# Refractive-index engineering and diode-side-pumped lasing of a rare-earth-ion-doped channel waveguide

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*Single-crystalline $KY_{1-x-y}Gd_xLu_y(WO_4)_2$ multi-layers are grown onto undoped $KY(WO_4)_2$ substrates by liquid-phase epitaxy. The lattice matching and refractive-index contrast between layer and substrate is engineered by choosing appropriate amounts of Y, Gd, and Lu. The refractive index at several wavelengths for different compositions and coefficients of the Sellmeier dispersion curves are determined. By microstructuring and subsequent overgrowth an actively ytterbium-doped tapered channel waveguide and a passive planar pump waveguide are created. Laser emission has been demonstrated by diode side pumping with a high-power, multi-mode diode bar. This result offers the potential for significantly increased output powers from channel waveguide laser devices.*

## Introduction

$KY(WO_4)_2$, $KGd(WO_4)_2$, and $KLu(WO_4)_2$ are excellent host materials for trivalent rare-earth-ion ($RE^{3+}$) doped solid-state lasers [1]. High-quality, single-crystalline thin layers of $KY(WO_4)_2:RE^{3+}$ have been grown onto undoped $KY(WO_4)_2$ crystals by liquid-phase epitaxy (LPE) using the solvent $K_2W_2O_7$ [2,3]. Doping of $Gd^{3+}$ and $Lu^{3+}$ to $KY(WO_4)_2$ increases the refractive index contrast and enables growing lattice-matched crack-free layers, as these two ions change the lattice constants of $KY(WO_4)_2$ in opposite directions[4]. This approach facilitates the fabrication of microstructured channel waveguides [5].

In this paper we report a study on engineering lattice matching and simultaneously optimizing the refractive index and active dopant concentration in $KY_{1-x-y-z}Gd_xLu_yYb_z(WO_4)_2$ epitaxial layers grown onto $KY(WO_4)_2$ substrates. Exploiting the large absorption cross-section of $Yb^{3+}$ in potassium double tungstates, the large $Yb^{3+}$ concentrations attainable in the co-doped layers, as well as the passive guiding properties of a $KY_{1-x-y}Gd_xLu_y(WO_4)_2$ layer, we demonstrate lasing in a cladding-side-pumped tapered channel waveguide.

## Growth of Co-doped Potassium Double Tungstate Layers

LPE was performed in a resistance-heated oven with a single-zone vertical temperature profile at ambient atmosphere. Thin layers of $KY_{1-x-y-z}Gd_xLu_yYb_z(WO_4)_2$ were grown onto 1-mm-thick $KY(WO_4)_2$ substrates with laser-grade-polished (010) faces of 1.0 × 1.0 $cm^2$ size in a $K_2W_2O_7$ solvent. After the growth, the layers were surface polished parallel to the substrate-layer interface with 1.5-nm (rms) roughness to the thickness desired for the specific investigation or application.

## Lattice matching and Refractive-index engineering

We performed studies on the compositions $KY_{1-x-y-0.025}Gd_xLu_yYb_{0.025}(WO_4)_2$ with a systematic variation of the fraction $1-x-y-0.025$ of $Y^{3+}$ ions and $KGd_xLu_yYb_{1-x-y}(WO_4)_2$ with a systematic variation of the fraction $1-x-y$ of $Yb^{3+}$ ions. In the former variation, the gradual replacement of $Y^{3+}$ ions by $Gd^{3+}$ and $Lu^{3+}$ ions, at a constant $Yb^{3+}$ concentration of typically a few at.% that is suitable for operating planar and channel waveguide lasers, allows us to optimize the refractive index contrast, hence the optical mode size, for the intended laser wavelength. In this manner excellent confinement of pump and laser light and efficient fundamental-mode lasing is obtained. In the latter variation, while maintaining lattice matching and the desired refractive index contrast, the concentration of the active $RE^{3+}$ ion can be significantly increased to allow for ultra-high optical gain in a $RE^{3+}$-doped waveguide amplifier [7].

