Highly Yb-doped $KGd(WO_4)_2$ Thin-film Amplifier

Y. S. Yong,[1,2] S. Aravazhi,[1] S. A. Vázquez-Córdova,[1,2] S. M. García-Blanco,[1,2] and M. Pollnau[1,3]

[1]Integrated Optical MicroSystems Group and [2]Optical Sciences Group,

[1,2]MESA+ Institute for Nanotechnology, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands

[3]Department of Materials and Nano Physics, School of Information and Communication Technology, KTH−Royal Institute of Technology, Electrum 229, Isafjordsgatan 22−24, 16440 Kista, Sweden

Author e-mail address: y.s.yong@utwente.nl

Abstract: We report record-high small-signal gain of 1050 dB/cm at 981 nm wavelength in a $KGd_{0.425}Yb_{0.575}(WO_4)_2$ thin film. The sensitivity of gain to the shift of beam-focus position, which is critical under non-waveguiding conditions, is investigated.

OCIS codes: (130.3130) Integrated optics materials; (140.4480) Optical amplifiers; (160.5690) Rare-earth-doped materials

1. Introduction

A rare-earth-doped amplifier is a key enabling device for modern communication systems due to its high-bit-rate and broadband amplification features. With the ever increasing demand on shorter-distance optical interconnects, the development of a rare-earth-doped material with high gain per unit length will be of utmost importance in realizing amplifiers for non-fiber-based, footprint-limited applications, such as photonic integrated circuits, optical sensing devices, and optical backplane systems. Recently, a 47.5at.% Yb-doped potassium double tungstate waveguide amplifier was reported with about 1000 dB/cm gain at 981 nm [1] and more than 150 dB/cm gain in the 977-1032 nm wavelength range [2], demonstrating the promising aspects of such a material system for the fabrication of high-gain amplifiers with device lengths at the millimeter scale.

Here we report the results of perpendicular gain measurements in a thin film of 57.5at.% Yb-doped potassium gadolinium double tungstate, $KGd(WO_4)_2$. Since the overlap of the pump and signal foci becomes critical for a highly doped thin film without waveguiding structure, a Gaussian-propagation numerical model is applied to examine the impact of beam focal shift to the gain. The simulation results calculated using this model agree well with the measured values.

2. Sample preparation

The 57.5at.% Yb-doped thin film is grown onto a 1-mm-thick $KY(WO_4)_2$ substrate by liquid phase epitaxy (LPE) in a $K_2W_2O_7$ solvent at 920-925 °C [3]. Optically inert gadolinium replaces yttrium in the thin film to reduce the lattice mismatch between the epitaxial layer and the substrate [4], thereby diminishing the stress induced in the thin film. The material composition of the epitaxial layer, $KGd_{0.425}Yb_{0.575}(WO_4)_2$, corresponds to an active-ion concentration of $N_d = 3.63 \times 10^{21}$ cm^{-3}. After the LPE growth, the rear surface of the substrate is polished to remove the second growth layer. The front-side active layer is lapped and polished to a thickness of ~32 μm.

3. Results and discussions

A pump-probe measurement is performed with the sample positioned perpendicular to the optical beams. A continuous-wave Ti:Sapphire laser tuned to 932 nm is used as the pump, whereas the signal beam at 981 nm is obtained with a super-continuum light source passing through a monochromator. The signal beam is mechanically chopped for lock-in detection to discriminate the detected signal from spontaneous emission produced by the sample and from noise. A launched signal power of only 100 nW is used to ascertain amplification in the small-signal-gain regime. Both the pump and signal beams are combined using a dichroic mirror and polarized to the N_m optical axis of the sample before being focused onto the sample with a ×22 microscope objective. A ×50 long-working-distance microscope objective is used to collect the amplified signal from the other end of the sample. The signal is directed to a spectrometer equipped with a pump filter, detected by a cooled InGaAs detector, and amplified by a lock-in amplifier. The gain per unit length resulting from the measurement is depicted in Fig. 1(a). A record-high value of 1050 dB/cm is obtained.

