1000 dB/cm gain in Yb^{3+}-doped double tungstates

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Abstract. *Rare-earth ions are impurities providing low gain, reaching ~10 dB/cm, because electronic transitions within their 4f subshell are parity forbidden, dictating low transition probabilities and cross-sections. Here we exploit the extreme inversion densities attainable in rare-earth-ion-doped microstructures in a host material, potassium double tungstate, that provides enhanced transition cross-sections and dopant concentrations, thereby demonstrating a gain of 935 dB/cm in channel-waveguide and 1028 dB/cm in thin-film geometry, comparable to the best values reported for semiconductor waveguide amplifiers. Further improvement seems feasible with larger dopant concentrations.*

Introduction

Amplification of optical signals is required whenever the optical losses per unit length times the total distance requires periodic recovery of the signal strength. Fiber amplifiers doped with trivalent rare-earth ions (specifically Er^{3+}) are a standard in optical communication systems due to their low insertion loss, low noise, negligible non-linearities, superior characteristics at high-speed amplification, and high overall gain (30-50 dB). However, this high gain comes at the expense of employing several meters of fiber length, making this solution unsuitable for on-chip integration. The amplifier length can be shortened to typically a few centimeters by increasing the dopant concentration of rare-earth ions accordingly, but this approach is limited by the solubility of rare-earth ions in the chosen host material as well as the scattering losses and spectroscopic quenching processes induced by these high dopant concentrations. The typical gain per unit length reported for rare-earth-ion-doped integrated waveguides has hardly exceeded a few dB cm^{-1} [1].

In this work, we show that by appropriate design of host material, dopant concentration, and geometry the modal gain of rare-earth-ion-doped waveguide amplifiers can be enhanced to values of ~1000 dB/cm, while simultaneously providing the desirable gain characteristics present in rare-earth-ion-doped fibers, therefore holding promise for a new generation of highly efficient optical gain materials.

Waveguide preparation

Our approach utilizes the family of monoclinic potassium double tungstates $KY(WO_4)_2$, $KGd(WO_4)_2$, and $KLu(WO_4)_2$, see Ref. [2] and Refs. therein. The transition cross-sections of rare-earth ions, specifically Yb^{3+}, doped into these materials are among the largest observed in rare-earth-ion-doped hosts.

We grow Yb^{3+}-doped thin layers onto undoped $KY(WO_4)_2$ substrates by liquid phase epitaxy, resulting in planar waveguides [3]. Co-doping the layers with appropriate percentages of optically inert Gd^{3+} and Lu^{3+} (or Yb^{3+}) ions [4], which change the lattice constant in opposite directions, enables lattice matching of highly doped $KGd_{0.447}Lu_{0.078}Yb_{0.475}(WO_4)_2$ layers with the undoped $KY(WO_4)_2$ substrate [5], see Fig.

1. Besides, we obtain an enhanced refractive-index difference between layer and substrate of > 1.5×10^{-2} [5], see Fig. 1, thereby enabling thinner active layers. Microstructuring of these layers by Ar^+ beam etching results in channel waveguides (Fig. 2) with tight pump and signal light confinement [6], ensuring enhanced pump intensity and modal overlap of pump and signal beam with the active waveguide region.

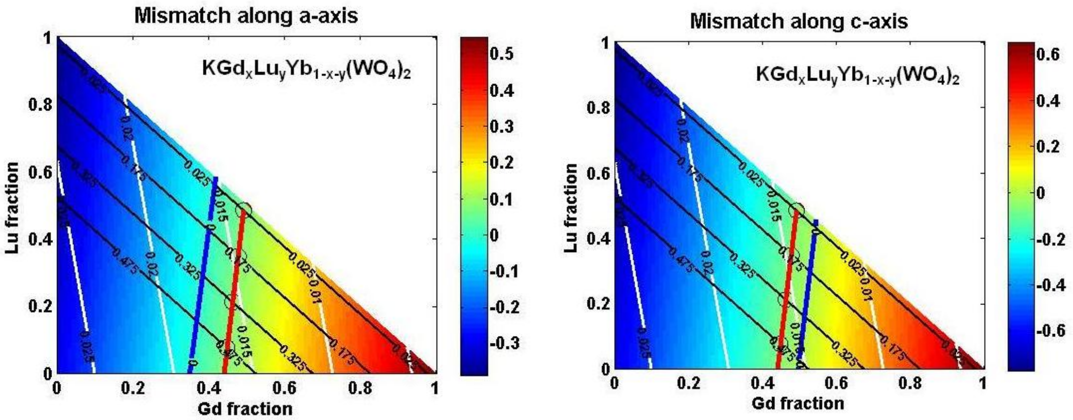

Fig. 1. Lattice mismatch (color bar) and refractive index contrast (white lines) of $KGd_xLu_yYb_{1-x-y}(WO_4)_2:RE^{3+}$ thin layers with the undoped $KY(WO_4)_2$ substrate versus Gd^{3+} and Lu^{3+} fractions along the crystal *a*-axis (left-hand side) and *c*-axis (right-hand side). The blue lines indicate the compositions for which lattice matching is achieved individually along each crystal axis, while the red lines (identical position for *a*- and *c*-axes) indicate the compositions for which minimum mismatch is obtained when considering both, the *a*- and *c*-axes. The black lines indicate the doped Yb^{3+} fraction. (Figure taken from Ref. [5].)

