Yb-doped $KY(WO_4)_2$ planar waveguide laser

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High-quality monoclinic $KY(WO_4)_2$ optical waveguides were grown by liquid-phase epitaxy, and laser operation of an Yb-doped $KY(WO_4)_2$ waveguide was demonstrated for the first time to our knowledge. Continuous-wave laser emission near 1 μm was achieved with both surface and buried planar waveguides. An output power of 290 mW was obtained in the fundamental mode and the slope efficiency was above 80%.

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Crystals of monoclinic $KY(WO_4)_2$ (KYW) doped with different rare-earth ions are recognized as very promising materials for solid-state lasers operating at room temperature, both in pulsed and continuous-wave (cw) mode.[1,2] Due to its high refractive indices, of the order of 2.0, KYW is highly suitable for the fabrication of integrated optical devices. Rare-earth ions incorporated into KYW exhibit very high absorption and emission cross sections. In particular, the Yb^{3+} ion in KYW has an absorption maximum near 981 nm with a cross section, for polarization parallel to the N_m principal optical axis, ~15 times larger than that of YAG:Yb. The short absorption length in highly doped KYW:Yb together with an extremely small laser quantum defect as low as 1.6% (Ref. 3) makes this material a favorable candidate for the thin-disk laser concept,[4] where the active medium is a thin crystal or deposited layer. Recently, cw laser operation normal to a thin layer of KYW doped with 20 at. % Yb (with respect to the Y site) on a KYW substrate was demonstrated and the maximum output power reached 40 mW at 1030 nm.[5]

In this Letter we report the epitaxial growth of high-quality optical waveguides and, for the first time to our knowledge, on waveguide laser operation based on a double tungstate crystal composite. The waveguide geometry provides potentially high pump-power densities and excellent overlap of pump and resonator modes. This approach requires fabrication of large-area, defect-free thin layers of KYW:Yb on appropriate substrates, having small lattice mismatch and close-to-perfect interfaces between the layer and the substrate to ensure low-loss propagation.

Liquid-phase epitaxy (LPE) is a well-known technique for producing high-quality oxide films for laser applications, in which a single-crystal layer can be grown from a molten solution on an oriented single-crystal substrate.[6] During LPE of rare-earth-ion-doped KYW layers employing a low-temperature chloride solvent,[7] 3D island nucleation generated insertion defects, which limited the maximum layer thickness to approximately 10 μm and led to nonoptimum interface quality.

The tungstate solvent $K_2W_2O_7$, which we employed successfully in the present work, can potentially offer larger thickness and good layer quality.[5,8] Undoped 1 mm thick KYW crystals grown by a modified Czochralski method with laser-grade polished (010) faces served as substrates. Building on previous work,[5] we employed the vertical dipping technique with partial immersion of the substrate, which allowed us to control the uniformity of the grown layer accurately during subsequent polishing of the layer surface parallel to the interface. Single-crystalline layers with thickness d of 10–100 μm and Yb^{3+} concentrations ranging from 1.2 to 2.4 at. % were grown at a growth rate of 18 μm/h. The Yb^{3+} concentration in the layer was nearly the same as in the initial growth solution, because the Yb distribution coefficient is close to unity.[5] Since KYW is isostructural to KYbW (100% of Y is substituted by Yb),[9] one can assume that the refractive indices of KYW:Yb layers increase linearly with increasing Yb concentration. Thus the refractive index change of a 1.8 at. % Yb^{3+}-doped layer with respect to the undoped substrate is expected to be 6×10^{-4}, which was confirmed experimentally by dark m-line spectroscopy.

Subsequently, the layer surface was polished to remove flux residuals and growth steps. Several active layers were overgrown by 20 μm thick undoped KYW overlays to obtain active buried waveguide structures with a symmetric refractive-index profile and potentially lower propagation losses due to a smaller refractive index step at the upper interface. The end faces of each layer were polished to laser-grade quality. The optical image of the end face of a KYW:1.8 at. % Yb^{3+} buried layer is shown in Fig. 1(a). Both interfaces are sharp and straight without any detectable defects.

The layers were tested as active and passive planar waveguides under diode-laser excitation at 980 nm. The pump light was coupled into the active layer along the crystallographic c direction by focusing

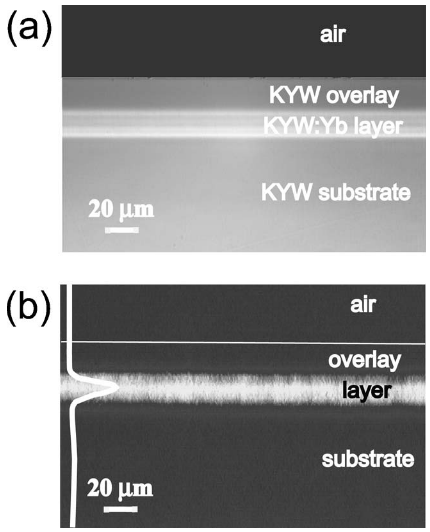

Fig. 1. As-grown, 22 μm thick buried $KY(WO_4)_2$:1.8 at. % Yb waveguide: (a) optical micrograph of the polished end face, (b) guided Yb^{3+} fluorescence and pump light in the planar waveguide and intensity distribution.