The modal gain is calculated as $g = 4.34\ \Gamma\ (\sigma_e N_2 - \sigma_a N_1)$, where Γ is the fractional overlap of the signal beam with the active region inverted by the pump beam. N_2 and N_1 are the population densities of excited and ground state, respectively. The emission and absorption cross-sections at 981 nm, $\sigma_e = 1.135 \times 10^{-19}$ cm^2 and $\sigma_a = 9.282 \times 10^{-20}$ cm^2, respectively, are calculated as weighted averages of the cross-sections of $KGd(WO_4)_2$:Yb and $KYb(WO_4)_2$ [1]. The theoretical modal gain with respect to the fractional population inversion, N_2/N_d, for the case of an ideal beam overlap, i.e., $\Gamma = 1$, is shown in Fig. 1(b). The calculation is repeated for a 47.5at.% Yb-doped sample as reported in [1] for comparison. With the known Boltzmann distributions of the Stark levels at room temperature, the maximum inversion achievable at transparency for the pump wavelength of 932 nm is ~90% [1]. The resulting theoretical gain limit for the 47.5at.% and 57.5at.% Yb-doped samples is about 1230 dB/cm and 1465 dB/cm, respectively, which indicates that a higher gain can be harvested from the 57.5at.% Yb-doped sample.

For achieving a high level of inversion in the highly doped thin film, a tight pump focus is required to provide a high pump intensity. The minimum pump-beam waist in our experiment is estimated to be ~2.7 μm. Therefore, a depth of focus of ~50 μm is expected. In view of the short depth of focus approaching the sample thickness, the overlap of pump and signal foci becomes critical. We applied a Gaussian-beam-propagation numerical model adapted from [5] to investigate the impact that a longitudinal shift of signal focal spot has on the modal gain. For the pump-beam waist being located at the center of the thin film and the signal-beam waist being shifted from this position in the propagation direction, the result of Fig. 1(c) obtains. In the absence of a signal-beam shift, a maximum gain of 1455 dB/cm is calculated for a launched pump power of 700 mW. A rapid decrease in attainable gain is observed when the signal focal spot is shifted by more than 15 μm, and less than half the peak gain remains as the signal focal spot is shifted by more than 30 μm. We simulated the gain in the 57.5at.% Yb-doped sample according to our experimental conditions, and the result is shown in Fig. 1 (a). The shift of signal focal spot is ~25 μm, and the simulation result is in good agreement with the measured values.

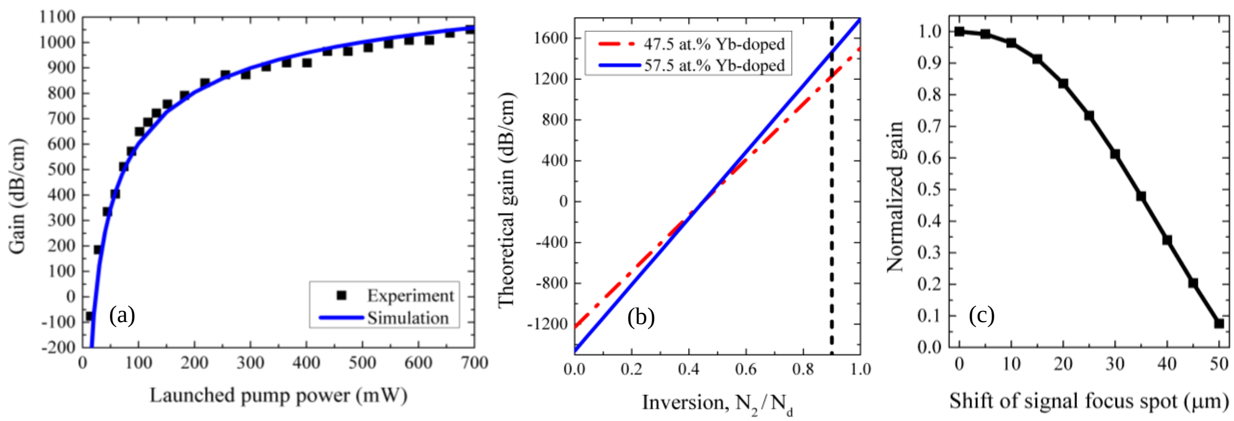

Fig. 1. (a) Gain per unit length versus launched pump power from the 57.5at.% Yb-doped sample. (b) Theoretical modal gain for 47.5at.% and 57.5at.% Yb-doped samples with respect to the level of inversion. The vertical dashed line marks the theoretical limit of inversion attainable at room temperature. (c) Simulation of the effect of shifted signal focal spot on the achievable gain, with the curve serving as an eye guide.

4. Conclusions

A 57.5at.% Yb-doped $KGd(WO_4)_2$ thin film with a record-high measured gain per unit length of 1050 dB/cm is reported. Further analysis shows that for a perpendicular gain measurement in a thin film without waveguide structure, a close proximity of pump-probe foci within 15 μm is required to achieve a high gain value. The simulation result taking into account the mismatch of foci agrees well with the experimental result.

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5. References

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