Efficient channel waveguide lasers based on thulium-doped double tungstates

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Monoclinic double tungstates, $KY(WO_4)_2$ (= KYW), co-doped with Gd^{3+}, Lu^{3+} and various Tm^{3+} concentrations of 1.5 - 8.0% were grown onto pure KYW substrates by liquid-phase epitaxy. Ridge-type channel waveguides were microstructured 1.5 µm deep by Ar^+-beam milling and overgrown with pure KYW. Lifetime measurements on the upper laser level ($^3F_4$) were performed for the different concentrations. Laser experiments on the 1.5% Tm^{3+}-doped channel waveguides revealed slope efficiencies as high as 31.5% and output powers up to 149 mW. Through measurements of the laser relaxation-oscillation frequency, an upper value of ~0.11 dB/cm for the waveguide propagation loss at the laser wavelength was determined.

Introduction

Sensing applications for health and (bio-)industries, based on absorption measurements in the 2-µm region require compact laser sources with output powers beyond tens of milliwatts. Gases such as CO_2 and NH_3 have absorption bands around 2 µm and can act as biomarkers for diseases. The sensitivity of absorption measurements greatly increases as more optical power is available, but up until now compact laser sources in the 2-µm region provide only several tens of milliwatts of output power. Amplification of the laser output by use of rare-earth-ion-doped fiber amplifiers has been used in various experiments, but this increases the form factor and cost of the detectors significantly [1]. Emission around 2 µm is provided by thulium, with it emission from ~1800 nm to well beyond 2000 nm. Highly efficient lasers with slope efficiencies up to 69% based on thulium in fibers and YAG have been demonstrated [2,3]. The demonstration of an even more efficient planar waveguide laser (>82%), based on Yb in KYW, more recently [4], has led us to believe that efficient thulium-based channel waveguide lasers in this host material is feasible. In this paper, we report on thulium-co-doped channel waveguide lasers with output powers exceeding 100 mW and slope efficiencies of 31.5%, which represents an important step forward toward compact and inexpensive gas detectors based on optical detection principles.

Fabrication

Pure substrates of KYW were overgrown with Tm-Y-Gd-Lu-co-doped layers with concentrations of 1.5 – 8.0 at.% Tm^{3+} using liquid-phase epitaxy (LPE). The layers, with an as-grown thickness of several tens of micrometers, were lapped and polished to a laser-grade surface uniformity. A photoresist mask was deposited onto the layers and patterned. Ar^+-beam milling was applied to the samples to produce ridge-type channel waveguides with widths of 7.5 – 25 µm and a maximum etch-depth of 1.9 µm [5]. Afterwards, the channels were overgrown with a pure KYW cladding layer to ensure a symmetric waveguide with good spatial overlap between the pump and laser modes and the doped layer. The sample with 1.5 at.% of Tm^{3+} was diced to a length of 8.4 mm and end-face polished to an optical finish.

Lifetime assessments and laser experiments

Lifetime measurements and laser experiments were carried out using a Ti:Sapphire pump laser at a wavelength of 794 nm with a transverse-magnetic (TM, $E \| N_p$) polarization. In-coupling of pump light into the channels was optimized using cylindrical lenses with focal lengths of 40 mm and 10 mm in horizontal and vertical directions, respectively. Luminescence originating from the $^3F_4$ upper laser level on de-excitation into the $^3H_6$ ground level was collected by a standard 9-µm fiber into a monochromator and focussed onto an InGaAs detector connected to an oscilloscope. The upper laser level lifetime was calculated from the exponential decay of the luminescence intensity that corresponds to the upper laser level population.

Laser experiments on the 1.5 at.% Tm^{3+}-doped sample were performed by butt-coupling dielectric mirrors with a reflectivity of 99.99% (HR) & 2%, HR & 8%, and twice 8% to either ends of the channel waveguides, using index-matching fluid. The laser output power was out-coupled from the other waveguide end via a microscope objective with a numerical aperture of NA = 0.25 and measured. The laser light was passed through a RG1000 high-pass filter to block any residual pump power. The laser wavelength was measured using a spectrometer and an oscilloscope was used to determine the relaxation-oscillation frequency.

