Efficient continuous-wave and Q-switched operation of a diode-pumped Yb:KLu$(WO_4)_2$ laser with self-Raman conversion

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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.[1–3] 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.[4,5] Yb:KLuW, which belongs to the same monoclinic space group $C2/c$ (C_{2h}^6), 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 1.18×10^{-19} cm^2 for light polarized parallel to the principal axis N_m, the emission cross section at this wavelength is 1.47×10^{-19} cm^2, and the fluorescence lifetime amounts to 375 μs.[4] 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.[4]

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).[6] Recently, self-Raman frequency conversion was demonstrated in diode-pumped Q-switched lasers based on both Yb:KYW and Yb:KGdW crystals.[7–9]

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. % ($N=3.47\times10^{20}$ cm^{-3}, in good agreement with $N=3.56\times10^{20}$ cm^{-3} obtained by optical absorption measurements). The 3 mm thick crystal was cut along the N_p ($\parallel b$ 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

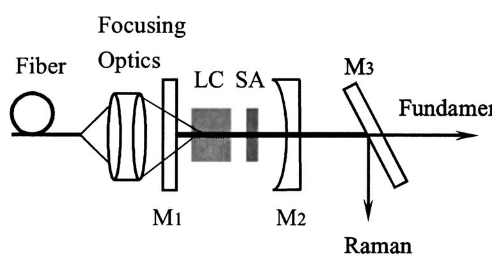

Fig. 1. Schematic diagram of the laser setup: LC, laser crystal; SA, saturable absorber.

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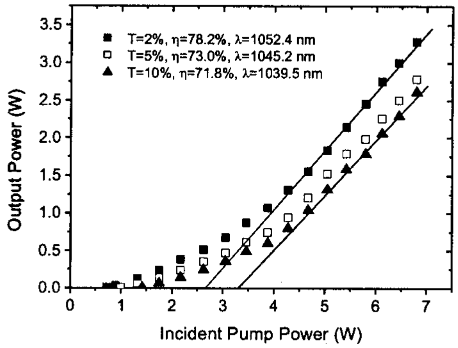

Fig. 2. Continuous-wave output power versus incident pump power for three output couplers.

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 μm (Gaussian waist) at the position of the Yb:KLuW crystal. The Yb:KLuW sample, wrapped in indium foil and held in a water-cooled copper block, was placed as close as possible (≈0.2 mm) to end mirror M1 for optimum mode matching, which is crucial in quasi-three-level lasers to minimize reabsorption losses. The Cr^{4+}:YAG crystal was positioned close to the laser medium.

First we studied the cw performance of the laser with no saturable absorber in the cavity. We optimized the laser by adjusting the cavity length, operating near the hemispheric configuration. The lasing wavelength was dependent on the output coupling, decreasing from 1052.4 nm for $T=2\%$ to 1039.5 nm for $T=10\%$. This behavior is typical of quasi-three-level lasers that have wavelength-dependent absorption losses. The laser beam was linearly polarized parallel to the N_m axis, independently of the output coupling.

Figure 2 shows the input–output characteristics for $T=2\%,5\%,10\%$; output couplings of 0.5–2% led to similar results. The present laser configuration precluded any measurement of the absorbed pump power under lasing conditions because of the strongly divergent nature of the pump beam. It is worthwhile to note that the absorbed pump power without lasing is significantly different from that measured under lasing conditions, owing to the recycling effect of the ground-state population.[5] Therefore the output power is plotted in Fig. 2 against the pump power incident upon the crystal. However, the absorbed power at threshold can be determined because the recycling effect disappears at low intracavity laser intensity. The absorbed pump power for reaching the laser threshold was 0.39, 0.57, and 0.81 W for $T=2\%,5\%,10\%$, respectively. We obtained the most efficient operation by applying the $T=2\%$ output coupler. At an incident pump power of 6.8 W the output power reached 3.28 W, leading to an optical efficiency of 48.2%; the slope efficiency at pump powers exceeding 4.0 W was 78.2%. We estimated the small-signal absorption for the pump light to be 0.85–0.90 by moving the crystal away from the pump focus. The recycling effect of the ground-state population will enhance the bleached absorption to a similar level.[5] Therefore the slope efficiency obtained here with respect to the absorbed pump power is close to the quantum-defect limit of 93%. For $T=5\%,10\%$, the highest output power obtained was 2.78 and 2.61 W, corresponding to slope efficiencies of 73.0% and 71.8%, respectively. The improved slope efficiencies compared to that reported in Ref. 4 could be attributed to a better overlap of the pump and resonator modes in the compact laser configuration. It is obvious from Fig. 2 that no saturation occurred at the highest pump power, which indicates a potential for further power scaling. The deviation of the input–output characteristics from the linear law in Fig. 2, i.e., the lower efficiency in the pump power range below 4.0 W, is attributed mainly to the lower absorption (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 ν_1 of the $[WO_4]^{2-}$ ion group.[10]

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

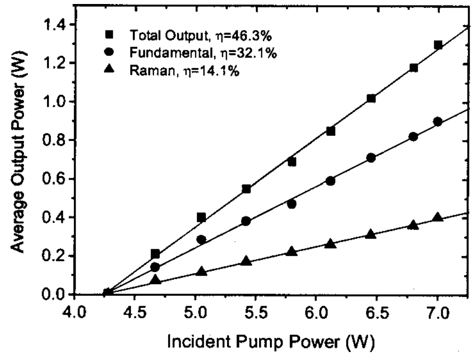

Fig. 3. Average output power versus incident pump power for total, fundamental, and Raman radiation.

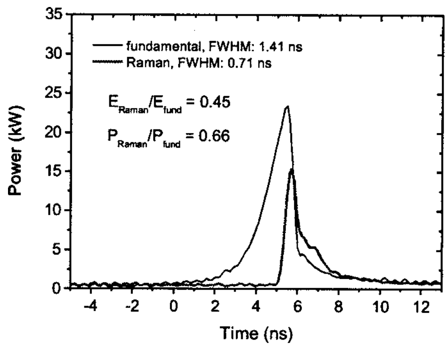

Fig. 4. Pulse profiles recorded for fundamental and Raman radiation at a PRF of 28 kHz. E, energy; P, peak power.

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 μJ, 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 comparison with that found previously for Yb:KYW and Yb:KGdW, the laser performance was significantly improved in terms of pulse energy, duration, and peak power.[7–9] Energy and peak power are higher by more than 1 order of magnitude than those reported in Refs. 7 and 8, and, although comparable pulse durations were specified in Ref. 9, the improvement in terms of energy and peak power is still at least 3–4 and 2 times, respectively. The efficiencies achieved in the present research are also higher. We believe that the Q-switched laser performance of Yb:KLuW can be further improved by use of an antireflection-coated crystal with optimized thickness and by proper choice of output coupling for both the fundamental and the Raman radiation.

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 μJ energy, and 23 kW peak power, and 1137.6 nm Raman pulses of 0.71 ns duration, 14.4 μJ 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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