Microstructured $KY(WO_4)_2:Gd^{3+}, Lu^{3+}, Yb^{3+}$ channel waveguide laser

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Abstract: Epitaxially grown, 2.4-μm-thin layers of $KY(WO_4)_2:Gd^{3+}$, Lu^{3+}, Yb^{3+}, which exhibit a high refractive index contrast with respect to the undoped $KY(WO_4)_2$ substrate, have been microstructured by Ar beam milling, providing 1.4-μm-deep ridge channel waveguides of 2 to 7 μm width, and overgrown by an undoped $KY(WO_4)_2$ layer. Channel waveguide laser operation was achieved with a launched pump power threshold of only 5 mW, a slope efficiency of 62% versus launched pump power, and 76 mW output power.

OCIS codes: (140.3615) Lasers, Ytterbium; (230.7380) Waveguides, channeled

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1. Introduction

The unique property of the family of monoclinic double tungstates, especially $KGd(WO_4)_2$, $KY(WO_4)_2$, and $KLu(WO_4)_2$, to strongly enhance the absorption and emission cross sections of optically active rare-earth ions doped into these host materials is widely recognized, see Ref [1]. and references therein. Combination of these enhanced absorption cross-sections with very large Yb^{3+} doping concentrations, reaching the stoichiometric structure $KYb(WO_4)_2$ [2], can reduce the pump absorption length near 980 nm to less than 20 µm. Also the quantum defect resulting from the difference between pump and laser photon energy can become very small in Yb^{3+}-doped double tungstates [3], making them excellent candidates for bulk [4,5], thin-disk [6], and waveguide [7,8] lasers.

For the latter purpose, rare-earth-ion-doped $KY(WO_4)_2$ (KYW) thin layers have been grown by liquid phase epitaxy (LPE) onto undoped KYW substrates [9,10,7]. Optimization of the doping concentration for efficient lasing results in KYW:Yb^{3+} planar waveguides with low Yb^{3+} concentrations of typically 1-3 at.%, which induces a refractive index contrast between layer and substrate of only a few $\times 10^{-4}$, thus requiring a layer thickness in excess of 10 µm for waveguiding. In such planar structures, laser operation was demonstrated with slope efficiencies up to 80% [7] and in a monolithic cavity under diode pumping [8]. Also a channel waveguide laser was demonstrated by strip loading such a planar layer [11], although the weak guiding in the horizontal direction led to unreliable performance. In a more reliable manner, channel waveguides were produced in bulk double tungstates by femtosecond-laser writing of refractive index changes [12], having resulted in the demonstration of Raman gain [13] and channel waveguide lasing [14], albeit with a rather large mode size and considerable waveguide propagation losses.

In an attempt to produce higher integrated structures with better mode confinement, the active layer was co-doped with large amounts of optically inert Gd^{3+} and Lu^{3+} ions [15]. Both ions provide a higher electron density than the Y^{3+} ion they replace, thus increasing the refractive index contrast of the layer with respect to the undoped substrate by an order of magnitude to ~7.5×10^{-3} [15], leading to few-µm-thin waveguide layers. Besides, Gd^{3+} and Lu^{3+} alter the lattice parameters of KYW in opposite directions, hence lattice matching of layer and substrate can be achieved by the appropriate choice of Gd^{3+} and Lu^{3+} concentrations [15,16]. This approach makes refractive index contrast and lattice matching constant design parameters over a wide range of Yb^{3+} doping concentrations, because the Yb^{3+} ions can now replace Lu^{3+} ions of similar ion radius and electron density. Such highly co-doped layers have recently been shown to maintain the favorable spectroscopic properties of the Yb^{3+} ion and enabled planar waveguide lasing with excellent light confinement and overlap of pump and laser mode, resulting in a record-high slope efficiency of 82.3% and a laser threshold as low as 18 mW of absorbed pump power [17].

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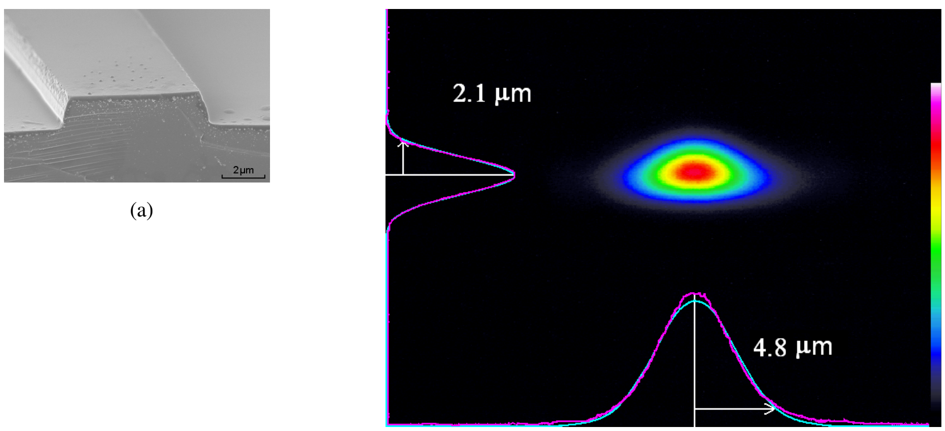
Furthermore, the much smaller layer thickness greatly facilitates microstructuring of double tungstates [15]. Exploiting this option, here we fabricate ridge channel waveguides in KYW:Gd^{3+}, Lu^{3+}, Yb^{3+} layers by use of standard photo-resist as a mask and Ar beam etching. The obtained waveguides with well-defined cross-sections of a few μm^2 and excellent mode confinement allow us to demonstrate a channel waveguide laser with a threshold of only 4.5 mW launched pump power, a slope efficiency of 62%, and an output power of 75 mW.

