Passive $Q$ switching and self-frequency Raman conversion in a diode-pumped Yb:KGd(WO$_4$)$_2$ laser

A. A. Lagatsky, A. Abdolvand, and N. V. Kuleshov

International Laser Center, Belarus State Polytechnical Academy, F. Scoryna Avenue 65, Minsk 220027, Belarus

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We report on the laser performance of a diode-pumped Yb:KGd(WO$_4$)$_2$ laser that is passively $Q$ switched with a Cr$^{4+}$:YAG saturable absorber. Raman conversion of fundamental laser emission in the laser crystal was demonstrated. $Q$-switched 3.4-$\mu$m pulses with a pulse width of 85 ns were obtained at the 1033-nm fundamental wavelength and 0.4-$\mu$m pulses with a pulse width of 20 ns were produced in a first Stokes at 1139 nm. © 2000 Optical Society of America

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Compact and efficient laser systems with short pulses in a stable TEM$_{00}$ mode operation are interesting for a variety of applications, such as medicine, lidar systems, micromachining, remote gas sensing, and nonlinear frequency conversion. Passive $Q$ switching of diode-pumped solid-state lasers is a simple and cost-effective way of obtaining nanosecond and subnanosecond pulses with high peak powers. Most of the work on passively $Q$-switched microchip lasers has concentrated on diode-pumped Nd lasers with a Cr$^{3+}$:YAG saturable absorber. The most powerful of these lasers produce 250-$\mu$m pulses of energy at 1.064-$\mu$m with a pulse duration of 380 ps and peak power in excess of 560 kW. More recently, a series of studies of passively $Q$-switched microchip lasers with semiconductor saturable-absorber mirrors (SESAM’s) were conducted. The SESAM replaces one of the mirrors of the microchip laser and allows for a significantly shorter cavity length (~200-$\mu$m) and therefore shorter pulses. A diode-pumped Nd:YVO$_4$ microchip laser with a SESAM that produced $Q$-switched pulses as short as 37 ps was demonstrated. In addition, microchip lasers at 1342 and at 1530 nm that were passively $Q$ switched by SESAM devices yielded pulse widths of 230 ps and 1.7 ns, respectively. In Ref. 5 what is to our knowledge the first Yb:YAG microchip laser that was passively $Q$-switched with a SESAM was presented. Pulses of 1.1-$\mu$m energy with a pulse width of 530 ps and a peak power of 2.1 kW at a repetition rate of 12 kHz were obtained. Yb$^{3+}$ solid-state lasers operating at 1-$\mu$m offer significant advantages, such as a smaller quantum defect for lower heat dissipation and greater slope efficiency and a simpler energy-level structure for reduced parasitic effects, relative to 1.06-$\mu$m Nd$^{3+}$ lasers. In addition, the long upper-state lifetime (~1 ms, compared with 240 $\mu$s in Nd:YAG) reduces the pump requirements in low-repetition-rate $Q$-switched systems.

In this Letter we report, for the first time to our knowledge, a diode-pumped Yb$^{3+}$:KGd(WO$_4$)$_2$ (Yb:KGW) laser, passively $Q$ switched with a Cr$^{4+}$:YAG saturable absorber, that emits at two wavelengths simultaneously, owing to Raman conversion of fundamental laser emission in the laser crystal.

Table 1. Material Properties of Yb$^{3+}$:KGW

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Yb$^{3+}$:KGW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Doping level</td>
<td>5%</td>
</tr>
<tr>
<td>Pump wavelength</td>
<td>981 nm</td>
</tr>
<tr>
<td>Laser wavelength</td>
<td>1026 nm</td>
</tr>
<tr>
<td>Absorption bandwidth</td>
<td>3.7 nm</td>
</tr>
<tr>
<td>Gain bandwidth</td>
<td>20 nm</td>
</tr>
<tr>
<td>Upper-state lifetime</td>
<td>0.6 ms</td>
</tr>
<tr>
<td>Gain cross section ($E | a$)</td>
<td>$2.7 \times 10^{-20}$ cm$^2$</td>
</tr>
<tr>
<td>Absorption cross section ($E | a$)</td>
<td>$1.2 \times 10^{-19}$ cm$^2$</td>
</tr>
<tr>
<td>Saturation intensity</td>
<td>2.8 kW/cm$^2$</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>0.033 W/cm K</td>
</tr>
<tr>
<td>$dn/dT$</td>
<td>$0.4 \times 10^{-6}$ K$^{-1}$</td>
</tr>
<tr>
<td>Refractive index</td>
<td>1.96–2.04</td>
</tr>
</tbody>
</table>

In comparison with SESAM, doped bulk crystals as saturable absorbers have some advantages, such as a high damage threshold, low cost, and simplicity. A Yb:KGW crystal used as a gain medium exhibits high slope efficiency with cw laser pumping (up to 78%) and with diode pumping at 980 nm (Ref. 8, up to 53%), owing to the small quantum defect (~5%), the high stimulated-emission cross section (up to $2.8 \times 10^{-20}$ cm$^2$ at 1026 nm), and an acceptable Stark-level structure. A relatively low pump saturation intensity of 2.8 kW/cm$^2$ leads to a comparatively low laser threshold, which is achievable at diode laser pumping. Moreover, KGd(WO$_4$)$_2$ has attracted much interest as one of the promising solid-state materials for stimulated Raman scattering. The material properties of Yb:KGW are summarized in Table 1.

