Highly efficient solid-state waveguide lasers

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Abstract: This paper reviews our recent results on highly efficient rare-earth-ion-doped planar and channel waveguide lasers in crystalline potassium double tungstates and amorphous aluminum oxide on silicon chips.

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1. Introduction

The quest for high efficiency when operating solid-state lasers is driven by various requirements. Typical reasons are a high output power required by the application for a maximum available pump power, cost, size, and weight reduction of the pump module, electrical energy efficiency, the suppression of detrimental heat generation, etc. Waveguide lasers, in particular, offer the potential for high efficiencies, because they provide excellent mode overlap between pump and oscillating laser beam as well as high pump intensity and, consequently, high population inversion, allowing for high outcoupling degrees. Also miniaturization and system or on-chip integration of laser sources becomes an increasing important aspect for which waveguide lasers provide a natural solution.

Here we review our recent on rare-earth-ion-doped planar and channel waveguide lasers in crystalline potassium double tungstates and amorphous aluminum oxide on silicon, capable of producing slope efficiencies reaching up to 82.3%.

2. Lasers in Crystalline Potassium Double Tungstates

The monoclinic potassium double tungstates $KY(WO_4)_2$, $KGd(WO_4)_2$, and $KLu(WO_4)_2$ are excellent candidates for solid-state lasers [1] because of their high refractive index of ~2.0-2.1 [2], the large transition cross-sections of rare-earth ions doped into these hosts [3], a long inter-ionic distance of ~0.5 nm that allows for large doping concentrations without lifetime quenching [4], and a reasonably large thermal conductivity of ~3.3 W m^{-1} K^{-1} [5].

Rare-earth-ion-doped $KY(WO_4)_2$ layers are grown by liquid-phase epitaxy onto undoped, (010)-oriented, laser-grade-polished, 1-cm^2-sized $KY(WO_4)_2$ substrates in a $K_2W_2O_7$ solvent at temperatures of 920–923°C. The first planar waveguide laser demonstrated in a double tungstate, $KY(WO_4)_2:Yb^{3+}$, produced >80% slope efficiency [6], demonstrating the high potential of this family of materials. Also a $KY(WO_4)_2:Tm^{3+}$ planar waveguide laser was demonstrated [7]. Co-doping the layers with appropriate percentages of optically inert Gd^{3+} and Lu^{3+} ions enables the growth of lattice-matched $KY_{1-x-y}Gd_xLu_y(WO_4)_2$ layers with enhanced refractive-index contrast up to $\sim 1.5 \times 10^{-2}$ between layer and substrate, allowing for thinner active layers [8]. Partial replacement of Lu^{3+} by Yb^{3+} or Tm^{3+} ions of similar ionic radius results in highly doped layers with active doping levels that can be adjusted between 0% and ~50%. The layer surface is polished down to 2−6 µm thickness. With such thin co-doped layers a $KY_{1-x-y}Gd_xLu_y(WO_4)_2:Yb^{3+}$ planar waveguide laser with 82.3% slope efficiency has been demonstrated [9].

Microstructuring by Ar-beam etching [10] leads to 1.4-µm-deep, 6-µm-wide ridge waveguides along the N_g optical axis, which ensure tight pump and signal light confinement and enhanced modal overlap with the active waveguide region. The structured samples are overgrown by a layer of undoped $KY(WO_4)_2$. We have demonstrated channel waveguide lasers in $KGd_{1-x}Lu_x(WO_4)_2:Yb^{3+}$ with 418 mW of continuous-wave output power and a slope efficiency of 71% at 1023 nm [11]. When pumping at 973 nm, lasing at the zero-phonon line at 980 nm with a record-low quantum defect of 0.7% was achieved [11]. The highest output power at this wavelength was 650 mW and a slope efficiency of 76% was obtained. Using focused-ion-beam milling, we produced deep Bragg gratings in a channel waveguide and demonstrated the first double tungstate laser with an integrated cavity [12]. In $KY_{1-x-y}Gd_xLu_y(WO_4)_2$ with 1.5at.% Tm^{3+} doping, a channel waveguide laser with 31.5% slope efficiency and 149 mW of output power at 1.9 µm has been obtained [13]. Very recently, by increasing the doping level, we have been able to increase the performance to 69.7% slope efficiency and ~300 mW output power [14].

Thanks to the high emission cross-sections of rare-earth ions doped into potassium double tungstates and the high dopant concentrations and inversion densities achieved in our waveguide structures, we have demonstrated a gain of ~1000 dB/cm at the 981-nm zero-phonon line in $KGd_{1-x}Lu_x(WO_4)_2:Yb^{3+}$, comparable to the best values reported for semiconductor waveguide amplifiers [15].

3. Lasers in Amorphous Aluminum Oxide on a Silicon Chip

Owing to inhomogeneous broadening due to varying local environments, amorphous materials provide gain cross-sections that are significantly lower than in crystalline hosts. On the other hand, their attraction arises from the fact that they can be deposited on different material platforms, among them standard silicon wafers. Although the small cross-sections increase the threshold pump power, this is often compensated by the large refractive-index contrast between waveguide and cladding materials, thus decreasing the lateral waveguide dimensions and providing higher pump intensities for the same pump power.

Amorphous aluminum oxide has attracted interest as a host material for integrated erbium amplifiers [16]. We have developed a reliable deposition method, reactive co-sputtering, to produce ~1-µm-thin, rare-earth-ion-doped films [17] and microstructuring by chlorine-based reactive ion etching to produce channel waveguides with propagation losses of ~0.2 dB/cm [18]. These channel waveguides can be directly integrated with silicon photonic wires [19].

The gain achieved in Al_2O_3:Er^{3+} is similar to other amorphous host materials due to the broadened emission lines and accordingly small cross-sections [20]. On the other hand, lasers in amorphous hosts can reach similar slope efficiencies as in crystalline hosts. The first laser demonstrated in our host was an Al_2O_3:Er^{3+} ring laser at 1.5 µm [21]. By laser interference lithography we produced Bragg gratings in Al_2O_3 channel waveguides and λ/4-phase-shifted cavities with quality factors exceeding 10^6 [22]. These grating structures have been employed to form distributed-Bragg-reflector (DBR) and distributed-feedback (DFB) lasers. An Al_2O_3:Er^{3+} DFB laser with 3 mW of output power and 41.3% slope efficiency was demonstrated [23]. The high-Q passive resonator, in combination with the enhancement of the Q-factor by stimulated emission resulted in a laser Q-factor [24] of 1.14×10^{11} and a laser line width of 1.7 kHz. Using Yb with its higher absorption cross-section as the laser ion, we demonstrated DBR [25] and DFB lasers with output powers up to 55 mW and slope efficiencies up to 67% versus launched pump power. With a dual-phase-shifted DFB structure, we have produced a dual-wavelength laser and generated a stable electronic beat signal at 15 GHz frequency [26].

4. References

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