^{-1}. These advantages have been exploited to demonstrate thin-disk lasers, broadly tunable and high-energy ultrashort-pulse lasers, and low-quantum-defect lasers.

1. Lattice-matched, High-refractive-index-contrast Double Tungstate Waveguides

We apply liquid phase epitaxy at temperatures of ~920°C in a $K_2W_2O_7$ solvent to grow RE^{3+}-doped double tungstate thin layers onto undoped, (010)-orientated, laser-grade polished KYW substrates of 1 cm^2 size, resulting in excellent layer and interface quality [2]. The first-ever laser operation of a double tungstate waveguide was demonstrated in 17-µm-thick KYW:Yb^{3+} planar layers with high slope efficiencies up to 80% [2].

A breakthrough was obtained by co-doping the active layer with optically inert Gd^{3+} and Lu^{3+} ions [3]. Since Gd^{3+} and Lu^{3+} change the lattice parameters in opposite directions, choice of the right fractions of these two ions allows for lattice matching of the RE^{3+}-activated layer with the undoped substrate. Besides, co-doping with large amounts of Gd^{3+} and Lu^{3+} ions increases the refractive index contrast between layer and undoped substrate by more than an order of magnitude to ~10^{-2} [4], thereby allowing for much thinner (only a few µm-thick) single-transverse-mode waveguides, resulting in tighter pump and laser mode confinement as well as easing the requirements on micro-structuring.

In such Yb^{3+}, Gd^{3+}, Lu^{3+} co-doped planar waveguides continuous-wave laser operation was observed at 1025 nm [5]. For 23% output coupling, an output power of 195 mW and a slope efficiency of 82.3% were obtained (Fig. 1, left). Recently, Yb^{3+}-doped potassium double tungstate planar waveguide lasers passively *Q*-switched by evanescent-field interaction with either carbon nanotubes (Fig. 1, right) [6] or graphene [7] were demonstrated.

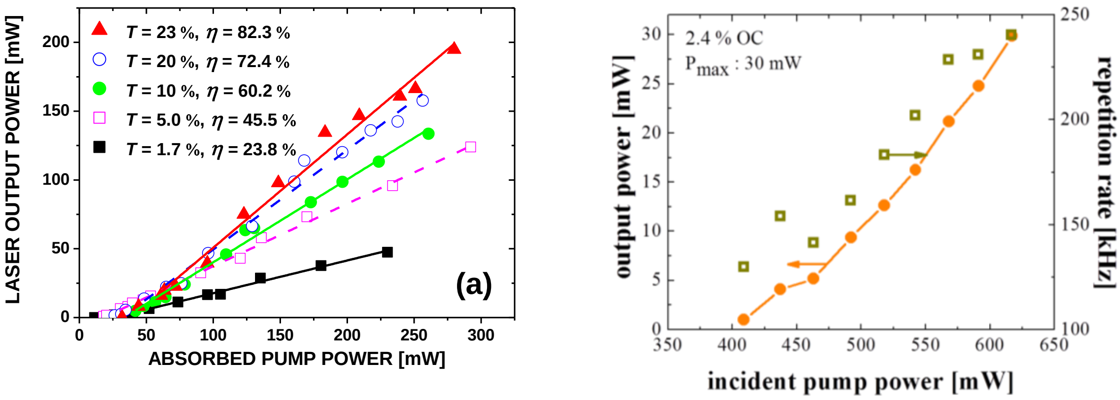

Fig. 1. (left) Laser output power from an Yb^{3+}, Gd^{3+}, Lu^{3+} co-doped planar waveguide as a function of absorbed pump power for various outcoupling mirror transmissions [5]. (right) Carbon-nanotube *Q*-switched Yb:KYW waveguide laser: average output power (solid line) and power-dependent repetition rate. [6].

2. Yb-doped Channel Waveguide Lasers

The small layer thickness of our co-doped waveguides greatly facilitates micro-structuring. By use of standard photo-resist as a mask and Ar^+ beam etching, we fabricated ridge channel waveguides in $KGd_xLu_yYb_{1-x-y}(WO_4)_2$ layers with cross-sections of a few μm^2 and excellent mode confinement (Fig. 2, left) [8]. This allowed us to demonstrate channel waveguide lasers with 418 mW of output power at 1023 nm and a slope efficiency of 71% versus launched pump power at 981 nm [9]. When operating the laser at the central line at 980.6 nm, these values were improved to 76% slope efficiency in a waveguide with small cross-section (Fig. 2, center) and 650 mW of output power in a waveguide with larger cross-section (Fig. 2, right) [10]. By grating tuning in an extended cavity and pumping at 930 nm, we demonstrated laser operation from 980 nm to 1045 nm [9]. When pumping at 973 nm, lasing at 980 nm with an extremely low quantum defect of 0.7% was achieved [9]. This is currently the world record for any rare-earth-ion-doped laser. Besides, by exploiting refractive-index engineering and high Yb^{3+} doping, we have demonstrated a cladding-side-pumped channel waveguide laser [4].

