

Ultra-high Gain in a Rare-earth-doped Micro-structure

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Rare-earth-doped amplifiers and lasers in bulk and fiber geometries have conquered numerous areas of applications. In contrast, the world of miniaturized light sources has been dominated by semiconductor materials and devices. Since the de-coherence time of excited states is on the same order of magnitude in semiconductor and rare-earth-doped materials, the allowed optical transitions of electron-hole-pair recombination in semiconductors result in the related transition cross-sections being orders of magnitude larger than those of parity-forbidden transitions within the $4f$ atomic sub-shell of rare-earth ions [1], see e.g. the comparison in Table 1 of Ref. [2]. Consequently, semiconductor waveguide optical amplifiers deliver a gain per unit length of hundreds of dB/cm, being typically two orders of magnitude larger than those values of a few dB/cm that have typically been reported in rare-earth-ion-doped materials.

The potassium double tungstates $\text{KGd}(\text{WO}_4)_2$, $\text{KY}(\text{WO}_4)_2$, and $\text{KLu}(\text{WO}_4)_2$ are excellent candidates for solid-state lasers, see Ref. [3] 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 $\text{KRE}(\text{WO}_4)_2$, and a long inter-ionic distance of ~ 0.5 nm that allows for large doping concentrations without lifetime quenching.

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

Liquid phase epitaxy (LPE) has been used to grow potassium double tungstate layers. While the use of low-temperature chloride solvents can lead to 3D island nucleation and insertion defects [4], the solvent $\text{K}_2\text{W}_2\text{O}_7$ results in excellent layer and interface quality [5]. We apply LPE at temperatures of $\sim 920^\circ\text{C}$ in the $\text{K}_2\text{W}_2\text{O}_7$ solvent to grow RE^{3+} -doped potassium double tungstate thin layers onto undoped, (010)-orientated, laser-grade polished $\text{KY}(\text{WO}_4)_2$ substrates of 1 cm^2 size.

A breakthrough was obtained by co-doping the active layer with optically inert Gd^{3+} and Lu^{3+} ions [6]. 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 (Fig. 1).

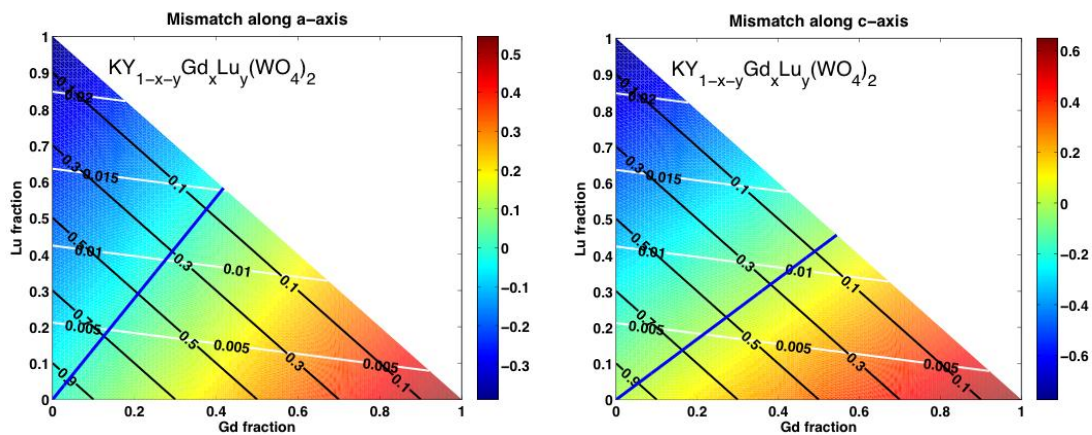


Fig. 1. Lattice mismatch along the a axis (left) and the c axis (right) for $\text{KY}_{1-x-y}\text{Gd}_x\text{Lu}_y(\text{WO}_4)_2$ versus the fractions of Gd^{3+} and Lu^{3+} ions. The blue lines indicate the compositions for which lattice matching is achieved individually along each crystal axis [7].