2. Sample fabrication

Active layers of $KY(WO_4)_2$:(43.3%)Gd^{3+}, (15%)Lu^{3+}, (1.7%)Yb^{3+} were grown by LPE onto undoped, (010)-orientated, laser-grade polished KYW substrates of 1 cm^2 size in a $K_2W_2O_7$ solvent at temperatures of 920-923°C, leading to crack-free layers with a thickness of ~5-10 µm. Subsequently, the layer surface was polished parallel to the layer-substrate interface to a uniform thickness of 2.4 µm with a measured rms surface roughness of 1.5 nm.

A photoresist (Fujifilm OiR 908/35) mask was deposited and patterned, and Ar beam milling [18] with an energy of 350 eV, resulting in an etch rate of 3 nm/min., was applied to the sample which was rotating at an angle of 20° in order to transfer the structures into the layer. In this manner, 1.4-µm-deep ridge waveguides with widths varying from 2 to 7 µm were created along the N_g optical axis. A scanning electron microscopy (SEM) picture of such a ridge waveguide is shown in Fig. 1(a). In order to reduce the propagation losses the structures were overgrown by an epitaxial layer of undoped KYW, resulting in buried channel waveguides.

The endfaces of the sample were polished perpendicular to the channels, i.e. parallel to the N_m optical axis. The final channel length was 7.5 mm. Dielectric mirrors were butt-coupled to the waveguide endfaces by use of fluorinated oil (Fluka) with a refractive index of 1.58, such that a monolithic cavity along the N_g optical axis was formed.



(a) (b)

Fig. 1. (a) SEM micrograph of a microstructured channel waveguide before overgrowth; (b) measured mode profile of the laser emission (both to scale).

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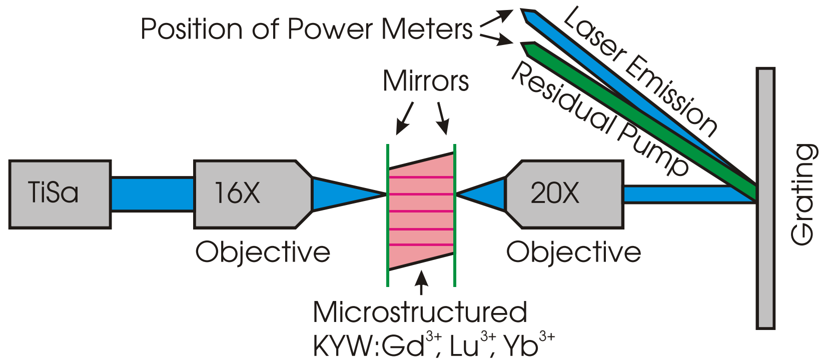

Fig. 2. Schematic of experimental setup

3. Laser experiments

Pump light from a continuous-wave Ti:Sapphire laser operating at a wavelength of 981 nm, at the Yb^{3+} absorption peak in KYW, was coupled with polarization parallel to the N_m optical axis into a 7-µm-wide channel waveguide by a × 16 microscope objective with a numerical aperture (N.A.) of 0.32. Residual transmitted pump light and laser light were coupled out at the other waveguide end by a × 20, N.A. = 0.4 microscope objective. A reflective grating was used as a dispersive element to separate the residual transmitted pump light from the laser emission. A schematic of the setup is shown in Fig. 2.

At the laser wavelength near 1028 nm the incoupling mirror had a reflectivity of 99.8%, while for the outcoupling mirror transparencies of 2%, 5%, 10%, and 23% were tested. Figure 3 shows the laser output power as a function of launched pump power. For the smallest outcoupling efficiency of 2%, laser oscillation commenced at a launched pump power as low as 4.5 mW. The laser threshold increased to a value of 5.5 mW for the largest outcoupling efficiency of 23%. Due to the low threshold which clamped the excitation of the upper laser level to a rather low excitation density, resulting in only a small fraction of ground-state bleaching, as well as the rather long waveguide length approx. 99% of the launched pump power was absorbed in the channel. Slope efficiencies of 11%, 23%, 53%, and 62% versus launched pump power and maximum extracted laser powers of 13 mW, 24 mW, 61 mW, and 76 mW were obtained for 2%, 5%, 10%, and 23% output coupling, respectively.

