Er-doped potassium double tungstate channel waveguides with high optical gain

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We report on the optical gain properties of channel waveguides patterned into layers of $KGd_xLu_yEr_{1-x-y}(WO_4)_2$ grown by liquid phase epitaxy onto undoped $KY(WO_4)_2$ substrates. Internal net gain is experimentally demonstrated, with a maximum of ~11 dB/cm at the peak wavelength of 1534.7 nm. Overgrowth of the active waveguide by an undoped $KY(WO_4)_2$ layer would reduce the propagation losses and improve the gain to ~14 dB/cm. A systematic investigation of gain is performed for five different erbium concentrations in the range from 0.75 to 10 at.%. Experimental and simulated results for all samples are compared, revealing good agreement.

Introduction

The family of potassium double tungstates $KY(WO_4)_2$, $KGd(WO_4)_2$, and $KLu(WO_4)_2$ comprises excellent host materials for rare-earth-doped solid-state lasers [1]. The thermo-mechanical [2] and spectroscopic parameters [3] of these materials compare favorably with those of many other crystalline and glass materials. Particularly, their strong anisotropy and high refractive index [3,4] are important, because these features contribute to the fact that rare-earth ions exhibit high transitions cross-sections in this family of materials, thereby supporting high optical gain. Consequently, micro-structured waveguides in potassium double tungstates exhibit excellent performance as optical amplifiers [5] and lasers [6,7].

In erbium-doped waveguide amplifiers and lasers operating at wavelengths around 1.5 µm [8] (Fig. 1), typically low values of the Er^{3+} concentration in the range of 1 to 2×10^{20} cm^{-3} are selected, because a parasitic spectroscopic process, namely energy-transfer upconversion, whose probability decreases with the distance between neighboring erbium ions to the power of six, depopulates the amplifier level, thereby limiting the achievable gain in practically all host materials [9–12]. Nevertheless, with low-doped and accordingly long waveguides, e.g. in spiral geometry, an internal net gain of 20 dB has been demonstrated [13].

Incorporation of erbium in potassium double tungstates can be achieved up to the stoichiometric structure $KEr(WO_4)_2$, which is equal to an erbium concentration of 6.3×10^{21} cm^{-3} [14]. The large distance between nearest-neighbor active ions [15,16] in potassium double tungstates diminishes the probability of energy-transfer upconversion and may enable higher erbium concentrations [17]. We have investigated the ETU as a function of erbium concentration as well as its influence on the achievable optical gain.

Experimental

When micro-structuring deposited thin films to form channel waveguides, high confinement and almost perfect mode overlap of high-intensity pump and signal light in the erbium-doped layer [18] is obtained, which allows one to utilize increased erbium concentrations in order to exploit higher optical gain.

We have studied the spectroscopy of erbium-doped waveguides in mixed potassium double tungstates (Fig. 1) with erbium concentrations of 0.75 to 10 at.%. The cross-sections of the transitions to and from the first and second excited state are derived. Fluorescence decay curves and excited-state lifetimes at 1.5 µm, 1 µm, and 550 nm are measured. The magnitude of ETU from the first excited versus erbium concentration is calculated by fitting the fluorescence decay curves from the first excited state with Zubenko's equation [19]. The gain around 1.5 µm is measured with a pump-probe technique and the influence of ETU on optical gain is investigated.

A maximum gain per unit length of ~11 dB/cm at the peak wavelength of 1534.7 nm is obtained. It is found that energy-transfer upconversion from the amplifier level is the main parasitic process that affects the gain value.

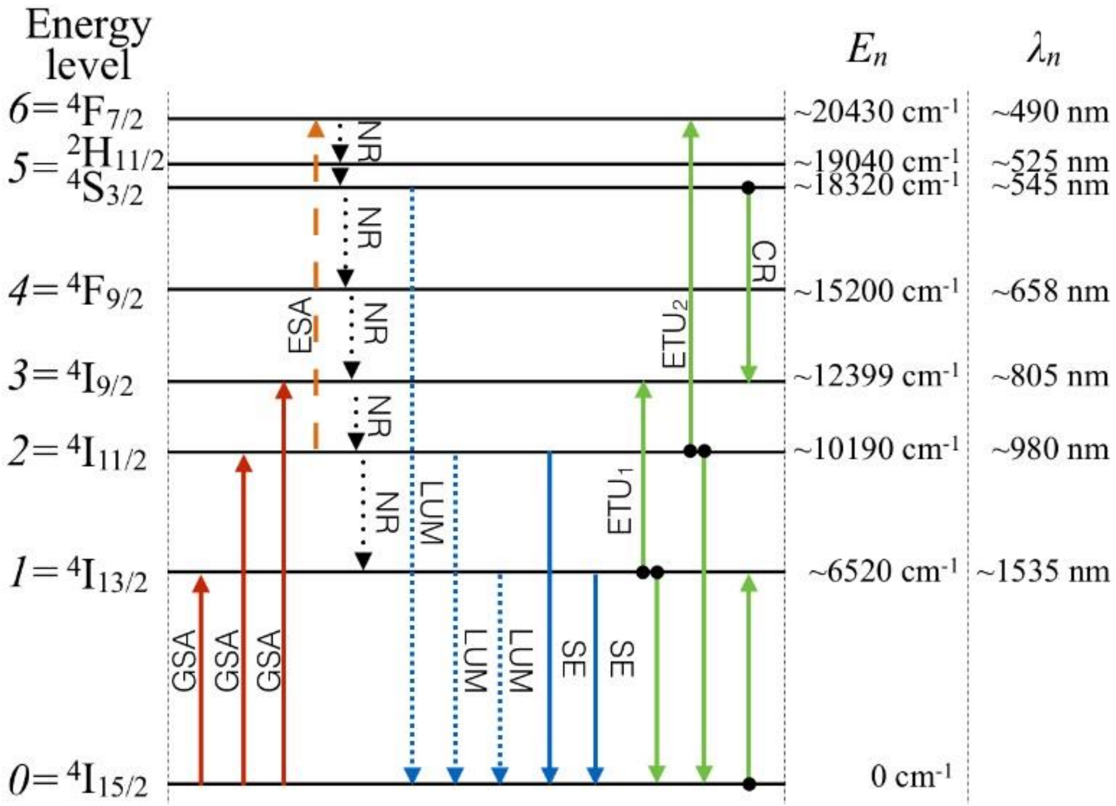

Fig. 1. Simplified energy-level diagram of erbium displaying absorption on the transitions to ${}^4I_{13/2}$, ${}^4I_{11/2}$, and ${}^4I_{9/2}$ near 1480 nm, 980 nm, and 800 nm, respectively, the transition from ${}^4I_{11/2}$ to ${}^4F_{7/2}$ near 980 nm, the fluorescence transitions from ${}^4I_{13/2}$, ${}^4I_{11/2}$, and ${}^4S_{3/2}$ to the ground state near 1530 nm, 980 nm, and 550 nm, respectively, stimulated emission on the transitions from ${}^4I_{13/2}$ and ${}^4I_{11/2}$ to the ground state near 1530 nm and 980 nm, respectively, multiphonon relaxation, and the energy-transfer processes from the first, second, and fifth excited states.

Conclusions

A detailed spectroscopic study in erbium-doped potassium gadolinium lutetium double tungstate channel waveguides has been performed. From the time dependence of fluorescence decay at different pump powers in samples with different doping concentrations, the interionic processes were investigated. Energy-transfer upconversion is the key spectroscopic process that affects the gain at 1.5 µm.

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