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 $\sim 10^{-2}$ (Fig. 2) [7], thereby allowing for much thinner (only a few μm -thick) single-transverse-mode waveguides, resulting in tighter pump and signal mode confinement as well as easing the requirements on microstructuring. Finally, the large fraction of Lu^{3+} ions can be replaced by active Yb^{3+} ions, enabling dopant concentrations of up to $\sim 50\%$ [7].

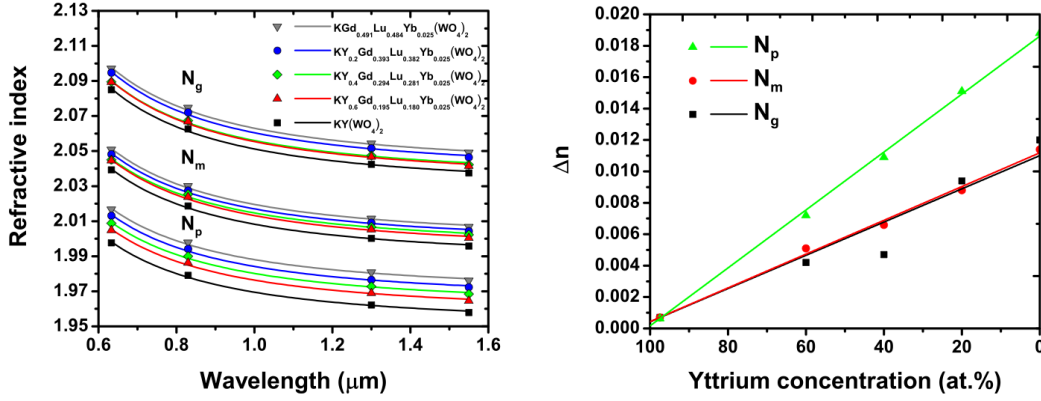


Fig. 2. (left) Refractive index versus wavelength measured (symbols) and calculated (lines) for a series of layers of $\text{KY}_{1-x-y-z}\text{Gd}_x\text{Lu}_y\text{Yb}_z(\text{WO}_4)_2$. (right) Refractive index increase versus remaining Y^{3+} concentration [7].

2. Weak Lifetime Quenching in Highly Yb^{3+} -doped Layers

The influence of concentration quenching on the Yb^{3+} luminescence lifetime was measured by pumping $\text{KY}_{1-x-y-z}\text{Gd}_x\text{Lu}_y\text{Yb}_z(\text{WO}_4)_2$ layers with a switched diode laser operating at 976 nm. Luminescence light at 1020 nm was collected normal to the sample surface. As a result of radiation trapping, the measured lifetime values were elongated from 261 μs to 292 μs for various Yb^{3+} concentrations increasing from 1.2at.% to 57.5at.%, respectively (Fig. 3) [7]. We fitted our experimental results and performed a de-convolution of concentration quenching from reabsorption. Due to the two-multiplet electronic level scheme of Yb^{3+} , which avoids parasitic spectroscopic processes, and the rather large distance between neighboring Yb^{3+} ions, which diminishes energy migration within the Yb^{3+} system and energy transfer to other impurities, the observed lifetime quenching is rather weak (Fig. 3), thus allowing for the utilization of large doping concentrations.

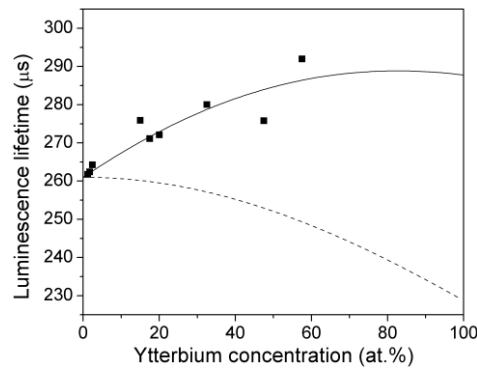


Fig. 3. Measured lifetimes in $\text{KY}_{1-x-y-z}\text{Gd}_x\text{Lu}_y\text{Yb}_z(\text{WO}_4)_2$ for Yb^{3+} concentrations ranging from 1.2at.% to 57.5at.% as a function of concentration (squares) [7]. The lines describe the combined effect of concentration quenching and reabsorption (solid line) or solely the concentration quenching (dashed line).

