Low-threshold and highly efficient Gd^{3+}, Lu^{3+} co-doped $KY(WO_4)_2:Yb^{3+}$ planar waveguide lasers

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Abstract: Co-doping with optically inert Gd^{3+} and Lu^{3+} ions improves refractive-index contrast and light confinement in $KY(WO_4)_2:Yb^{3+}$ planar waveguides. Lasing with 18 mW threshold and record-high slope efficiency of 82.3% versus absorbed pump power is demonstrated.

***OCIS codes**: (140.3615) Lasers, ytterbium; (230.7390) Waveguides, planar; (140.3070) Infrared and far-infrared lasers; (140.3580) Laser, solid-state.*

1. Introduction

Potassium yttrium double tungstate, $KY(WO_4)_2$ (hereafter abbreviated as KYW), is an excellent host material for solid-state lasers, see Ref. [1] and Refs. therein. Large absorption and emission cross sections and broad linewidths of rare-earth ions doped into this material and, in particular, very large concentrations [2] and a very small quantum defect [3] when incorporating Yb^{3+} ions add to its attractiveness. Co-doping of $KYW:Yb^{3+}$ layers with large amounts of optically inert Gd^{3+} and Lu^{3+} ions during liquid phase epitaxy (LPE) results in an enhanced refractive-index contrast of $\sim 7.5\times10^{-3}$ with respect to the substrate [4], allowing for small layer thicknesses of a few micrometers for single-mode guiding and improved light confinement compared to singly-doped $KYW:Yb^{3+}$ layers [5, 6]. In those single-doped systems the refractive-index contrast of $\sim 6\times10^{-4}$ relies solely on the low Yb^{3+} concentration which needs to be optimized for laser performance and, therefore, cannot attain a high level.

Here we report on planar waveguide lasing with record-high slope efficiency of 82.3% versus absorbed pump power and a low laser threshold of 18 mW absorbed pump power in Gd^{3+}, Lu^{3+} co-doped $KYW:Yb^{3+}$ samples for 23% and 1.7% out-coupling efficiency, respectively. The maximum obtained output power is 195 mW.

2. Layer growth and characterization

Crack-free layers of $KYW:Gd^{3+},Lu^{3+},Yb^{3+}$ with a thickness of ~10 μm were grown by LPE onto undoped, (010)-orientated laser-grade-polished KYW substrates of 1 cm^2 size. The layer surface was polished parallel to the layer-substrate interface, creating a waveguide with a uniform thickness of 4.6 μm. After overgrowth of this active layer with an undoped KYW layer the endfaces of the sample were polished parallel to the N_m optical axis, such that by butt-coupling dielectric mirrors to the waveguide endfaces a monolithic cavity along the N_g optical axis was formed. The composition of these co-doped layers was investigated by laser-ablation inductively-coupled-plasma mass spectrometry, revealing a segregation coefficient of nearly unity for all doping types during LPE growth. X-ray diffraction studies on these layers confirmed a single crystalline layer.

The spectroscopic properties were investigated by luminescence lifetime measurements and by recording the emission spectra. To measure the luminescence lifetime, single- and co-doped active waveguides were excited by a diode laser at 976 nm. The luminescence decay at 1040 nm was monitored via a monochromator by an InGaAs detector after switching off the pump laser. Comparison of single- and co-doped samples resulted in a slightly shorter lifetime of 260 μs for the co-doped layer versus a lifetime of 267 μs for the single-doped layer (Fig. 1). For the luminescence measurements the active ions were excited at 932 nm, the luminescence light was collected normal to the sample surface and analyzed by a spectrometer. The FWHM of the emission peak at ~980 nm in the single-doped film was 3.6 nm (Fig. 2a), which is only slightly smaller than the corresponding value of 3.8 nm obtained for the co-doped film (Fig. 2b). Both the shorter lifetime and broader emission linewidth are attributed to the co-doping; however, the small deviations detected in the co-doped layers indicate that incorporation of large percentages of Gd^{3+} and Lu^{3+} ions has no strong adverse effect on these laser-relevant spectroscopic properties of the fabricated layers.

