Ultra-high, broadband gain in a lattice-engineered, Yb-doped double tungstate channel waveguide

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***Abstract*—150 dB/cm gain over 55 nm wavelength range between 977-1032 nm is obtained in a 47.5% Yb-doped potassium double tungstate waveguide amplifier. The dependence of luminescence lifetime and gain on Yb concentration is investigated.**

Keywords-Double tungstate; optical amplifier; rare-earth ions; integrated optics

I. Introduction

On-chip photonic integration requires the regeneration of optical signals at very high rates. Semiconductor optical amplifiers operate in the saturated regime, hence their gain recovery time limits the maximum achievable data rates. Rare-earth-ion-doped fiber amplifiers provide superior characteristics for high-speed amplification, but their gain of ~30-50 dB requires employing several meters of fiber length, making this solution unsuitable for on-chip integration. Recently, we have demonstrated that Yb^{3+}-doped potassium double tungstate can provide a modal gain up to ~1000 dB/cm in channel-waveguide and thin-film geometry [1], making this material highly suitable for amplification and lasing in micro- and nano-structured optical devices. Here we investigate the Yb^{3+}-concentration and wavelength dependence of modal gain around 1 µm in microstructured $KGd_xLu_yYb_{1-x-y}(WO_4)_2$ channel waveguides.

II. Sample Fabrication

Yb^{3+}-doped $KY(WO_4)_2$ layers were grown by liquid-phase epitaxy onto undoped, (010)-oriented, laser-grade-polished, 1-cm^2-sized $KY(WO_4)_2$ substrates in a $K_2W_2O_7$ solvent at temperatures of 920–923°C [2]. Co-doping the layers with appropriate percentages of optically inert Gd^{3+} and Lu^{3+} ions enables the growth of lattice-matched layers with enhanced refractive-index difference between layer and substrate, allowing for thinner active layers [3]. Partial replacement of Lu^{3+} by Yb^{3+} ions of similar ionic radius resulted in up to 47.5at.% Yb^{3+}-doped $KGd_xLu_yYb_{1-x-y}(WO_4)_2$ layers with a refractive-index contrast between layer and substrate of up to ~2 × 10^{-2} (Fig. 1). The samples were between 180–320 µm long and the layer surface was polished down to 2.2–3.5 µm thickness. Microstructuring by Ar-beam etching [4] provided 1.4-µm-deep, 6-µm-wide ridge waveguides along the N_g optical axis (Fig. 2). The microstructured samples were overgrown by a layer of undoped $KY(WO_4)_2$.

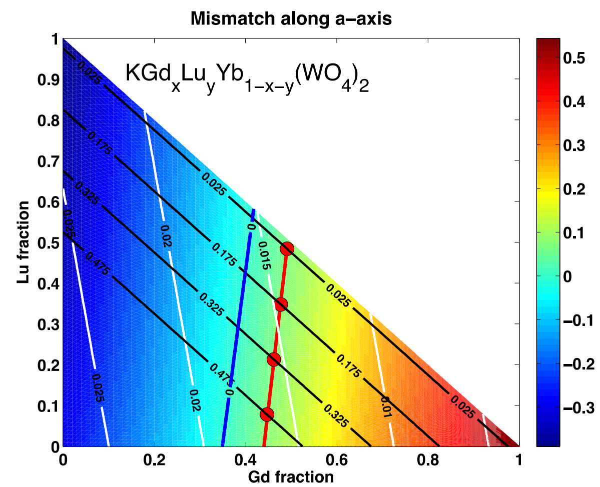

Figure 1. Lattice mismatch (color bar), refractive index contrast (white lines), and doped Yb^{3+} fraction (black lines) of $KGd_xLu_yYb_{1-x-y}(WO_4)_2$ thin layers with the undoped $KY(WO_4)_2$ substrate versus Gd^{3+} and Lu^{3+} fractions, calculated along the crystal *a*-axis. The blue line indicates the compositions for which lattice matching is achieved along this crystal axis, while the red line indicates the compositions for which minimum mismatch is obtained when considering both, the *a*- and *c*-axes.

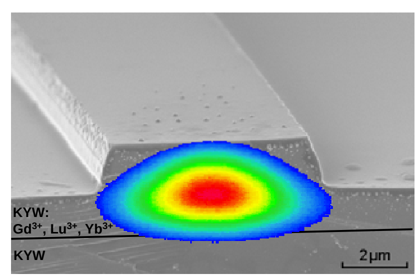

Figure 2. Cross-section of a channel waveguide prior to $KY(WO_4)_2$ overgrowth.

III. Amplifier Performamce

Lifetime-quenching processes induced by increased energy migration among Yb^{3+} ions and subsequent energy transfer to impurities or cooperative upconversion can diminish the achievable excitation density. Luminescence-decay

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measurements show an increasing lifetime with increasing Yb^{3+} concentration, see the measured data and fit in Fig. 3, which is an effect of radiation reabsorption. Using the formalism presented in Ref. [5], we corrected the measured lifetime for this effect (blue line), resulting in a lifetime quenching from ~270 µs to slightly less than 200 µs at 47.5at.% Yb^{3+} concentration. Apparently this small amount of quenching does not affect the achievable gain significantly.