The measured near-field mode profile of Fig. 1(b) shows a triangular shape, caused by the ridge waveguide geometry. A Gaussian fit of the intensity profile in both horizontal and vertical directions results in a beam size of $4.8 \times 2.1\ \mu m^2$. According to simulations, the tested waveguide of 7 µm width supports 2 propagating modes; hence we assume that the laser output is transverse multi-mode. When analyzing the obtained slope efficiencies versus output coupling according to the theory for laser devices exhibiting reabsorption [17] an intracavity roundtrip loss of 11% is derived. This value includes the waveguide propagation losses and losses occurring due to butt-coupling of the mirror substrates to the endfacets. Therefore, the value of 11%, equaling 0.34 dB/cm, is the upper limit for the propagation loss at 1028 nm in the microstructured channel waveguide.

Figure 4 compares the Yb^{3+} single-doped KYW and KGW and Gd^{3+}, Lu^{3+}, Yb^{3+} co-doped KYW waveguide lasers reported in the literature to date with respect to their measured slope efficiency as a function of transmission of the outcoupling mirror. Apparently, the maximum achieved slope efficiency for each set of layer composition, waveguide geometry, and pump conditions depends greatly on pump and laser mode confinement and overlap, waveguide propagation losses, but also on the largest output coupling degree available to the experimentalist. From the graphs it is easy to predict that as long as the laser is operated well above threshold, further improvement in slope efficiency can be expected with higher degrees of output coupling from the laser cavity in almost all the investigated configurations. Furthermore, waveguides with losses below ~0.5 dB/cm are required to obtain high-performance waveguide lasers. Generally, the results summarized in Fig. 4 suggest that

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$KYW:Yb^{3+}$ waveguide lasers are highly promising devices for future applications. For comparison, channel waveguide lasers with slope efficiencies of 43% in a Yb:YAG multimode channel waveguide, created by use of bonding techniques [19], 27% in a Nd:GGG ion-implanted microchannel [20], 48% in Nd:GGG ion beam milled channel structures [21], as well as 60% [22] and 59% [23] in femtosecond-laser-written channel waveguides in Nd:YAG ceramics and bulk crystals, respectively, have been reported.

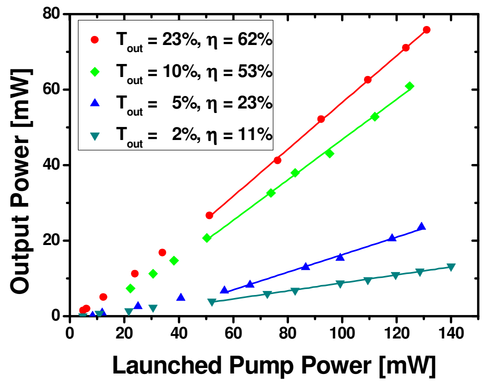

Fig. 3. Measured output power as a function of launched pump power (approx. 99% of the launched pump power was absorbed) for different transmission values T_{out} of the outcoupling mirror.

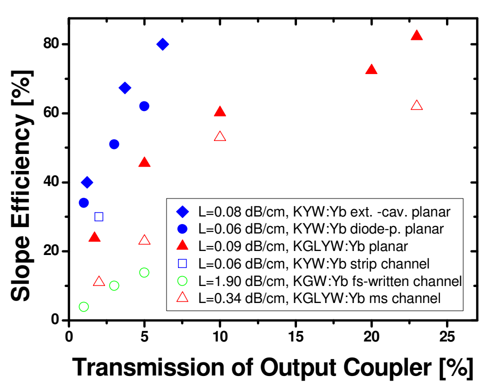

Fig. 4. Measured slope efficiencies (vs. absorbed pump power) as a function of transmission of the output coupler for different samples (blue = $KYW:Yb^{3+}$, green = $KGW:Yb^{3+}$; red = $KYW:Gd^{3+}$, Lu^{3+}, Yb^{3+}), waveguide geometries (solid symbols = planar waveguide; open symbols = channel waveguide) and pump/resonator configurations: solid diamonds = extended-cavity, Ti:Sapphire pumped [7]; solid circles = diode pumped [8]; solid triangles = Ti:Sapphire pumped [17]; open square = strip-loaded channel, Ti:Sapphire pumped (unreliable data) [11]; open circles = fs-laser-written channel, diode pumped [14]; open triangles = microstructured channel, Ti:Sapphire pumped [this work].

4. Conclusions

We have demonstrated, to the best of our knowledge, the first microstructured double tungstate channel waveguide laser. Excellent control over the lateral waveguide dimensions, resulting in tight confinement of pump and laser mode, in combination with the high absorption and emission cross-sections present in Yb^{3+}-doped double tungstates, make it an attractive high-gain laser device.

In the future, replacing the butt-coupled mirrors with an on-chip integrated cavity by etching Bragg reflectors or a distributed-feedback grating into the channel waveguide [1] or employing a ring-resonator configuration will make the device more robust and environmentally stable, such that real-world applications can seriously be envisaged.

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