with a 10× microscope objective. The propagated light was imaged onto the sensor of a CCD camera with a 16× microscope objective. For the 22 μm thick waveguide shown in Fig. 1(b), the emitted Yb^{3+} fluorescence was guided together with the pump light in the buried KYW:Yb layer. The vertical intensity profile of the outcoupled light is close to a Gaussian distribution. At least 3 TE modes at $\lambda = 980$ nm are supported by the 22 μm thick planar buried waveguide in vertical direction.

One 2.4 at. % Yb-doped buried waveguide and one 1.2 at. % Yb-doped surface waveguide, both with polished end and surfaces, uncoated, 17 μm thick, and 6 mm long, were selected for laser experiments. First, an astigmatically compensated Z-shaped cavity was chosen. The planar KYW:Yb waveguides were positioned at the Brewster angle between two folding mirrors with a radius of curvature ROC=−10 cm, such that the resonator waist was located at both end faces of the waveguide and negligible diffraction losses occurred for the resonator mode at the waveguide interfaces. The waveguide orientation corresponded to propagation approximately along the N_g principal optical axis and polarization along the N_m axis. The sample was mounted on a copper plate without active cooling. The KYW:Yb layers were pumped in a single pass by a cw Ti:sapphire laser at 980.5 nm, delivering 2 W of output power. The measured absorbed power under nonlasing conditions in the buried KYW:Yb waveguide amounted to only 56% of incident pump power, partly due to the larger pump spot diameter of 30 μm.

Independent of the output coupler transmission T, which was chosen between $T = 1.7$ and $T = 13.5\%$, stable cw oscillation near $\lambda = 1025$ nm could be achieved for both waveguides (Fig. 2). Since reabsorption of oscillating laser light in this three-level laser system could be greatly reduced due to the high pump-light confinement in the active layer, the spectral laser emission corresponds to the maximum of the gain curve. The output was 95% linearly polarized.

The better laser performance was achieved with the 1.2 at. % Yb^{3+}-doped surface waveguide. With a 3.7% transmission output coupler the laser threshold was only 80 mW of absorbed pump power and the maximum output power amounted to 290 mW, resulting in a slope efficiency versus absorbed pump power of $\eta = 67.4\%$. A maximum slope efficiency of 80.4% was obtained for $T = 6.2\%$, corresponding to an overall efficiency versus absorbed pump power of 58.9% [Fig. 2(a)]. Although a buried waveguide should, in principle, exhibit lower propagation losses, the laser performance in the buried KYW:2.4 at. % Yb waveguide was slightly inferior [Fig. 2(b)], presumably as a result of the higher doping concentration, which led to higher reabsorption losses. When a chopper with a duty cycle of 10% was applied, the output power decreased 10 times. Hence it can be concluded that no thermal problems occur up to the maximum applied pump power despite the absence of cooling. Cavity round-trip losses between 1.8% and 2.1% were derived from the obtained slope efficiencies.[10] Attributing these losses completely to

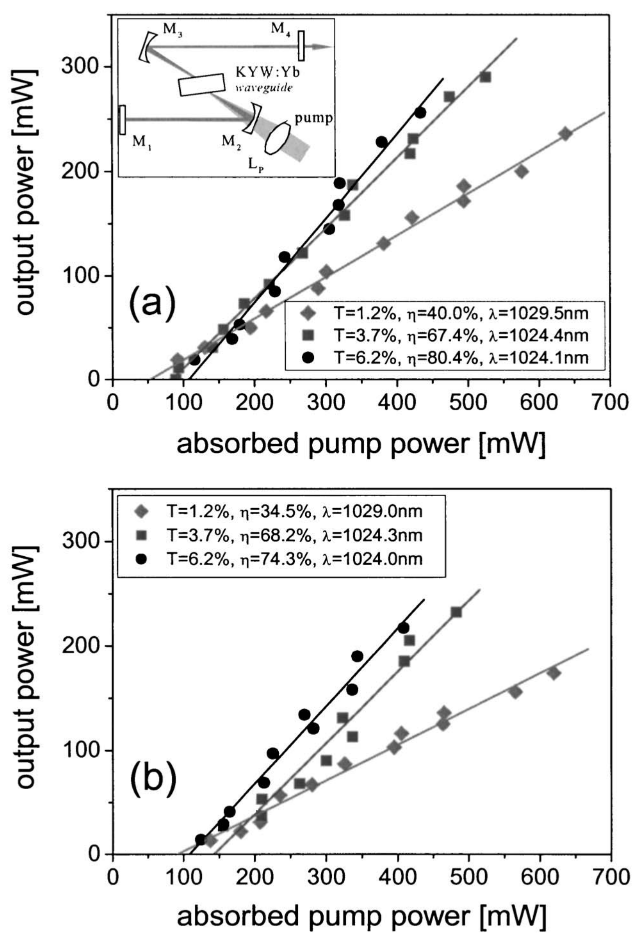

Fig. 2. Laser output power versus absorbed pump power of (a) 17 μm thick surface and (b) 17 μm thick buried KYW:Yb planar waveguides for different transmissions of the output coupler. Inset (a), setup of the Z-shaped laser cavity. L_p, focusing pump lens; M_1, M_2, M_3, high reflecting mirrors (M_2, M_3; ROC=−10 cm); M_4, plane output coupler.