Lifetimes and laser performance

Figure 1a shows the $^3F_4$ upper laser level lifetime as a function of the Tm^{3+} concentration in different samples. The lifetime decreases from 1.42 ms for a Tm^{3+} concentration of 1.5 at.% to lifetimes of 1.33, 1.23 and 1.13 ms for Tm^{3+} concentrations of 3.0, 5.0 and 8.0 at.%, respectively. The decrement of the laser level lifetime can be attributed to a decrease of the average thulium ion-ion distance, facilitating up-conversion as well as cross-relaxation processes, as the thulium concentration increases.

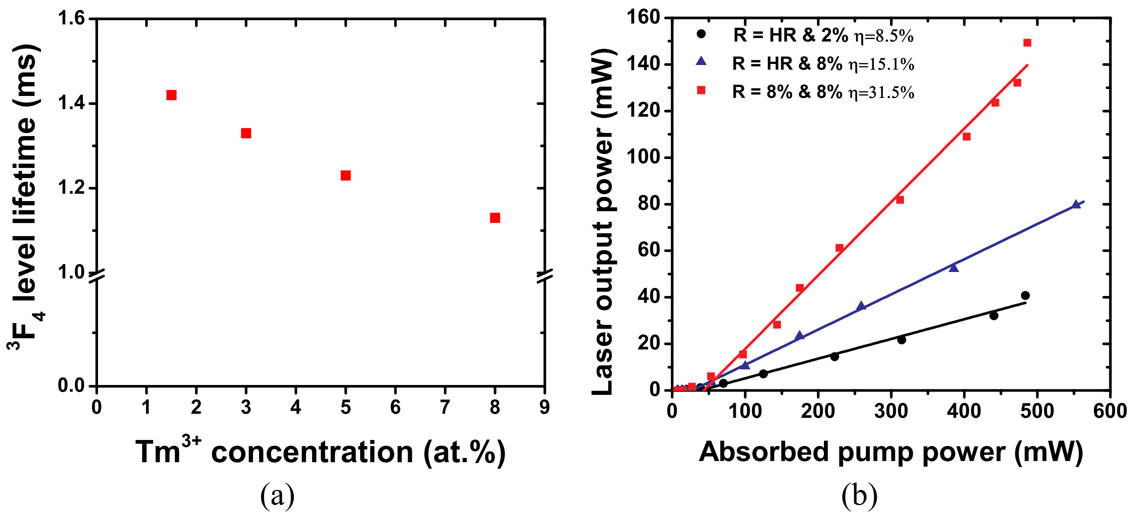

Fig 1. a) The $^3F_4$ upper laser lifetime as a function of Tm^{3+} concentration in a co-doped double tungstate channel waveguide. b) The laser output power of a 1.5 at.% Tm-doped channel waveguide pumped at 794 nm in TM polarization.

The laser output power as a function of absorbed pump power is displayed in Fig. 1b. A maximum slope efficiency of 31.5% and a maximum output power of 149 mW was measured with 16% out-coupling (8% out-coupling from both end-facets). Output powers and slope efficiencies decreased to a 80 mW and 41 mW, and 15.1% and 8.5%, for out-coupling efficiencies of 8% and 2%, respectively. The laser with 2% out-coupling started lasing at a threshold pump power of only 7 mW.

