Low-threshold, mirrorless emission at 981 nm in an Yb,Gd,Lu:KYW inverted rib waveguide laser

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ABSTRACT

In this work, we demonstrate 3-level laser operation in a Yb,Gd,Lu:KYW waveguide laser fabricated by combination of liquid phase epitaxy and Ar^+ ion beam milling. Laser emission was observed at 981 nm with an absorbed threshold power of 23 mW and a slope efficiency of 58% without the use of any mirrors. With an HR/6%T cavity, the threshold was reduced to 13 mW. The output was single mode with beam radii of 4.8 μm and 3 μm in the in-plane and out-of-plane direction respectively. Laser emission was also observed at 999.8 nm with a threshold of 8 mW by using mirrors favouring the 999.8 nm transition and forming an HR/5%T cavity.

Keywords: Ytterbium doped gain media, waveguide laser, double tungstate, liquid phase epitaxy, ion beam milling, 3-level laser

1. INTRODUCTION

Ytterbium-doped media are traditionally operated as quasi-3-level lasers and have been extensively used to demonstrate efficient and low threshold lasers operating around 1030 nm [1]. Yb^{3+}-doped laser materials have several useful features such as a low quantum defect, a relatively long lifetime and low parasitic losses. In particular, potassium double tungstates $KY(WO_4)_2$ (KYW) when doped with Yb^{3+} have a very large fluorescence bandwidth and can be used for generating short pulses [2]. Liquid phase epitaxy has been used to fabricate planar [3, 4] and channel [5, 6] waveguide lasers in Yb^{3+} doped KYW to demonstrate lasing around 1030 nm. Such waveguide devices could be used to realise compact ultrafast laser sources around 1 micron with repetition rates of a few GHz [7], which can have applications in frequency metrology, optical sampling and non-linear microscopy.

There have been recent reports of a Yb:KYW planar waveguide laser co-doped with Ga^{3+} and Lu^{3+}, operating as a pure 3-level system at the zero–phonon line at 981 nm [8], with a threshold power of 75 mW and a channel waveguide laser with an output power of 11 mW [9].

In this paper we demonstrate mirrorless lasing at 981 in an Yb,Gd,Lu:KYW laser with a very low threshold power of 23 mW. The threshold is reduced to 13 mW by using an HR mirror and a 6% transmission output coupler. Output power as high as 17 mW was achieved, limited only by the available pump power. We also discuss lasing results around 1000 nm and the competition between lasing at 981 nm and 1000 nm.

2. FABRICATION OF THE WAVEGUIDE

2.1 Growth of KYW substrate

Substrates for the liquid phase epitaxy (LPE) growth were obtained from KYW bulk crystals grown by the top seeded solution growth slow-cooling (TSSG-sc) technique in a vertical tubular furnace. The solute/solvent ratio was 12 mol% $KY(WO_4)_2$ / 88 mol% $K_2W_2O_7$. The analytical grade purity (99.99%) powder precursors were melted inside a cylindrical platinum crucible (~125 cm^3). The 300 g solution was homogenized by keeping the temperature 10 K above the expected saturation temperature, T_s, for 6 hours. T_s was accurately determined by using a **b**-oriented KYW crystal seed placed in contact with the surface of the solution, rotating at 42 rpm, and by controlling its dissolution or growth with a precision of 10 µm. Thus T_s was established as the temperature at which neither dissolution nor growth of the crystal seed could be observed. The KYW bulk crystal started to grow from the seed in contact with the surface of the solution by slow cooling (0.15 K/hour) from T_s down to ~ 30 K below T_s. Once the cooling ramp was over, the grown crystal was slowly extracted from the supersaturated solution (at 0.1 mm/min) and held slightly above the surface of the solution to avoid cracking due to thermal shocks. Finally, the furnace was cooled at a rate of 20 K/hour down to room temperature. The as-grown KYW crystal was then cut in slices perpendicular to the **b**-crystallographic direction, with typical dimensions (10 × 2.5 × 25 mm^3) and polished to high quality.

