Efficient continuous-wave and Q-switched operation of a diode-pumped Yb:KLu(WO$_4$)$_2$ laser with self-Raman conversion

Junhai Liu, Uwe Griebner, and Valentin Petrov
Max-Born-Institute for Nonlinear Optics and Ultrafast Spectroscopy, 2A Max-Born-Strasse, 12489 Berlin, Germany

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Efficient cw and passively Q-switched operation with self-stimulated Raman scattering conversion was demonstrated in a compact diode-pumped Yb:KLu(WO$_4$)$_2$ laser. A cw output power of 3.28 W was obtained with an optical efficiency of 48.2% and a slope efficiency of 78.2% with respect to the incident pump power. Stable Q-switched operation was achieved with a Cr$^{4+}$:YAG saturable absorber, generating 32.4 µJ fundamental pulses with a duration of 1.41 ns at 1030.6 nm and 14.4 µJ Raman pulses with a duration of 0.71 ns at 1137.6 nm. At an incident pump power of 7.0 W, the average output power reached 0.9 and 0.4 W for fundamental and Raman radiation, with slope efficiencies of 32.1% and 14.1%, respectively. © 2005 Optical Society of America

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The ytterbium-doped potassium double tungstates, Yb:KY(WO$_4$)$_2$ (Yb:KYW) and Yb:KGd(WO$_4$)$_2$ (Yb:KGdW), have demonstrated their great potential for building practical diode-pumped cw and ultrashort pulsed laser sources because of their unique advantages including large absorption and emission cross sections, broad absorption and emission bands, and negligible concentration quenching. A new member of this family of potassium tungstates, Yb:KLu(WO$_4$)$_2$ (Yb:KLuW), was developed recently in an effort to improve the quality of epitaxially grown Yb-doped thin-film active elements. Yb:KLuW, which belongs to the same monoclinic space group C2/c ($C_{2h}^{2}$), is similar to Yb:KYW and Yb:KGdW in most physical and spectroscopic properties; the main absorption band is centered at 981 nm, with a maximum cross section of $1.18 \times 10^{-19}$ cm$^2$ for light polarized parallel to the principal axis $N_m$, the emission cross section at this wavelength is $1.47 \times 10^{-19}$ cm$^2$, and the fluorescence lifetime amounts to 375 µs. The optical quality of Yb:KLuW, however, is expected to be superior to some extent to that of other Yb-doped potassium tungstates because of the closer ionic radii of Lu and Yb, especially in the case of higher Yb-doping levels. With an Yb:KLuW crystal, cw laser operation was achieved for Ti:sapphire laser pumping with a four-mirror folded cavity, generating 1 W of output power with a slope efficiency of 57%; with diode pumping, 170 mW of output power was obtained, with a slope efficiency of 42%, from the same cavity configuration.

In addition to being promising host media for the Yb ion, the potassium double tungstates also possess large nonlinear optical susceptibility $\chi^{(3)}$, making them efficient frequency converters through stimulated Raman scattering (SRS). Recently, self-Raman frequency conversion was demonstrated in diode-pumped Q-switched lasers based on both Yb:KYW and Yb:KGdW crystals.

In this Letter we report on highly efficient laser operation of a bulk Yb:KLuW crystal that is end-pumped by a fiber-coupled diode laser both in the passively Q-switched mode with simultaneous SRS frequency conversion and in the cw regime.

The Yb:KLuW crystal used in this experiment was grown by the flux method. The Yb concentration in the crystal was measured by x-ray fluorescence analysis to be 5.24 at. % ($N=3.47 \times 10^{20}$ cm$^{-3}$ in good agreement with $N=3.56 \times 10^{20}$ cm$^{-3}$ obtained by optical absorption measurements). The 3 mm thick crystal was cut along the $N_m$ (||b axis) principal axis. The aperture of the uncoated sample was 4 mm × 4 mm. The compact plano-concave cavity used is depicted schematically in Fig. 1. M1 was a plane mirror highly reflecting from 1015 to 1230 nm and highly transmitting for 880–990 nm, with an antireflection coating on its rear surface. Several mirrors with radii of curvature of 25 mm and different transmissions for the fundamental (T) and the Raman radiation wavelengths were used as output couplers (M2). Dichroic beam splitter M3 (highly reflecting for…

