

Gain characterization of a lattice-engineered potassium double tungstate thin film with 57.5 at.% ytterbium concentration

Y.S. Yong^{1,2}, S. Aravazhi¹, S.A. Vázquez-Córdova^{1,2}, S.M. García-Blanco^{1,2}, and M. Pollnau^{1,3}

¹ Integrated Optical MicroSystems Group, MESA+ Institute for Nanotechnology, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands

² Optical Sciences Group, 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

We report the measurement results on an ytterbium-activated potassium gadolinium double tungstate (KGW) thin film grown onto a potassium yttrium double tungstate (KYW) substrate. The 57.5 at.% Yb-doped active layer, in which the material composition reaches the upper limit of Yb concentration lattice matched to the KYW substrate, was grown by liquid phase epitaxy and polished to ~ 32 μm thickness. The measured lifetime indicates that lifetime quenching is rather insignificant. Besides, a high gain per unit length of about 1050 dB/cm was obtained. The results show that this material is favorable for the fabrication of waveguide amplifiers for short optical interconnects requiring compact device footprint.

Introduction

Rare-earth-doped amplifiers are well known for their capability of supporting high-gain, high-bit rate, and broadband amplification. However, it remains a great challenge to reduce the length of these devices to realize on-chip waveguide amplifiers for emerging footprint-limited applications, such as photonic integrated circuits, optical sensing devices, and optical backplane systems, to name just a few. Typical rare-earth-doped waveguide amplifiers possess a material gain of only a few dB/cm, mainly due to the small emission cross-sections resulting from the combination of a long emission lifetime and a fast atomic dephasing time [1], and the limited dopant concentration of rare-earth ions in the host materials. Therefore, device lengths of tens of centimeters are usually needed for practical amplification.

In order to achieve high gain per unit length, the amplifier material must exhibit both high transition cross-sections and high doping concentration [2]. Therefore, in this work, a lattice-engineered approach [3,4] is employed to maximize the concentration of ytterbium (Yb) ions in a potassium double tungstate [5] crystalline film grown onto a substrate of potassium yttrium double tungstate, $\text{KY}(\text{WO}_4)_2$ (denoted as KYW hereafter). The method was applied successfully to fabricate a 47.5 at.% Yb-doped potassium double tungstate waveguide amplifier with ~ 1000 dB/cm gain at 981 nm [2]. Here we report the successful growth of 57.5 at.% Yb-doped layers of potassium gadolinium double tungstate, $\text{KGd}(\text{WO}_4)_2$ (denoted as KGW hereafter) onto KYW. Characterization results show that the thin-film gain material does not exhibit significant lifetime quenching. Apart from that, a gain per unit length of more than 1000 dB/cm is obtained from pump-probe gain measurements.

Lattice Engineering Approach and Gain Material Preparation

It is essential that the lattice parameters of the active layer match those of the substrate to obtain high-quality crystalline thin films. Table 1 shows the lattice constants of $\text{KY}(\text{WO}_4)_2$, $\text{KYb}(\text{WO}_4)_2$, and $\text{KGd}(\text{WO}_4)_2$ at 298 K as summarized in [4]. Overall, $\text{KYb}(\text{WO}_4)_2$ has smaller lattice dimensions than $\text{KY}(\text{WO}_4)_2$. Hence, optically inert $\text{KGd}(\text{WO}_4)_2$ is added to the active layer to compensate for lattice mismatch, thereby reducing the accumulated stress in the thin film.

Table 1: Lattice constants of selected rare-earth-doped potassium double tungstates [4]

	a (nm)	b (nm)	c (nm)
$\text{KY}(\text{WO}_4)_2$	1.06313(4)	1.03452(6)	0.75547(3)
$\text{KYb}(\text{WO}_4)_2$	1.06003(12)	1.02673(12)	0.75066(8)
$\text{KGd}(\text{WO}_4)_2$	1.06890(6)	1.04438(5)	0.76036(4)

We grew thin $\text{KGd}_{0.425}\text{Yb}_{0.575}(\text{WO}_4)_2$ active layers on 1-mm-thick KYW substrates in a $\text{K}_2\text{W}_2\text{O}_7$ solvent by liquid phase epitaxy at 920-925°C. The corresponding doping concentration is $3.63 \times 10^{21} \text{ cm}^{-3}$. After the growth, the rear surface of the substrate is polished to remove the residual growth layer. The front active layer is first lapped using Al_2O_3 slurry with 3 μm grain size to obtain a flat surface. Next, a fine polishing step is performed using OP-U suspension (Struers). The resulting thickness of the active layer measured using a profilometer (Dektak) is about 32 μm .

