High-gain waveguide amplifiers based on potassium rare-earth double tungstates

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The down-scaling of the rare-earth-doped amplifier to chip-scale device length is beneficial for signal amplification within short-reach interconnects such as optical backplanes [1, 2] and for the realization of novel active/passive integrated optical chips. Thus far, with the demonstration of 20 dB net gain [3], high bit-rate operation at 170 Gb/s [4], and gain bandwidth over 80 nm [5] in the C-band, as well as 14.4 dB net gain at 1064 nm wavelength [6], rare-earth-doped amorphous Al_2O_3 is a very promising material for waveguide amplifiers. The corresponding peak gain per unit length of Er^{3+}- and Nd^{3+}-doped Al_2O_3 are ~2.0 dB/cm [5] and 6.3 dB/cm [6], respectively. To further increase the gain per unit length, a host material with higher transition cross-sections and higher active-ion solubility is needed. In this work, it is shown that highly Yb^{3+}-doped and Er^{3+}-doped monoclinic potassium rare-earth double tungstate, $KRE(WO_4)_2$ epitaxial layers match these two conditions and produce higher gain per unit length.

Yb^{3+}-doped and Er^{3+}-doped $KRE(WO_4)_2$ layers were grown on undoped potassium yttrium double tungstate, $KY(WO_4)_2$, substrates with the dimension of 1 mm × 10 mm × 10 mm by liquid phase epitaxy [7]. Optically inert Lu^{3+} and Gd^{3+} are included in the epitaxial layer for: i) maintaining lattice matching conditions with respect to the substrate, ii) increasing the refractive index contrast between active layer and substrate, and iii) maximizing the active ion concentration. The index of refraction of the substrate at $E||n_m$ is ~2.0 for the wavelength range of 1000-1550 nm and the refractive index contrast between the active layer and the substrate is ~0.012.

Figure 1(a) shows the absorption and emission cross-sections of the $KYb_{0.57}Gd_{0.43}(WO_4)_2$ layer determined with the procedure described in [8]. The 57 at.% Yb^{3+} in the epitaxial layer corresponds to an active ion density of $\sim 3.8\times10^{21}$ cm^{-3}. The peak absorption and emission cross-sections are 13.1×10^{-20} cm^2 and 16.2×10^{-20} cm^2, respectively, at ~981 nm, which is about an order of magnitude higher than those of Al_2O_3:Yb^{3+} [9]. The transition cross-sections of Er^{3+}-doped $KRE(WO_4)_2$ layers are displayed in Fig. 1(b). The luminescence spectra and luminescence lifetime measurements were performed on a layer with the lowest available Er^{3+} concentration of 0.75 at.% ($\sim 0.47\times10^{20}$ cm^{-3}) to avoid reabsorption effects, while the reciprocity theorem was used to calculate the absorption cross-section. The Er^{3+} peak transition

cross-sections are ~4.3× higher in potassium double tungstates than in Al_2O_3.

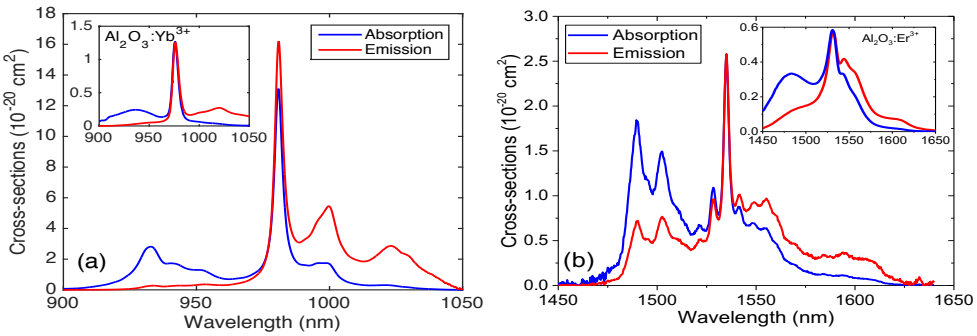

Fig. 1. Transition cross-sections of (a) Yb^{3+}-doped and (b) Er^{3+}-doped potassium rare-earth double tungstate epitaxial layers. The insets show the corresponding transition cross-sections for the same active ion doped into Al_2O_3 [5, 9] for comparison purpose.

The luminescence lifetime measured from $KYb_{0.57}Gd_{0.43}(WO_4)_2$ is merely ~7% less than the lifetime from low-doped (1.2 at.% Yb^{3+}) sample (245 µs), indicating a very weak lifetime quenching. The averaged lifetime of the first excited state ($^4I_{13/2}$) for the samples with 0.75-10 at.% Er^{3+} is ~3.05 ms. No sign of lifetime quenching was observed for the samples within the range of Er^{3+} concentrations investigated. However, like in many Er^{3+}-doped materials, excitation-density-dependent energy-transfer upconversion significantly shortens the luminescence-decay time.

Pump-probe measurements are conducted to determine the optical gain. By launching both optical beams perpendicular to the 32 µm-thick $KYb_{0.57}Gd_{0.43}(WO_4)_2$ layer, a net gain of >900 dB/cm is determined at the 981 nm signal wavelength by pumping at 932 nm wavelength. The reduction of transition cross-sections at elevated temperatures [8] due to pump-induced heating may be the gain-limiting mechanism. The 6 at.% Er^{3+}-doped $KRE(WO_4)_2$ channel waveguides, micro-structured using ion-beam etching, produce gain >10 dB/cm at the 1534.75 nm signal wavelength by pumping at 984.5 nm, which is much higher than most of the singly Er^{3+}-doped materials. The gain of the Er^{3+}-doped $KRE(WO_4)_2$ waveguides is limited by energy-transfer upconversion and excited-state absorption processes. As a result, higher Er^{3+} concentration does not lead to better gain.

In summary, Yb^{3+}- or Er^{3+}-doped $KRE(WO_4)_2$ epitaxial layers exhibit large transition cross-sections and limited luminescence lifetime quenching at high doping concentrations. High optical gain of >900 dB/cm for highly Yb^{3+}-doped layers (57 at.%) at 981 nm wavelength and >10 dB/cm for the Er^{3+}-doped layers (6 at.%) at 1534.75 nm wavelength were demonstrated.

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