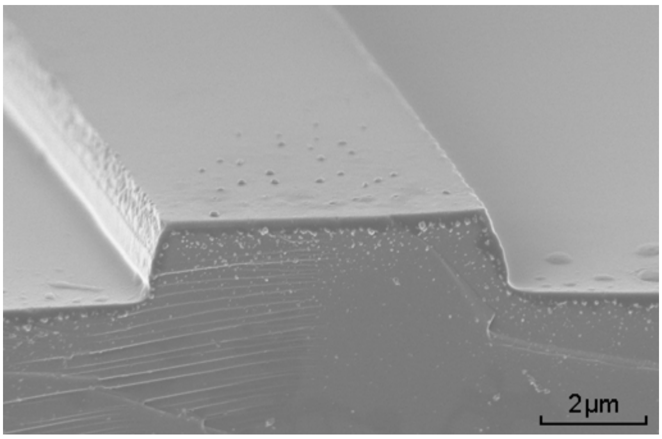

Fig. 2. SEM micrograph of a microstructured channel waveguide before overgrowth. (Figure taken from Ref. [6].)

Optical gain

We perform two gain experiments [7]. In the first approach, we tightly focus pump and signal light perpendicularly through a planar active layer of thickness of 25 µm. The net gain of 2.57 dB results in a modal gain of 1028 dB cm^{-1}. In the second experiment, we focus pump and signal light in-plane into a channel waveguide. The tight pump and signal foci are maintained over the whole waveguide length of 180 µm. By use of mode-solver software, we estimate the overlap of the signal mode with the active medium to be 88%, resulting in an expected modal gain of 946 dB cm^{-1} at the highest available pump power (Fig. 3, solid curve). In excellent agreement with this expectation, we measure a modal gain of 935 dB cm^{-1} in this waveguide (Fig. 3, circles).

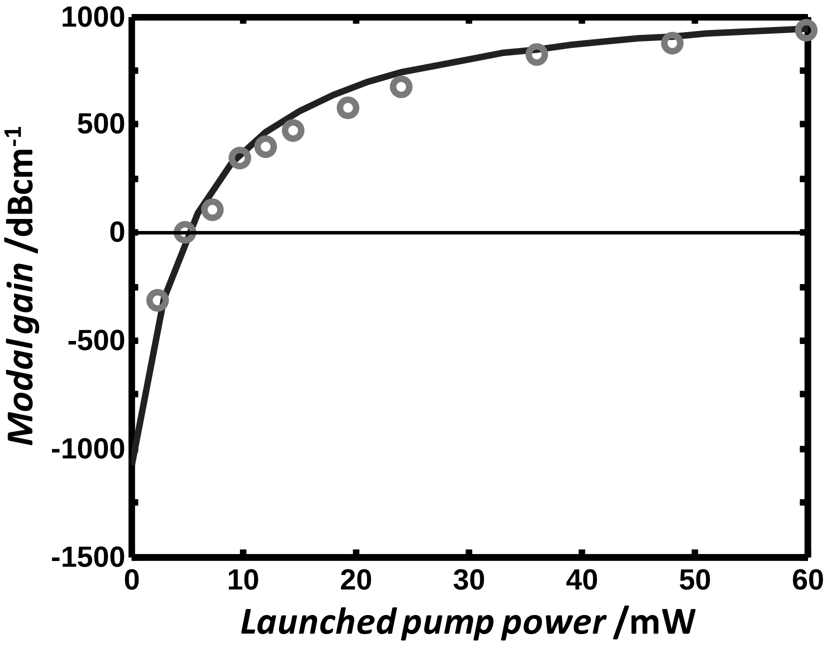

Fig. 3. Modal gain per unit length, predicted (line) and measured (circles) in a 47.5at.% Yb^{3+}-doped potassium double tungstate channel waveguide, versus launched pump power. (Figure taken from Ref. [7])

Conclusions

By an appropriate choice of host material, dopant concentration, and mode confinement we have achieved ~1000 dB/cm gain in a rare-earth-ion-doped dielectric waveguide, which is two orders of magnitude higher than previously reported for rare-earth ions and comparable to the best results achieved in semiconductor optical waveguide amplifiers.

Acknowledgment

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