2.2 Ion-beam milling of the substrate

A photoresist layer was spun on the substrate, which was then photolithographically patterned by UV exposure and consequent development of the mask. The mask transferred on the substrate was a dark field mask with openings of widths 3 µm- 10 µm in steps of 0.2 µm. This was then etched by ion beam milling in an Ionfab 300 Plus Ion Beam system using inert Ar^+ ions. The sample was etched for 4 hours and 30 minutes with a current of 100 mA and a voltage of 500 V. The resist was then removed by solvents and plasma-ashing in OPT Plasmalab 80 Plus Reactive Ion Etcher. The etch depth was measured by KLA Tencor P-16 Stylus Profiler and was found to be to be 5µm as shown in figure 1. The resulting grooves, fabricated parallel to the $\boldsymbol{N_g}$ optical direction, were used as the basis for growth of inverted rib waveguide structures, as described below.

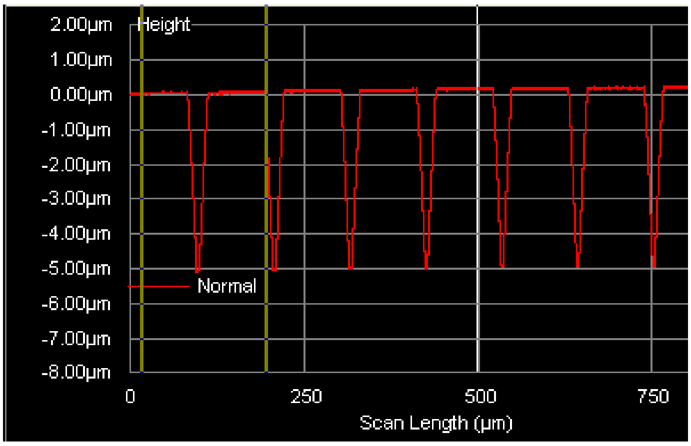


Figure 1. 2-d Profile of the etched KYW substrate

2.3 Growth of Yb,Gd,Lu:KYW and KYW cladding layer by liquid phase epitaxy (LPE)

A KYW layer substituted with 18 mol% Gd, 25 mol% Lu and activated with 3 mol% Yb was grown over the microstructured KYW substrate by LPE following an original procedure of our laboratory [10]. Gd was introduced into the KYW matrix in order to increase the refractive index with respect to the substrate and Lu was added in compensation, to match the lattice parameter of the layer structure to that of the substrate [11]. In this case, 80 g of solution in the solute/solvent ratio 7 mol% $KY(WO_4)_2$/93 mol% $K_2W_2O_7$ were mixed inside a cylindrical platinum crucible (~50 cm^3). After homogenization, the saturation temperature T_s was determined in the same way as for the KYW bulk crystals. The substrate was vertically dipped into the solution at 1 K above T_s over a period of 5 minutes with the aim of inducing dissolution of its surface and hence avoiding the introduction of defects in the subsequent layer growth. The epitaxial growth of the layer started on suddenly decreasing the temperature of the solution 3 K below T_s and finished 3 hours later by holding the substrate with the grown layer at 1 mm above the surface of the solution. The furnace was cooled down to room temperature at 15 K/hour. The as-grown layer had a thickness of 50 µm, measured with respect to the surface not exposed to the Ar^+-milling. The epitaxial layer grown over the etched face of the substrate was polished down to a thickness of < 1µm. A KYW cladding layer was then grown over the channels by LPE, following the same procedure as for the doped layer. The sample was then cut perpendicular to the N_g optical direction in such a way that light could be coupled into the inverted ribs either polarized horizontally (**E**//N_m) or vertically (**E**//N_p) whilst propagating parallel to N_g. The sample was then polished to a length of 3 mm. Figure 2 shows the SEM image of the end face of the waveguide. It can be seen that the polishing of the active layer to the desired thickness wasn't perfect leading to a non-uniform thickness, which could be one of the major factors contributing to the high propagation loss as discussed later.

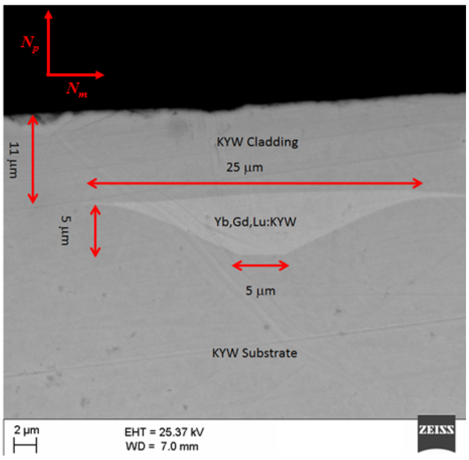


Figure 2. SEM cross- section view of the "inverted" waveguide

3. EXPERIMENTAL SETUP

The schematic diagram of the setup for the laser experiments is shown in figure 3. A Ti:sapphire laser, tuned to 932 nm, was used as the pump source. A variable attenuator was used to control the power and a half wave plate was used to rotate the polarization of the pump. A 6× objective was used to launch the pump in the waveguide and a 10× objective was used to collimate the output from the waveguide. The pump was horizontally polarized (E//N_m).