3. Ultra-high Gain in Rare-earth-ion-doped Microstructures

The fabrication of channel waveguides in bulk double tungstates by femtosecond-laser writing [8] or ion-beam implantation typically induces considerable waveguide propagation losses and leads to comparatively small refractive-index changes, necessitating rather large mode sizes. The comparatively large refractive-index contrast between layer and substrate and the accordingly 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 $\text{KGd}_{1-x}\text{Lu}_x(\text{WO}_4)_2:\text{Yb}^{3+}$ layers with cross-sections of a few μm^2 and excellent mode confinement [9].

Semiconductor optical waveguide amplifiers deliver high gain per unit length (up to $\sim 1000 \text{ dB cm}^{-1}$), enabling light amplification over short distances in integrated devices. In contrast, rare-earth ions are regarded as impurities providing low gain (up to $\sim 10 \text{ dB cm}^{-1}$) because of their low transition probabilities and cross-sections. We exploited the large transition cross-sections (Fig. 4, left), high dopant concentrations, in this case 47.5at.%, and accordingly large inversion densities attainable in our Yb^{3+} -doped, Gd^{3+} , Lu^{3+} co-doped potassium double tungstate micro-structures, thereby demonstrating a gain of 935 dB cm^{-1} in channel-waveguide (Fig. 4, right) and 1028 dB cm^{-1} in thin-film geometry [2]. This result improves the gain reported in rare-earth-ion-doped materials by two orders of magnitude and is comparable to the best values reported for semiconductor waveguide amplifiers. This gain is sufficient to compensate propagation losses in plasmonic nanostructures [10], making rare-earth-doped materials interesting for nanophotonic devices.

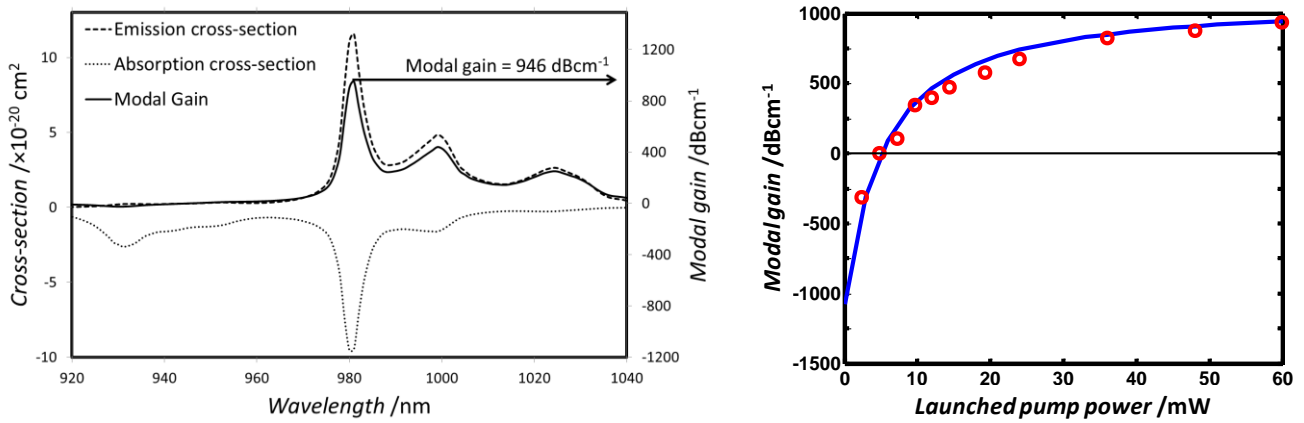


Fig. 4. (left) Effective absorption (dotted line) and emission (dashed line) cross-sections of Yb^{3+} as a function of wavelength in the co-doped sample $\text{KGd}_{0.447}\text{Lu}_{0.078}\text{Yb}_{0.475}(\text{WO}_4)_2$. The continuous curve represents the effective gain cross-section, resulting in a calculated modal gain as indicated on the right-hand ordinate.; (right) modal gain per unit length, predicted (line) and measured (circles) in a 47.5at.% Yb^{3+} -doped potassium double tungstate channel waveguide, versus launched pump power [2].

Collaborations

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