Experimental Procedure

The lifetime of the ${}^2\text{F}_{5/2}$ upper energy level state of Yb is measured by collecting the emission perpendicular to the pump direction [6], as depicted in Fig. 1. Emission from a laser diode at 976 nm wavelength is delivered to the edge of the sample to excite the Yb ions from their ${}^2\text{F}_{7/2}$ ground state. A spontaneous-emission collection fiber is placed as close as possible to the sample's surface to minimize the elongation of luminescence lifetime due to reabsorption [7]. A monochromator is used to select the emission at 1020 nm and to discriminate it from the residual pump. An InGaAs detector is placed at the other end of the monochromator. The detected signal is amplified and coupled to an oscilloscope set to average the signal over 4096 times.

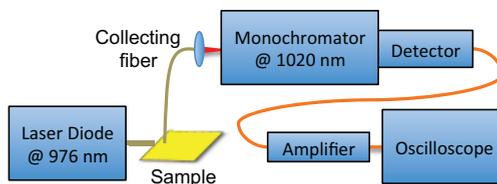


Figure 1: Experiment setup for lifetime measurement.

The gain experiment is performed using a Ti:Sapphire laser tuned to 932 nm as the pump source. Signal light at 981 nm wavelength is free-space coupled with the pump beam using a dichroic mirror. Both optical beams are polarized to the N_m axis and focused perpendicularly to the sample with a $\times 22$ microscope objective. The launched signal power is approximately 100 nW, whereas the maximum launched pump power is about 700 mW. A $\times 50$ long-working-distance microscope objective is used to collect the emission from the other end of the sample. The output beams are directed to an

InGaAs detector attached to an iHR550 spectrometer equipped with a pump filter. A lock-in detection system is used in the experiment.

Results and Discussions

Figure 2 shows the result of a lifetime measurement at 1020 nm wavelength. The collected data points follow a single-exponential decay with a lifetime of 289 μs . Similar measurements were performed on samples with lower doping concentrations. By taking radiation trapping into consideration, the lifetime for 57.5 at. % Yb concentration is found to be $\sim 250 \mu\text{s}$ as compared to the lifetime value of 261 μs at low doping concentration [6]. This indicates that lifetime quenching is rather insignificant even at a doping concentration as high as $3.63 \times 10^{21} \text{ cm}^{-3}$.

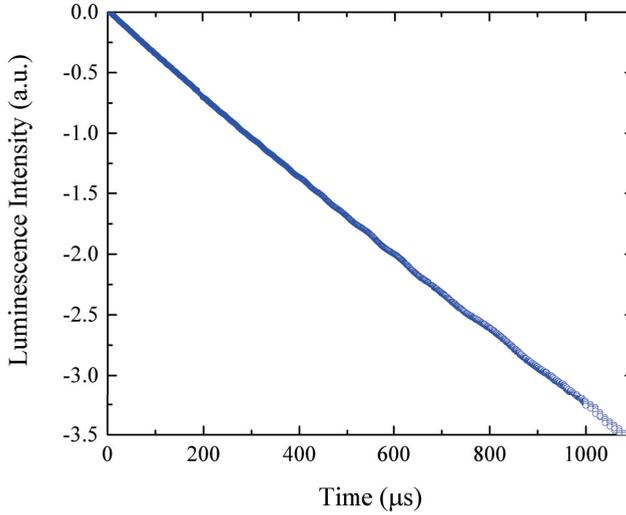


Figure 2: Measured lifetime decay in $\text{KGd}_{0.425}\text{Yb}_{0.575}(\text{WO}_4)_2$ [6].

The small-signal gain of the sample is determined from the expression of $10\log_{10}(I_L/I_0)$, where I_0 and I_L are the respective signal powers at the beginning and at the end of the sample. The signal amplification is determined from the measured signal enhancement ratio which can be related to the gain by

$$\begin{aligned} G &= 10\log_{10}(I_L/I_0) \\ &= 10\log_{10}(I_{L,pumped}/I_{L,unpumped}) + 10\log_{10}(I_{L,unpumped}/I_0) \quad , \\ &= 10\log_{10}(I_{L,pumped}/I_{L,unpumped}) - \alpha \end{aligned}$$

where $I_{L,pumped}$ represents the detected signal power when the sample is pumped, $I_{L,unpumped}$ is the detected signal power when the sample is not pumped, and α is the total loss of the signal which is dominated by the absorption of the Yb ions amounting to 4.718 dB. The maximum measured ratio of $I_{L,unpumped}$ to $I_{L,pumped}$ is 8.107 dB, resulting in a gain per unit length of about 1050 dB/cm.

The lifetime and gain results further support the advantage of using a lattice-engineered KYW-based material for waveguide amplifiers delivering high gain over short device lengths. With a suitable waveguide structure design, it should be possible to realize waveguide amplifiers with a high total gain (30-50 dB) with device lengths less than a millimeter.

Conclusion

We have reported the growth of $\text{KGd}_{0.425}\text{Yb}_{0.575}(\text{WO}_4)_2$ thin films on $\text{KY}(\text{WO}_4)_2$ substrates. Our experimental results show that there is no significant lifetime quenching despite the high Yb doping concentration. Gain per unit length as high as 1050 dB/cm has been obtained. The results are promising for the realization of high-gain, small-footprint waveguide amplifiers.

Acknowledgement

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