A dichroic mirror was used to separate the pump and laser wavelengths. The reflected laser beam was captured by a CMOS camera to measure the mode size or by a power meter for output power measurements, or was incident onto an optical spectrum analyzer (OSA) to measure the spectrum. M1 and M2 are thin dielectric mirrors butt-coupled to the waveguides by a fluorinated liquid (FC-70 by Sigma Aldrich).

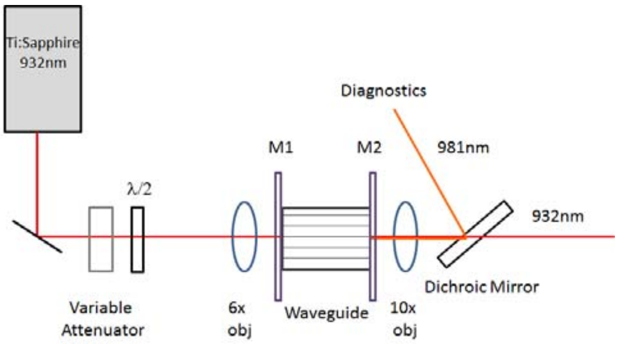


Figure 3. Schematic of the setup for lasing experiments

4. RESULTS AND DISCUSSIONS

4.1 Lasing at 981nm

For these set of experiments, the first cavity formed was without the use of any external mirrors, the feedback being provided by the Fresnel reflections (11%) from the end facets. The input and output powers were measured and the slope efficiency was found to be 58% with respect to absorbed power (which was calculated by measuring transmission of the pump through the waveguide on and off absorption near the threshold power), with a threshold of 23 mW. The maximum power extracted in this configuration was 17 mW. Similar experiments were repeated with different cavities ie: HR/Fresnel cavity, HR/24%T cavity and HR/6%T cavity. The results are presented in figure 4 and summarized in table 1. The lowest threshold power obtained was 13 mW for the HR/6%T cavity.

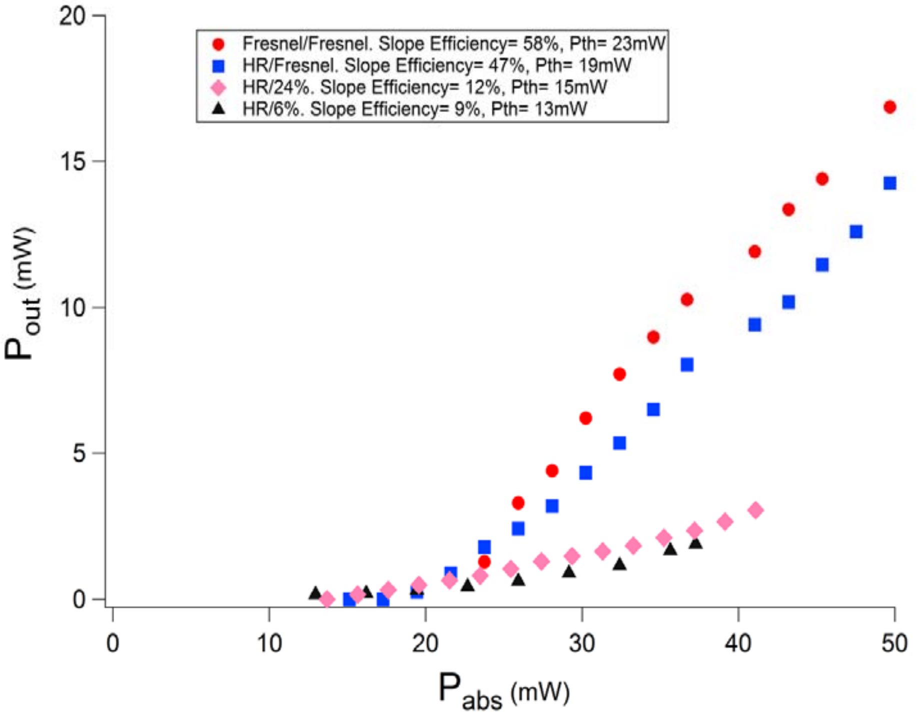


Figure 4. Output power (P_{out}) vs. Absorbed power (P_{abs}) for different cavity configurations

Table 1. Summary of threshold powers and slope efficiencies for different cavities.