Following an approach for nano-structuring of silicon [11], deeply etched Bragg gratings were fabricated by focused ion beam (FIB) milling in $KGd_xLu_yYb_{1-x-y}(WO_4)_2$. Grating structures more than 4 µm in depth with a sidewall angle of ~5° were obtained. An on-chip integrated laser cavity at ~980 nm was achieved by defining a FIB reflective grating and FIB polished waveguide end-facet. With this cavity, an integrated waveguide laser was demonstrated in $KGd_xLu_yYb_{1-x-y}(WO_4)_2$ [12].

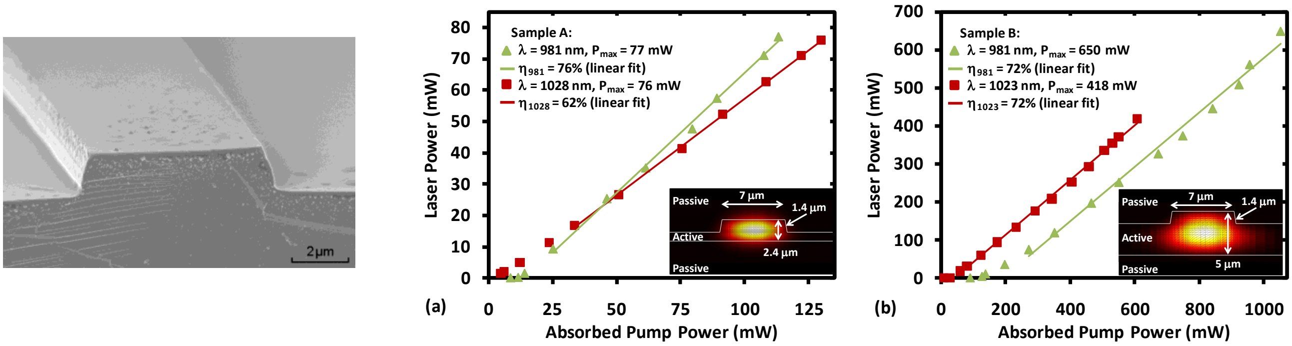

Fig. 2. (left) SEM micrograph of a microstructured channel waveguide before overgrowth [8]; (center and right) input-output curves of $KGd_xLu_yYb_{1-x-y}(WO_4)_2$ channel waveguide lasers pumped at 981 nm and lasing at 1023 nm [10].

3. Tm-doped Double Tungstate Waveguide Lasers

Doping with Tm^{3+} ions has resulted in similarly astounding laser performance. For the first time, planar waveguide lasing in the 2-µm spectral range was demonstrated in a double tungstate waveguide [13]. In our first $KY_{0.4}Gd_{0.295}Lu_{0.305}(WO_4)_2$:$Tm^{3+}$ channel waveguides with 1.5at.% Tm^{3+} doping, we demonstrated an output power of 149 mW and a slope efficiencies of 31.5%. The lowest threshold was 7 mW [14]. In channel waveguides with higher Tm^{3+} doping of 5at.% and 8at.%, a maximum slope efficiency of 70% and output powers up to 300 mW around 2.0 µm were obtained in a mirror-less laser resonator by pumping with a Ti:Sapphire laser near 800 nm [15]. Comparison of the laser performance at different dopant concentrations (Fig. 3, left) suggests that increasing the thulium concentration to 8at.% improves the cross-relaxation efficiency. Lasing was obtained at various wavelengths between 1810 nm and 2037 nm [15].

Recently, in an 8at.% doped channel waveguide we could increase the output power to 1.6 W and the slope efficieny to >80% (Fig. 3, right) [16]. This result represents the most efficient 2-µm channel waveguide laser to date.