Fig. 1. Schematic diagram of the laser setup: LC, laser crystal; SA, saturable absorber.
1130–1380 nm and highly transmitting for 800–1090 nm) was used to separate the Raman radiation from the fundamental. For passive Q-switched operation, a 1 mm thick Cr\(^{4+}\):YAG crystal was inserted as a saturable absorber. It was antireflection coated for the fundamental wavelength on both faces and had an initial transmission of 80%. The pump source used was a fiber-coupled diode laser module (116 μm core diameter; 0.2 NA; Boston Laser, Inc.) providing a maximum output of 7.2 W at a center wavelength near 978 nm (unpolarized emission with a multipeak bandwidth of ~8 nm). The pump beam was focused by \(f=6.2\) mm micro-optics (Schäfter & Kirchhoff) through the 3 mm thick quartz substrate of M1 to a spot radius of 40 mm. The laser beam was linearly polarized with a multipeak bandwidth of 8 nm. The pump absorption variation is caused by the wave-length shift of the diode laser; the center wavelength (0.55–0.57, compared to 0.6–0.72 for pump powers above 4.5 W, measured without lasing). This pump absorption variation is caused by the wavelength shift of the diode laser; the center wavelength changed from 973 to 978 nm with increasing output power.

By introducing the Cr\(^{4+}\):YAG saturable absorber into the cavity, we achieved passively Q-switched operation. To stabilize the laser, we shortened the physical cavity length from 25 to 22 mm. To prevent the laser from multipulse operation, a sufficiently large output coupling is required. The most appropriate output coupler available for this experiment had a transmission of 10% at 1030 nm and of ~20% near the Raman line at 1140 nm.

The passively Q-switched laser reached threshold at an incident pump power of 4.28 W, corresponding to an absorbed pump power of 2.65 W. Slightly above threshold, stimulated Raman scattering occurred in the Yb:KLuW crystal. The output spectrum consisted of the fundamental line at 1030.6 nm and the first-order Stokes line at 1137.6 nm, which obviously corresponds to the Raman-active internal vibration mode \(v_1\) of the \([WO_4]^{2-}\) ion group.

Figure 3 shows the output characteristics of the passively Q-switched Yb:KLuW laser with simultaneous SRS self-conversion. At the highest available pump power (7 W incident upon the Yb:KLuW crystal), the total average output power reached 1.3 W. The Raman part of the radiation was 0.4 W. The optical conversion efficiencies with respect to the incident pump power were 18.6%, 5.7%, and 12.9% for the total, the Raman, and the fundamental radiation, respectively. The corresponding slope efficiencies were 46.3%, 14.1%, and 32.1%. One can see from Fig. 3 that, as in the case of cw operation, no saturation...
occurred up to the highest pump power, suggesting that the laser can be further power scaled. The linear dependence of the output characteristics in Fig. 3 is due to the high $Q$-switching threshold and is consistent with cw operation at higher pump powers.

For a passively $Q$-switched laser, the pulse-repetition frequency (PRF) depends on the pump power. The PRF was found to increase almost linearly from 6 kHz at threshold to 28 kHz at the highest pump level. The maximum pulse energies of the fundamental and the Raman radiation were estimated to be 32.4 and 14.4 $\mu$J, respectively, at a PRF of 28 kHz.

The temporal pulse profiles (see Fig. 4) were studied with a fast (80 ps rise time) photodiode and a 2 GHz oscilloscope. Pulse durations (FWHM) of 1.41 ns for the fundamental and 0.71 ns for the Raman radiation were measured. The pulse-to-pulse fluctuations for both the fundamental and the Raman radiation were estimated to be less than 5%. A peak power of 23 kW for the fundamental pulse was calculated from the values of the pulse energy and the duration. For accurate estimation of the peak power of the Raman pulse we took into account its exact temporal shape and arrived at 15.2 kW (Fig. 4).

In conclusion, we have demonstrated a compact diode-pumped Yb:KLuW laser that has operated efficiently in both cw and passively $Q$-switched modes with simultaneous SRS self-conversion. A cw output power of 3.28 W was obtained with an optical efficiency of 48.2% and a slope efficiency as high as 78.2% with respect to the incident pump power. Passively $Q$-switched operation generated 1030.6 nm fundamental pulses of 1.41 ns duration, 32.4 $\mu$J energy, and 23 kW peak power, and 1137.6 nm Raman pulses of 0.71 ns duration, 14.4 $\mu$J energy, and 15.2 kW peak power. The average output power reached 0.9 W for fundamental and 0.4 W for Raman radiation with optical efficiencies of 12.9% and 5.7% and slope efficiencies of 32.1% and 14.1%, respectively.

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