Cavity	Absorbed threshold power (mW)	Slope efficiency (%)
Mirrorless (Fresnel/Fresnel)	23	58
1 Mirror (HR/Fresnel)	19	47
HR/24%	15	12
HR/6%	13	09

The losses were estimated by a Caird analysis [12] and transmission measurements to be 2.7 dB/cm. This is higher than previously reported values in this material [5], which may be attributed to the imperfect polishing of the active layer as seen from figure 2. The output spectrum was measured by an OSA and was centred at 980.8 nm as shown in figure 5 and the laser output was horizontally polarized (E//$\boldsymbol{N_m}$).

The output beam was imaged onto a CMOS camera and is shown in figure 6. The output is single mode with beam radii of 4.8 µm and 3 µm in the x (in-plane) and y (out-of-plane) direction respectively. The measured and simulated (using OlympIOs commercial software) beam profiles are in reasonable agreement with each other, with the predicted mode radii being 4.1 µm and 2.2 µm in the x and y directions respectively.

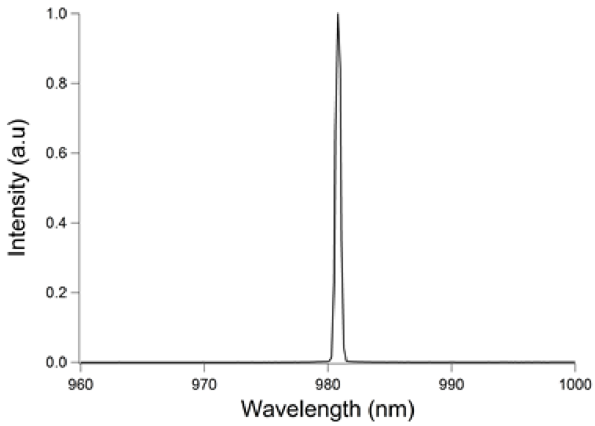


Figure 5. The measured spectrum centred at 980.8 nm.

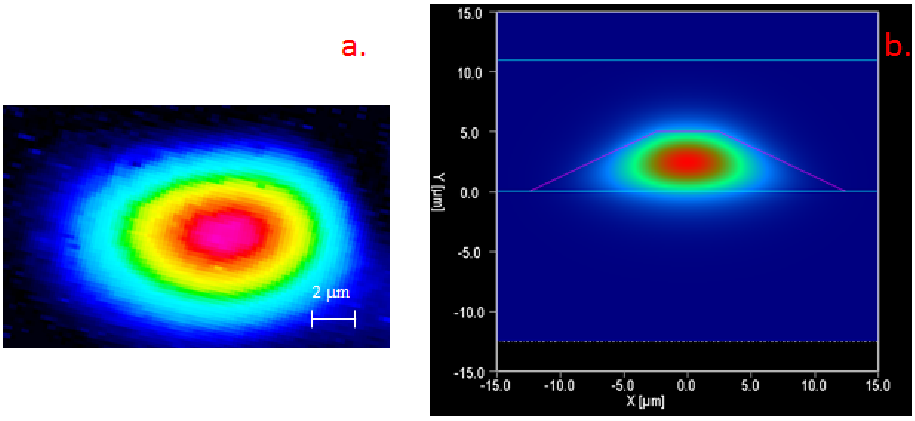


Figure 6. a. Measured laser mode. b. Simulated laser mode.

4.2 Lasing at 999.8nm

The mirrors were changed for these set of experiments, with the input mirror having >99.8% transmission at 932 nm and <1% transmission at 999.8nm and the output mirror having a transmission of 5% at 999.8 nm. The threshold was observed to be 8 mW and the slope efficiency was found to be 4.8%. The input output characteristics are shown in figure 7. The lasing wavelength was found to be 999.8 nm.

