Influence of temperature on the transition cross-sections and the optical gain of highly Yb-doped potassium double tungstates

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We report the temperature dependence of transition cross-sections and optical gain in a high-ytterbium-concentration (3.8×10^{21} cm^{-3}) epitaxy layer of $KYb_{0.57}Gd_{0.43}(WO_4)_2$ grown onto an undoped $KY(WO_4)_2$ substrate for chip-scale waveguide amplifiers. The transition cross-sections strongly depend on crystal temperature via Boltzmann re-distribution and linewidth broadening at elevated temperatures. Consequently, the theoretical gain of an amplifier operating at 80 °C is limited to 67% of the gain at 20 °C. Nevertheless, numerical results show that >900 dB/cm of net gain is achievable at a signal wavelength of 981 nm without active thermal management, hence high-gain waveguide amplifiers operating without active cooling are feasible.

Introduction

The Yb^{3+}-doped potassium double tungstates are promising materials for amplifiers and lasers due to their favorable transition cross-sections which are much higher than in YAG:Yb^{3+} [1, 2], as well as the possibility of incorporating a high amount of Yb^{3+} ions without significant lifetime quenching [2, 3]. Such material has been used for multi-watt microchip lasers [4], planar [5] and channel [6] waveguide lasers, small quantum defect lasers [6, 7], *Q*-switched [8] and mode-locked lasers [9]. Using a lattice engineering approach [10], epitaxial films with high Yb^{3+} concentration and sufficient refractive index contrast for waveguiding can be grown onto undoped potassium yttrium double tungstate, $KY(WO_4)_2$ [3, 11].

Due to the small mode-field diameter in the guided-wave structure, high pump intensity is achieved in the waveguide device even with a moderate amount of pump power. Such intensity, which is maintained along the propagation length, yields high population inversion of >50% which in turn permits device operation at the central line of 981 nm wavelength using a pump wavelength of 933 nm. On the basis of a waveguide structure, optical amplification with a record net gain of 935 dB/cm [12] and efficient laser operation [13] at 981 nm wavelength were demonstrated.

With a high pump intensity concentrated within a small active volume, excessive heat may be generated in the waveguide amplifier due to the quantum defect, or the difference in energy between a pump photon and a signal photon. Therefore, understanding the gain characteristics above room temperature is beneficial for the design optimization of waveguide amplifiers. In this work, the transition cross-sections of a $KYb_{0.57}Gd_{0.43}(WO_4)_2$ epitaxy layer grown onto an undoped $KY(WO_4)_2$ substrate are evaluated at 20 ˚C and at 80 ˚C. Besides, the theoretical optical gain achievable at these temperatures is investigated.

Sample and Measurement Setup

The sample consists of a $KYb_{0.57}Gd_{0.43}(WO_4)_2$ epitaxial layer grown onto an undoped $KY(WO_4)_2$ substrate by liquid phase epitaxy [3]. It is held by a home-made copper holder which is put into contact with a Peltier element and a temperature sensor. A thermoelectric temperature controller is used to regulate the temperature of the sample. The absorption experiment is performed using a spectrophotometer with a spectral bandwidth of 1 nm. A near-infrared polarizer is in place before the sample during the measurement to determine the absorption at $E||N_m$ polarization. The absorption data are corrected for the spectral response of the polarizer and the Fresnel reflections of the sample.

Results

The effective absorption cross-section, σ_{abs}, of the sample at 20 ˚C and 80 ˚C, respectively, was determined. It is noted that the peak cross-section on the central absorption line at 981 nm decreased from 13.1×10^{-20} cm^2 to 9.53×10^{-20} cm^2. Besides, a less drastic decrease of the absorption of about ~20% is observed at the pump wavelength of 933 nm. The transition cross-sections strongly depend on crystal temperature via Boltzmann re-distribution and linewidth broadening at elevated temperatures [14].

The effective emission cross-section, σ_{emi}, is determined at 20 ˚C and 80 ˚C using the reciprocity method [15-17] and the energy levels of KYW:Yb^{3+} [16]. Using the transition cross-sections determined at 20 ˚C and at 80 ˚C, the gain cross-section at 981 nm wavelength can be deduced [17]. With a pump wavelength of 933 nm, the maximum inversion achievable at the excited state N_2/N_{Yb} is governed by the fractional population of the starting Stark level within the ground state manifold, b_{11} and the fractional population of the terminating Stark level within the excited state, b_{23} [12]. The maximum theoretical inversion at 20 ˚C is calculated as 90.7 %. As the temperature is increased to 80 ˚C, it is lowered to 86.4 %.

The combination of the reduction of the maximum theoretical inversion and the decrease of the transition cross-sections lead to a reduction of the gain cross-section from 13.5×10^{-20} cm^2 at 20 ˚C to 9.1×10^{-20} cm^2 at 80 ˚C. Considering N_{Yb} = 3.8×10^{21} cm^{-3} in the sample, the theoretical gain values calculated at the abovementioned temperature are 2236 dB/cm and 1502 dB/cm, respectively. In other words, the device operating at 80 ˚C is expected to exhibit 67% of the gain achievable at 20 ˚C.

In contrast to flash-lamp side-pumped devices, end-pumped amplifiers exhibit non-uniform population inversion distribution along the propagation direction. The influence of reduced inversion can be accounted for by factoring in a lower average value of the maximum theoretical inversion. With a decrease to 0.9 and 0.8 of the maximum achievable inversion at 80 ˚C, gain values of 1193 dB/cm and 883 dB/cm are obtained, respectively. Hence, high-gain waveguide amplifiers may still be feasible even if they are operating at elevated temperatures. Given the operating conditions of a temperature < 80 ˚C and a maximum achievable inversion > 70 %, a gain of > 900 dB/cm would be attainable without active cooling.

Conclusions

The temperature-dependent transition cross-sections of a $KYb_{0.57}Gd_{0.43}(WO_4)_2$ layer grown onto an undoped $KY(WO_4)_2$ substrate are investigated. It is shown that the temperature of the crystal has a significant influence on the optical gain. For a device operating at 80 ˚C and 80% of maximum population inversion, the expected gain is 883 dB/cm, which is substantially lower than the gain of 2236 dB/cm calculated at 20 ˚C and complete inversion. Nevertheless, a device operating at such temperature may work without active thermal management, hence high-gain waveguide amplifiers operating without active cooling are still feasible.

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