## Refractive-index measurements

Refractive index measurements were carried out with a Metricon 2010M film prism coupler by dark-*m*-line spectroscopy at 633 nm, 830 nm, 1300 nm, and 1550 nm. The refractive indices of the co-doped layer gradually increased when replacing $Y^{3+}$ by a lattice-matching combination of $Gd^{3+}$ and $Lu^{3+}$, while in all compositions the $Yb^{3+}$ concentration remained fixed at 2.5at.%. The observed increase in refractive index is due mainly to the partial replacement of $Y^{3+}$ by $Lu^{3+}$. The motivation for investigating the growth of $KY_{1-x-y-z}Gd_xLu_yYb_z(WO_4)_2$ layers is the quest for a large refractive index contrast between layer and substrate and/or large active dopant concentration. The larger the refractive index contrast between layer and substrate, the smaller is the layer thickness that leads to guiding of only the fundamental optical mode in this layer and the tighter is the confinement of this mode.

## Microstructured channel waveguides

To confine guided light also in the horizontal direction, a channel waveguide geometry is required. Therefore, grown layers were microstructured by $Ar^+$ beam etching [5], resulting in channel ridge waveguides of typically 2−6 μm height and 4−10 μm width. Growth of a pure $KY(WO_4)_2$ cladding layer on top of the microstructured channel waveguide further improves the mode overlap with the channel waveguide region [5].

## Cladding-side-pumped Channel Waveguide Laser

We fabricated a multi-layer sample comprising a lattice-matched, highly activated $KGd_xLu_yYb_{1-x-y}(WO_4)_2$ channel waveguide on a $KY(WO_4)_2$ substrate, which was surrounded by a lattice-matched, passive $KY_{1-x-y}Gd_xLu_y(WO_4)_2$ planar waveguide.

As an application we demonstrated a cladding-side-pumped channel waveguide laser. Pump light from a high-power multi-mode diode bar was side-coupled to the passive planar waveguide and guided to the active channel waveguide. The channel waveguide had a 50-µm-wide multi-mode region that allowed us to increase the pump absorption, connected by a waveguide taper to a fundamental-mode region that acted as a lasing-mode selector in the horizontal direction. To further enhance pump absorption, we chose a high $Yb^{3+}$ concentration of 47.5at.%. The channel waveguide was oriented along the $N_m$ optical axis to ensure efficient absorption of $N_m$-polarized pump light.

By use of a fluorinated oil, mirrors with a reflection of 99.8% and 90% at 1038 nm were butt-coupled to the polished end-facets of the wide and narrow channel waveguide part, respectively. The laser output was collected from the narrow waveguide end with an objective lens.

A maximum quasi-continuous-wave laser power of 8 mW was measured. The laser wavelength was slightly shifted from the typical 1022–1029 nm [3,5-6] to a wavelength of 1038 nm, at which losses owing to reabsorption were diminished, thereby indicating a low population inversion that was caused by non-optimal excitation of the $Yb^{3+}$ ions in the active waveguide. Besides the fundamental laser mode, two weaker horizontal side lobes were observed, which originated from the non-adiabatic taper.

## Conclusions

Our investigations on the range of compositions $KY_{1-x-y-0.025}Gd_xLu_yYb_{0.025}(WO_4)_2$ and $KGd_xLu_yYb_{1-x-y}(WO_4)_2$ grown onto $KY(WO_4)_2$ substrates has shown that, with an appropriate choice of co-dopants, compositions up to the complete replacement of the $Y^{3+}$ ions can be grown crack-free with high optical quality. A maximum lattice mismatch in the *a*- and *c*-axis of 0.07378% and a maximum refractive-index contrast between layer and substrate of $2 \times 10^{-2}$, resulting in tight optical mode confinement in planar and channel waveguides, are found. Optically active doping with $Yb^{3+}$ ions up to ~50at.% becomes possible. As an application a two-fold refractive-index-engineered sample combining a highly activated channel and passive planar waveguide was fabricated and a cladding-side-pumped channel waveguide laser was demonstrated.

## References

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