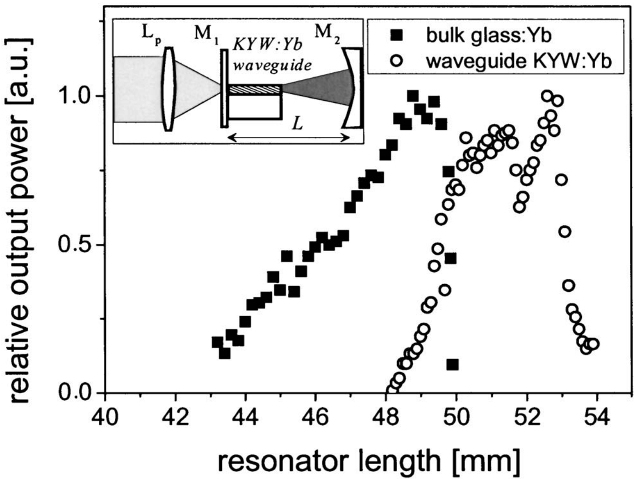

Fig. 3. Comparison of relative laser output power versus resonator length L for a 6 mm long glass:Yb bulk sample and a 6 mm long KYW:1.2 at. % Yb surface waveguide. Inset, setup of the linear laser cavity; L_p, focusing pump lens; M_1, plane dichroic mirror; M_2, output coupler (ROC $= -5$ cm).

waveguide propagation losses leads to an upper limit of 0.08 dB cm^{-1} for the waveguide losses.

Despite the multimode structure of the waveguide, the observed far-field intensity distribution indicates that the laser output is close to the diffraction limit and that the resonator mode is well matched within the physical dimensions of the planar crystal waveguide.[11]

In order to demonstrate the waveguiding effect of the layers, a simple linear laser cavity was used. In this second resonator setup (inset in Fig. 3), we compared the laser performance of bulk and waveguide samples versus the resonator length L. For the chosen, nearly hemispherical resonator with a ROC of the output coupler equal to -5 cm, the losses are expected to increase rapidly when the resonator length L exceeds this ROC and the resonator becomes unstable.

The active media were positioned as close as possible to the plane mirror, and an index-matching liquid was used to minimize the Fresnel loss. The samples were end pumped through the plane dichroic mirror by the same cw Ti:sapphire laser near 980 nm. The focused pump spot had a waist diameter of 22 μm. The cw output powers measured versus resonator length for a glass:Yb bulk sample and a 17 μm thick KYW:Yb surface waveguide are shown in Fig. 3. The bulk laser operated for resonator lengths between 43 and 49.9 mm. No lasing could be achieved for resonator lengths longer than 49.9 mm, as expected from the resonator stability criterion. When replacing the 6 mm long bulk by the waveguide sample, laser operation could be achieved for resonator lengths extending to 54 mm.

The shift between the two curves in Fig. 3 indicates that the waist of the resonator mode is moved from the plane mirror toward the opposite waveguide end face without substantially changing the resonator losses, i.e., the laser resonator remains stable even for $L > \text{ROC}$.[11] This is a clear indication of the guiding behavior of the active layer. The observed cavity extension is shorter than the waveguide length, because the positive waveguiding effect occurs in only one transverse direction.

In this simple resonator configuration, a maximum output power of 121 mW at 1025 nm for a resonator length of 52.6 mm was obtained at $T=1\%$ with the KYW:Yb waveguide. The strong decrease of the output powers for smaller resonator lengths is due to the inferior overlap between the pump and resonator modes as well as inferior coupling into the waveguide.

In conclusion, epitaxial planar waveguides of a monoclinic double tungstate were manufactured with high optical quality by the LPE method. KYW:Yb layers with a thickness between 10 and 100 μm were grown on undoped KYW substrates. Using 6 mm long, 1.2 and 2.4 at. % Yb-doped KYW layers with a thickness of 17 μm, planar surface and buried waveguide laser operation based on monoclinic double tungstate crystals was demonstrated for the first time to our knowledge. Cw lasing at 1025 nm with a maximum output power of 290 mW and slope efficiencies as high as 80.4% was obtained at room temperature. Laser emission close to diffraction-limited performance was achieved in the multimode planar waveguide structures.

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