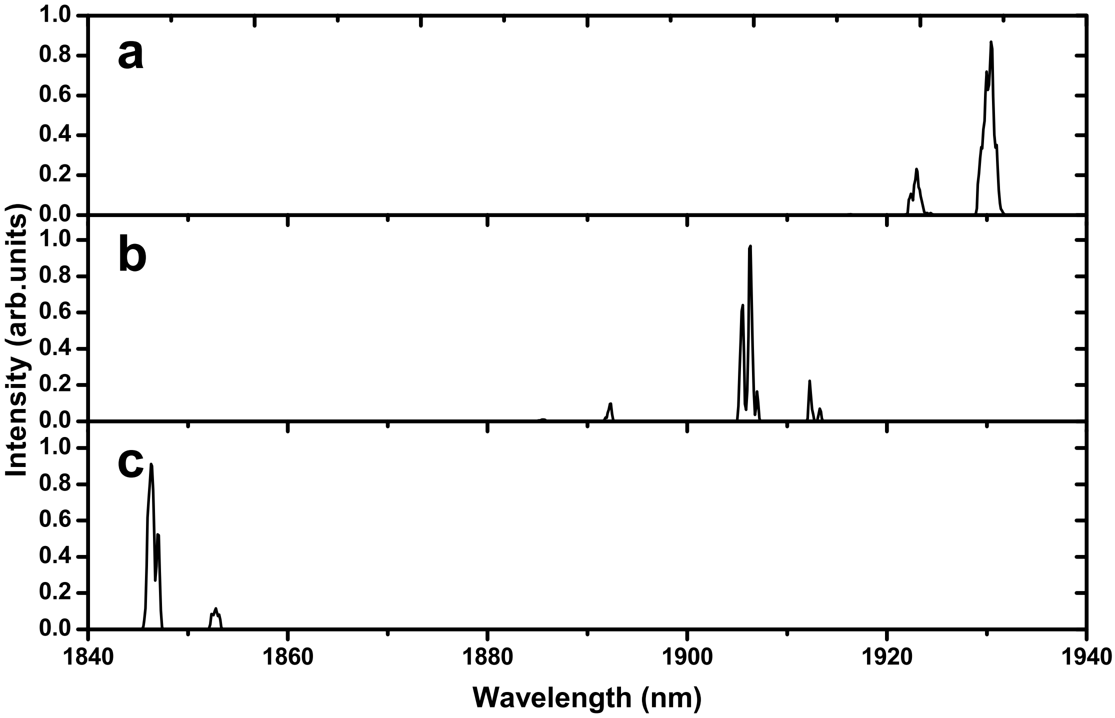

Fig 2. Laser spectra of a 1.5 at.% Tm-doped channel waveguide pumped at 794 nm in TM polarization.with an outcoupling efficiency of: a) 2% b) 8% c) 16%.

The laser spectra for different mirror combinations were recorded and shown in Figure 2. For an out-coupling efficiency of 2%, the laser was found to oscillate around 1930 nm. The laser wavelength shifted via 1906 nm for 8% out-coupling to 1846 nm when 16% of the laser light was out-coupled. As the out-coupling efficiency increases, and hence the cavity losses, the threshold inversion increases and the laser is forced to operate at lower wavelengths where the maximum gain is higher.

Via measurements of the relaxation-oscillation frequency, an upper limit for the waveguide propagation loss of 0.11 ± 0.4 dB/cm was calculated [6,7].

Conclusions

Lifetimes of the $^3F_4$ upper laser level have been calculated from luminescence decay measurements, yielding lifetime values of 1.42, 1.33, 1.23, and 1.13 ms, for Tm^{3+} concentrations of 1.5, 3.0, 5.0, and 8.0 at.%, respectively. Laser experiments on a 1.5 at.% thulium-doped channel waveguide with butt-coupled mirrors demonstrated a maximum slope efficiency of 31.5% and an output power of 149 mW, when pumped at 794 nm in TM polarization. The operating wavelength of the laser could be tuned from 1846 nm via 1906 nm to 1930 nm, by using different out-coupling mirror configurations of 16%, 8%, and 2%, respectively. The demonstrated slope efficiency and output powers around 2 μm will allow for more sensitive detection of gases at this wavelength.

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