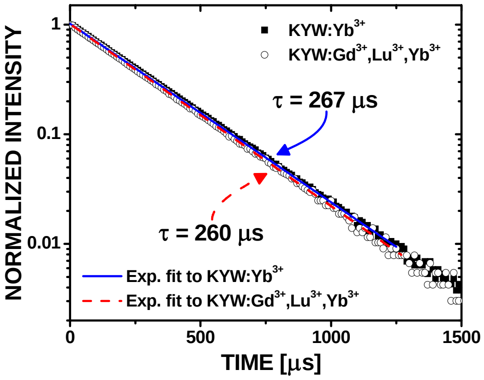

Fig. 1. Decay curves of the luminescence at 1040 nm in KYW:Yb^{3+} and KYW:Gd^{3+},Lu^{3+},Yb^{3+} films

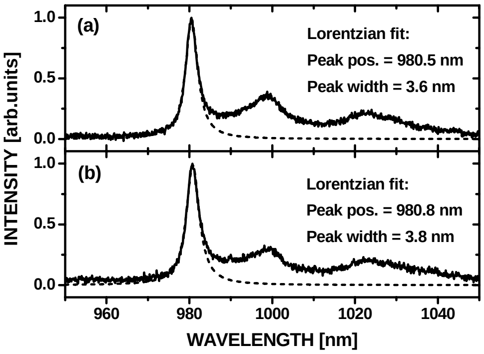

Fig. 2. Luminescence emission spectra from (a) a KYW:Yb^{3+} layer and (b) a KYW:Gd^{3+},Lu^{3+},Yb^{3+} layer. The dashed line is a Lorentzian fit of the main emission peak.

3. Laser experiments

Room-temperature laser operation was investigated under continuous-wave Ti:sapphire pumping at the Yb^{3+} absorption peak near 981 nm with pump polarization parallel to the N_m optical axis of the waveguide layer. Two cylindrical lenses were used to adapt the pump mode to the laser mode, resulting in a pump waist radius of ~30 µm in the horizontal direction formed by a f = 4 cm cylindrical lens, while optimal coupling to the waveguide in the vertical direction with a spot size of ~ 7 µm was obtained with a second cylindrical lens with f = 1 cm.

At the laser wavelengths the incoupling mirror had a reflectivity of 99.8%, while for the outcoupling mirror transparencies of 1.7%, 5%, 10%, 20%, and 23% were tested. Figure 3a shows the laser output characteristics as a function of absorbed pump power. The highest slope efficiency of 82.3%, which to the best of our knowledge represents the highest value yet reported for a planar waveguide laser to date, and a maximum extracted laser power of 195 mW for an absorbed pump power of 280 mW were obtained using the 23% outcoupling mirror. The lowest laser threshold of only 18 mW absorbed pump power obtained with the 1.7% outcoupling mirror represents a reduction by more than a factor of two compared to previous experiments [5, 6] and highlights one of the advantages of the tight optical confinement achieved by the enhanced refractive-index contrast. The best laser performance in all cases was found for 1025 nm, although the emission wavelength could be varied from 1000 nm to 1042 nm by slightly changing the alignment, which was probably caused by the etalon effects of the gaps between the mirrors and the waveguide endfaces. As expected from the cavity design and pump geometry, in all investigated configurations the laser emission had a highly elliptical Gaussian profile with FWHM of ~4.5 µm perpendicular and ~60 µm parallel to the waveguide plane (Fig. 3b).