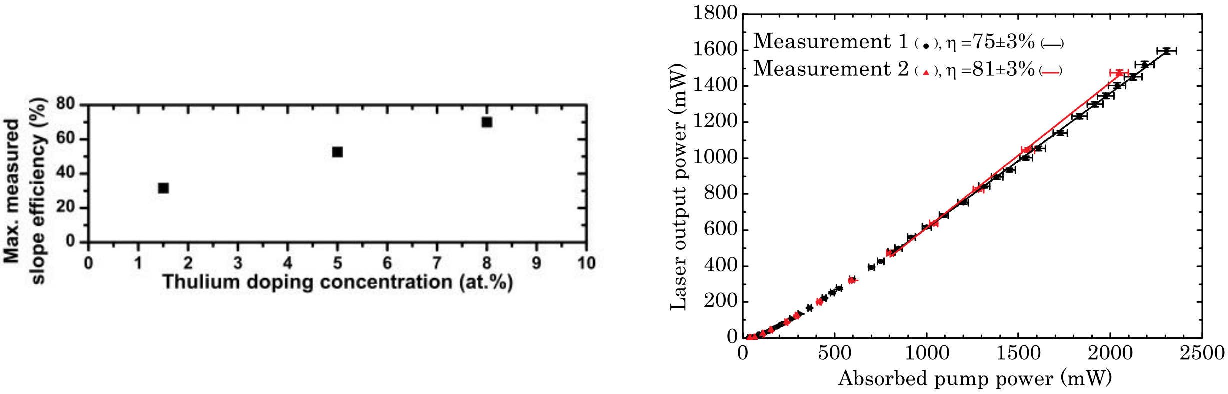

Fig. 3. (left) Maximum measured slope efficiencies for thulium-doped monoclinic double tungstate channel waveguide lasers with different doping levels [15]. (right) Laser output power at 1840 nm versus absorbed pump power at 794 nm in TM polarization. Displayed are two independent measurements (red and black dots) and linear fits of the laser slope efficiency at higher powers (red and black lines) [16].

The theoretical limit of the slope efficiency depends on the pump quantum efficiency η_q, which is influenced by the CR process ($^3H_4$, $^3H_6$) → ($^3F_4$, $^3F_4$) that quenches the effective luminescence decay time $\tau_{3,eff}$ of the $^3H_4$ pump level with incdreasing Tm^{3+} concentration (Fig. 4, left). If short-pulse excitation into the $^3H_4$ level is weak enough not to bleach the ground-state population density N_0, the decay is approximately exponential and the decay rate per unit time and volume of the $^3H_4$ population density N_3 is given by [16]

$$R_3 = -\left(\frac{1}{\tau_3} + W_{CR} N_0\right) N_3 = -\frac{1}{\tau_{3,eff}} N_3 , \quad \text{with} \quad W_{CR} = C_{CR} N_d \, . \tag{1}$$

W_{CR} is the macroscopic CR parameter, which is proportional to the dopant concentration N_d. With an intrinsic lifetime of τ_3 = 242 μs, we derive $C_{CR} = 2.5 \times 10^{-37}$ cm^6/s, resulting in $W_{CR} = 1.27 \times 10^{-16}$ cm^3/s for the relevant Tm^{3+} concentration of 5.07×10^{20} cm^{-3}. The pump quantum efficiency is [16]

$$\eta_q = 1 + \frac{W_{CR} N_0}{1/\tau_3 + W_{CR} N_0} , \quad \text{and} \quad \eta_{slope} = \frac{dP_{out}}{dP_{abs}} = \eta_{mode} \eta_{St} \eta_q \eta_{out} \, . \tag{2}$$

If ground-state bleaching is absent, $N_0 = N_d$, we obtain η_q = 1.94 for a Tm^{3+} conc. of $N_d = 5.07 \times 10^{20}$ cm^{-3} (Fig. 4, right). This laser has a mode overlap of η_{mode} = 1 and a Stokes efficiency of η_{St} = 794 nm / 1840 nm = 0.432. With an output-coupling efficiency of $\eta_{out} = \ln[1-T_{out}]/\ln[(1-T_{out})(1-L_{RT})]$ = 0.99, the theoretical limit of the slope efficiency η_{slope} is calculated to be 83%. The maximum experimental slope efficiency of 81% is only slightly lower than this theoretical limit [16].

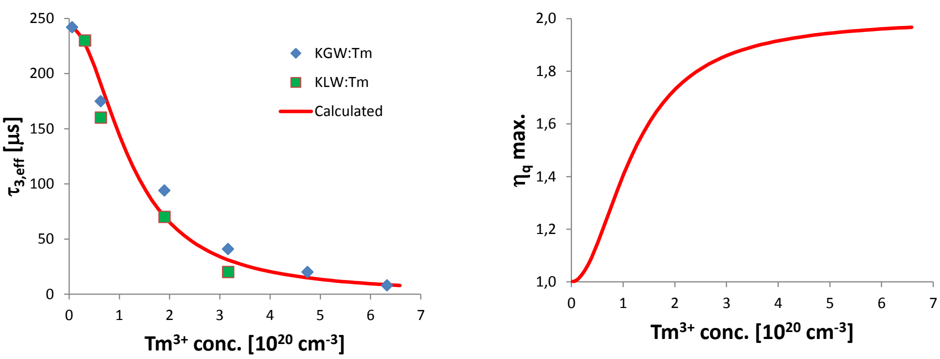

Fig. 4. (left) Effective luminescence decay time measured in $KGd(WO_4)_2$ (red circles) [Güell *et al.*, J. Appl. Phys. 95, 919 (2004)] and $KLu(WO_4)_2$ (black squares) [Silvestre *et al.*, Appl. Phys. B 87, 707 (2007)] and fit (red line) according to Eq. (1) [16]. (right) Maximum quantum efficiency according to Eq. (3) [16].

Collaborations

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