Wavelength-dependent optical gain in a $\text{KGd}_x\text{Lu}_{1-x}(\text{WO}_4)_2:\text{Yb}^{3+}$ waveguide amplifier

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Abstract—The gain of $\text{KGd}_{0.447}\text{Lu}_{0.078}\text{Yb}_{0.475}(\text{WO}_4)_2$ waveguide optical amplifiers in the wavelength range from 980 nm to 1023 nm is reported. Values above 150 dB/cm were obtained with peak gain of 935 dB/cm at 981 nm.

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

I. INTRODUCTION (HEADING 1)

The current trend towards very large photonic integration requires the capability to regenerate the optical signals at very high rates, low power consumption, and occupying a very small footprint. Current state-of-the-art semiconductor optical amplifiers (SOA) work in the saturated regime and, therefore, the gain recovery time limits the maximum data rates that can be amplified without distortion. Recent advances in quantum dot SOAs have demonstrated amplifications at more than 40 Gbps thanks to a very fast gain recovery dynamics [1] but at the expense of a reduced achievable modal gain (i.e., few tens of dB/cm). Rare-earth (RE) doped fiber amplifiers and, in particular, the erbium-doped fiber amplifier (EDFA), are a standard in optical communication systems due to their low insertion loss, low noise, negligible non-linearities, and superior characteristics at high-speed amplification. However, the overall gain provided, ~30-50 dB, requires employing several meters of fiber length, making this solution unsuitable for on-chip integration. Attempts at exploiting the excellent gain characteristics of RE ions by doping them into different materials [2,3] have resulted in typical gain in amorphous host materials not exceeding a few dB/cm, requiring device lengths not compatible with very large scale photonic integration.

The potassium double tungstates $\text{KY}(\text{WO}_4)_2$, $\text{KGd}(\text{WO}_4)_2$ and $\text{KLu}(\text{WO}_4)_2$, doped with RE ions are excellent candidates for very compact on-chip amplifiers. The long excited-state lifetime of RE ions, typically in the millisecond range, permits amplification without distortion of high-rate signals. The large inter-atomic distance of ~0.5 nm permits high RE dopant concentration without significant lifetime quenching [4]. Finally, these host materials provide very high absorption and emission cross-sections to the RE ions doped into them [5].

In this paper, a study of the wavelength dependence of the modal gain obtained in $\text{KGd}_{0.447}\text{Lu}_{0.078}\text{Yb}_{0.475}(\text{WO}_4)_2$ channel waveguides will be presented. A gain of >150 dB/cm over the wavelength range 980 nm to 1023 nm has been experimentally demonstrated, with peak gain of 935 dB/cm at 981 nm, which

is comparable with the best results reported for semiconductor optical amplifiers (SOAs).

II. EXPERIMENTAL

Crack-free, Gd^{3+} , Lu^{3+} co-doped [6], lattice-matched $\text{KGd}_{0.447}\text{Lu}_{0.078}\text{Yb}_{0.475}(\text{WO}_4)_2$ layers were grown by liquid phase epitaxy onto undoped, (010)-oriented, laser-grade-polished $\text{KY}(\text{WO}_4)_2$ substrates of 1 cm^2 size. A $\text{K}_2\text{W}_2\text{O}_7$ solvent was used for the growth at temperatures of 920–923°C. The layer surface was then polished parallel to the layer-substrate interface to 2.2- μm thickness, with 1.5-nm (rms) roughness. A photoresist mask was deposited and patterned. Ar-beam milling [7] with an energy of 350 eV, providing an etch rate of 3 nm/min, was used while rotating the sample at an angle of 20°, creating 1.4- μm -deep, 6- μm -wide ridge waveguides along the N_g optical axis (Fig. 1). The ridge waveguides were overgrown by undoped $\text{KY}(\text{WO}_4)_2$, resulting in buried waveguides. The devices were diced to a length of 180 μm . Dicing was performed at an angle to suppress parasitic lasing [8]. Small-signal-gain measurements were performed in a pump-probe-beam set-up [9], with a pump wavelength of 932 nm.

Figure 1. Cross-section of a channel waveguide prior to $\text{KY}(\text{WO}_4)_2$ overgrowth.

III. DISCUSSION

Using a spatially resolved rate-equation model, the pump power that produces transparency at the signal wavelength λ_s was determined. In the model, a value for the emission and absorption cross-sections was utilized that employed the values reported in the literature for $\text{KGd}(\text{WO}_4)_2$, $\text{KLu}(\text{WO}_4)_2$, $\text{KY}(\text{WO}_4)_2$ and $\text{KYb}(\text{WO}_4)_2$ pondered by the crystal composition used in this particular device, $\text{KGd}_{0.447}\text{Lu}_{0.078}\text{Yb}_{0.475}(\text{WO}_4)_2$. This approach was very important in order to obtain a good fit to the experimental data. Relative to this 0-dB transmitted signal intensity I_t , transmitted

signal intensities, I_s , at other pump powers were investigated. A fraction of incident signal light remains uncoupled during the measurements, being neither amplified nor attenuated. Due to the short device lengths, at I_t the stray light that reaches the detector is estimated to account for $\rho \approx 50\%$ of the detected intensity. Whereas the stray light deteriorates the measurement at low pump power, at high pump power its influence is negligible compared to the strongly amplified guided fraction. The modal gain can therefore be obtained by

$$g_{\text{mod}}(\text{dB/cm}) = \frac{1}{\ell} 10 \log_{10} \frac{I_s - \rho I_t}{(1 - \rho) I_t}, \quad (1)$$

where ℓ is the device length in cm. The modal gain as a function of pump power for the signal wavelength 981 nm is shown in Fig. 2. A maximum gain of 935 dB/cm is measured. The results for different signal wavelengths are shown in Fig. 3. As can be seen, a gain of >150 dB/cm is measured over the wavelength region from 980 nm to 1023 nm.

IV. CONCLUSION

The gain of $\text{KGd}_{0.447}\text{Lu}_{0.078}\text{Yb}_{0.475}(\text{WO}_4)_2$ waveguide amplifiers has been studied in the wavelength range from 980 nm to 1023 nm for different launched pump intensities. A modal gain of >150 dB/cm has been demonstrated for the whole wavelength range, with a peak of 935 dB/cm at 981 nm. Such broad gain bandwidth can find applications in on-chip amplification, tunable laser sources, and ultrashort-pulse integrated lasers.

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Figure 2. Experimental (dots) and simulated (solid line) modal gain at 981 nm as a function of launched pump power.

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Figure 3. Modal gain as a function of signal wavelength for different launched pump intensities (pump wavelength 932 nm).