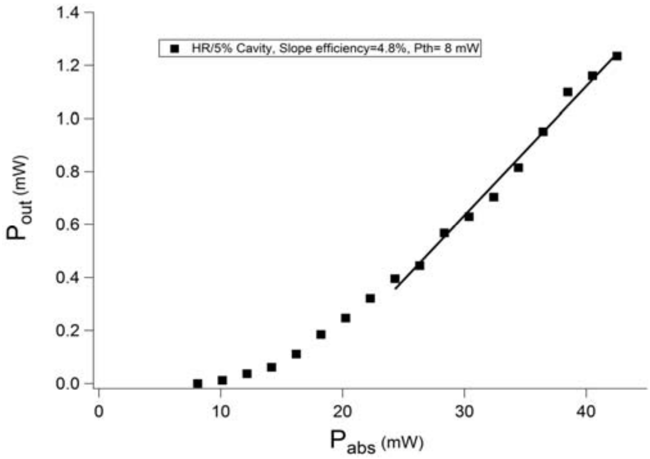


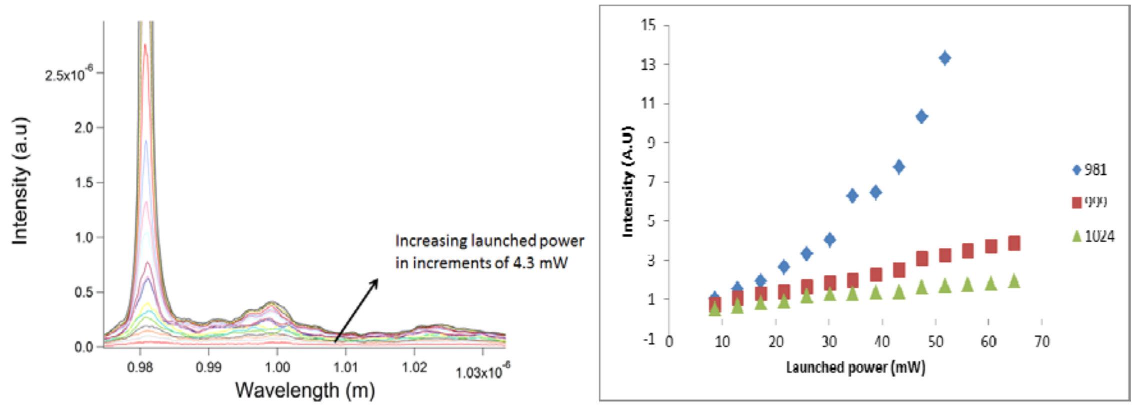
Figure 7. Output power (P_{out}) vs. Absorbed power (P_{abs}) for the HR/5% cavity

4.3 Discussion

As described in the previous sub-sections, 981 nm was the preferred lasing wavelength when compared to the more commonly operated 1024 nm transition. The evolution of the fluorescence spectra with increasing launch power was studied in the mirrorless cavity configuration. A fiber coupled OSA was used to take these spectra with the fiber at the end of the waveguide. Figure 8.a shows the measured spectra and figure 8.b shows the extracted peak intensity for each power. It is clearly seen that most of the gain is taken by the 981 nm wavelength and hence is the preferred wavelength when compared to 999.8 nm and 1024 nm laser wavelength. This observation is consistent with calculations carried out assuming a propagation loss of 2.7dB/cm. The calculated threshold powers for 1024 nm, 999.8 nm and 981 nm for a mirrorless cavity are 32 mW, 20 mW and 17 mW, hence the 981nm wavelength reaches threshold first.

For the HR/5%T cavity the laser threshold is calculated to be 3.5 mW for the 1024nm wavelength compared to 16.5 mW for the 981 nm and 3 mW for the 999.8nm. Hence the 999.8 nm radiation reaches threshold first.

In each case, the balance between gain, reabsorption loss, propagation loss and cavity loss allows selection between these wavelengths.



a. b.

Figure 8: a. Evolution of spectra with launched pump power measured end-on b. extracted peak intensities for 981nm, 999.8 nm and 1024 nm as a function of power.

5. CONCLUSIONS

We have demonstrated pure 3- level laser emission at 981 nm for a Yb,Gd,Lu:KYW inverted waveguide laser fabricated by a combination of liquid phase epitaxy and ion beam milling. A threshold power as low as 13 mW and a slope efficiency as high as 58% was observed. The output was single mode with a beam radii of 4.8 µm horizontally and 3 µm vertically. Laser emission was also obtained at 999.8nm by using mirrors designed especially for that wavelength. A discussion has also been provided to explain preferential operation at 981 nm when compared to quasi 3- level laser operation.

ACKNOWLEDGEMENTS

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