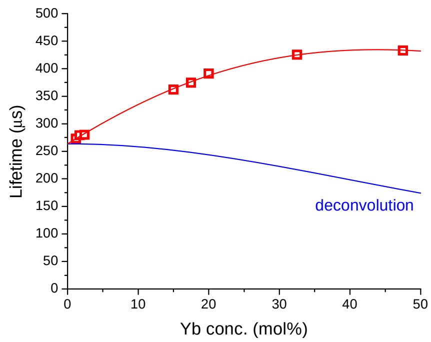

Figure 3. $^2F_{5/2}$ lifetime as a function of Yb^{3+} concentration. The red line is the fit with the equation given in [5], while the blue line is the deconvolution of the fit that shows the self-quenching contribution.

We performed small-signal-gain measurements using a pump-probe-beam set-up with a Ti:Sapphire pump laser operating at 932 nm, a broadband probe-beam source polarized parallel to the N_m optical axis, mechanically modulated with a frequency of 142 Hz, and a monochromator selecting the signal wavelength λ_S. Pump and signal light were combined and coupled into the channel waveguide by an objective lens. Light emitted from the opposite waveguide end was collimated by an objective lens and residual pump light was suppressed by a dichroic filter and a spectrometer set to 980.6 nm. The amplified signal was detected by an InGaAs detector and discriminated from luminescence at this wavelength by lock-in amplification. Using a spatially resolved rate-equation model, we determined the pump power establishing transparency at λ_S. Relative to this 0-dB transmitted signal intensity, transmitted signal intensities at other pump powers were investigated and the modal gain was determined [1]. Results for different Yb^{3+} concentrations of 15at.%, 20at.%, and 47.5at.% versus launched pump power are displayed in Fig. 4. With increasing dopant concentration the gain increases because of an accordingly increasing absorbed pump power density and Yb^{3+} excitation density.

For the 47.5at.% sample we investigated the gain at different signal wavelengths experimentally and theoretically, exploiting the transition cross-sections determined for this mixed compound. While the measured peak gain amounted to 935 dB/cm at the zero-phonon line of 980.6 nm, we could achieve gain exceeding 150 dB/cm at several other wavelengths spanning a large wavelength range, indicated by the symbols in Fig. 5. Comparison with the calculated data (lines) shows that this gain level of > 150 dB/cm can be achieved continuously over a wavelength range of 55 nm, between 977 nm and 1032 nm.

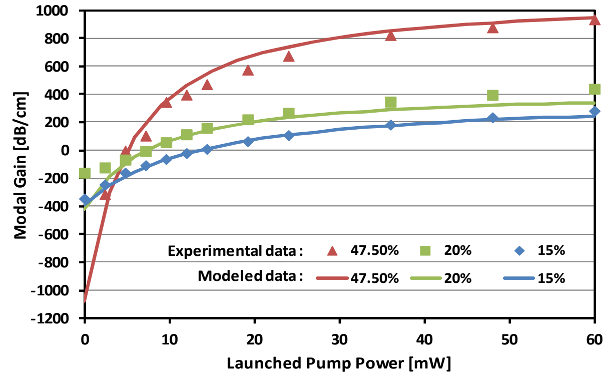

Figure 4. Waveguide modal gain at 981 nm versus launched pump power for different Yb^{3+} concentrations.

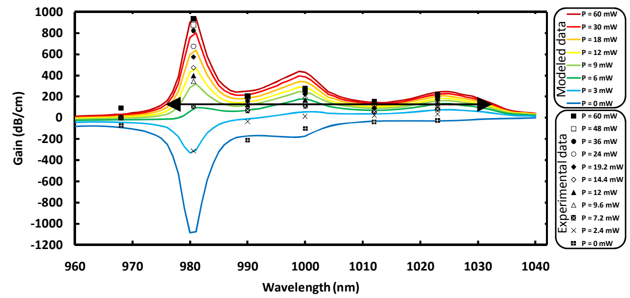

Figure 5. Waveguide modal gain for an Yb^{3+} concentration of 47.5% and different launched pump powers, calculated (lines) and measured (symbols); indication (arrow) of the spectral range of 55 nm with g_{mod} > 150 dB/cm.

V. CONCLUSIONS

Ultra-high gain has been demonstrated in $KGd_xLu_yYb_{1-x-y}(WO_4)_2$ channel waveguides over a wide wavelength range around 1 µm wavelength. Further improvement seems feasible with higher dopant concentrations. These results suggest that Yb^{3+}-doped waveguides may set a new wavelength standard at 1 µm for on-chip signal amplification.

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