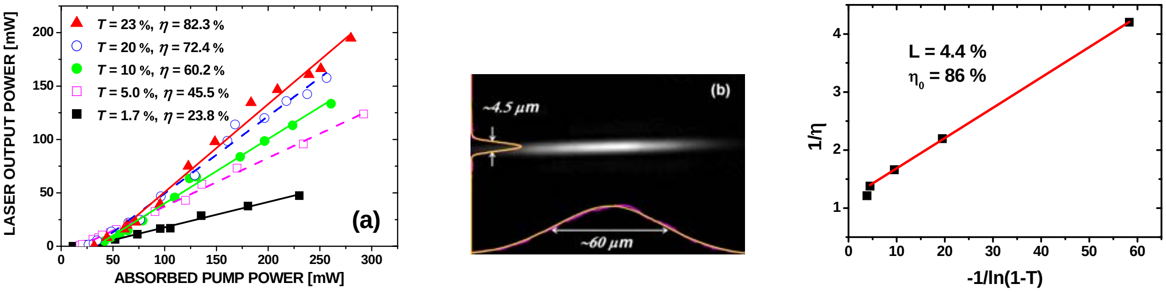

Fig. 3. (a) Laser output power as a function of absorbed pump power for various outcoupling mirror transmissions; (b) laser mode profile emitted by the KYW:Gd^{3+},Lu^{3+},Yb^{3+} planar waveguide; (c) inverse slope efficiency 1/η as a function of inverse logarithmic reflection -1/ln(1-T) of the outcoupling mirror. The solid line is a linear fit based on values obtained with the outcoupling mirrors with transmission values of 1.7%, 5%, 10%, and 20% according to Eq (1).

4. Roundtrip loss analyses

Based on the theoretical behavior of lasers exhibiting reabsorption losses [7], the intracavity round-trip loss L and the laser efficiency parameter η_0 were derived by plotting the inverse of the measured slope efficiency η versus the inverse of the transparency T of the output mirror according to

$$\eta = \eta_0 \frac{\ln(1-T)}{\ln[(1-L)\cdot(1-T)]} \quad \Rightarrow \quad \frac{1}{\eta} = \frac{1}{\eta_0} + \frac{-\ln(1-L)}{\eta_0} \cdot \frac{(-1)}{\ln(1-T)} \cdot \qquad (1)$$

Equation 1 represents a modified version of the corresponding expression for the slope efficiency η in [7]. It avoids approximation of the logarithmic function and allows a more accurate estimation of the round-trip loss for outcoupling mirrors with higher transmission values. The result based on laser performance obtained with the 1.7%, 5%, 10%, and 20% outcoupling mirrors is displayed in Fig. 3c. A fairly high value of 4.4% was derived for the round-trip loss L compared to previous results [5, 6]. This increased loss is attributed to the tighter confinement due to the smaller waveguide dimensions, which results in higher beam divergence at the waveguide endfaces and, consequently, higher losses at the gaps between endfaces and butt-coupled mirrors. The laser performance obtained with the 23% outcoupling mirror was not taken into account in this analysis, because the flatness of this mirror was better, resulting in a smaller gap between the endface and the mirror and, thus, in lower intracavity round-trip loss and enhanced laser performance.

The laser efficiency parameter η_0 indicates the pump-light conversion efficiency of the laser and strongly depends on the overlap of the pump with the laser mode, reabsorption losses, and Stokes efficiency. Due to an optimized overlap between pump and laser mode a high value of $\eta_0 = 86\%$ was calculated, which is 13% higher than a previously reported value [6].

5. Conclusions

KYW:Gd^{3+},Lu^{3+},Yb^{3+} layers were grown on undoped KYW substrates and their composition, structural, and spectroscopic properties investigated. Planar waveguide lasers with record-high slope efficiency of up to 82.3%, maximum output power of 195 mW, and low laser threshold of 18 mW were demonstrated. Besides reducing the required threshold pump power significantly, the enhanced refractive-index contrast and, consequently, smaller waveguide dimensions paves the way for future implementation of micro-structured channel waveguides and integrated laser resonators.

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