Laser experiments were performed with a nearly hemispherical laser cavity consisting of a Yb:KGW crystal chip and a 50-mm radius-of-curvature output coupler. A Yb:KGW ($\chi_{\text{yb}} = 2.2 \times 10^{20}$ cm$^{-3}$) crystal with a thickness of 1.7 mm was used. One of the crystal surfaces was coated for high transmission at the pump wavelength and for high reflection at laser wavelengths. The opposite side of the crystal was antireflection coated at the laser wavelengths. A 1.2-W cw fiber-bundled diode laser ($\lambda = 980$ nm; $\phi = 150$ $\mu$m; N.A., 0.19) was used to pump the active element.
longitudinally along the b axis. Using a lens of 4.7-mm focal length, we focused the pump beam at a 43-μm radius spot in the active medium. The output couplings employed ranged from 1.1% to 6.5% transmission. The absorbed fraction of the pump power was estimated to be 0.7 for 1.7-mm Yb:KGW, which corresponded to an effective absorption cross section of approximately $4 \times 10^{-20}$ cm$^2$ and a pump saturation intensity of 8.5 kW/cm$^2$. The cavity-mode diameter at the active element was determined to be 88 μm for the TEM$_{00}$ transverse mode. For the Q-switched laser experiments a 50-μm-thick antireflection-coated Cr$^{4+}$:YAG crystal with an initial transmittance of 0.99 was inserted into the resonator 4 mm from the active medium, where the cavity-mode diameter was estimated to be 115 μm.

Without the Cr$^{4+}$:YAG in the cavity, a maximum of 120 mW of cw output was produced at 1044 nm, with a slope efficiency of 53% with respect to absorbed power. The average output power, repetition rate, and pulse width in a Q-switched mode were measured as functions of absorbed pump power for different output couplers. The pulse energy was determined from the average output power and repetition rate. The peak power was determined from the pulse energy and pulse width. We obtained 3.4-μJ Q-switched pulses with a pulse width of 85 ns, resulting in a peak power of 38 W at a repetition rate of 17 kHz with $T_{\text{out}} = 2.4\%$ at 605-mW absorbed pump power. The highest average output power of 61 mW was obtained with $T_{\text{out}} = 1.1\%$ (Fig. 1). The threshold for Q-switched operation of the Yb:KGW laser was 280 mW of absorbed pump power with $T_{\text{out}} = 1.1\%$ and 450 mW with $T_{\text{out}} = 6.5\%$. The Q-switch conversion efficiency, defined as the ratio of Q-switched average output power to the cw output without the absorber, reached up to 62% with a 2.4% output coupler. It was found that the laser wavelength depended on the output-coupler transmission both for cw and for Q-switched operation. For a 1.1% output coupler, cw laser action was observed at 1044 nm and was shifted close to the peak of the stimulated-emission band of Yb:KGW at 1026 nm with increasing output-coupler transmission ($\lambda_{\text{out}} = 1035$ nm at $T_{\text{out}} = 2.4\%$ and $\lambda_{\text{out}} = 1026$ nm at $T_{\text{out}} = 6.5\%$). For Q-switched operation, laser emission was observed at 1033, 1030, and 1026 nm with $T_{\text{out}}$ of 1.1%, 2.4%, and 6.5%, respectively. It is associated with the presence of reabsorption losses in the range of gain due to the three-level laser scheme of Yb$^{3+}$.8

Figure 1 shows the pulse energy, peak power, and average power as a function of the absorbed pump power for two different output couplers. The pulse energy and the peak power increase with increasing absorption pump power in the range 300–600 mW, whereas at nearly 600 mW of absorbed pump power they reach a constant value, as theory predicts.11,12 The repetition rate increases linearly and the pulse width decreases with increasing pump power (Fig. 2). Since the absorption cross section of the saturable absorber ($5 \times 10^{-18}$ cm$^2$ for Cr$^{4+}$:YAG) is much greater than the cross section of the lasing transition ($2.8 \times 10^{-20}$ cm$^2$ for Yb$^{3+}$:KGW), the resulting pulse width is 12

$$t_p = \frac{0.86t_{\text{rt}}}{\gamma_{\text{sat,rt}}} \left[ \frac{\delta(1 + \delta)\eta}{\delta - \ln(1 + \delta)} \right],$$  

(1)

where $t_{\text{rt}}$ is the round-trip time of light within the laser cavity, $\eta$ is the energy-extraction efficiency of the laser pulse, given by $\eta = (1 + \delta) - \ln(1 - \eta)$; $\delta = \gamma_{\text{sat,rt}}/(\gamma_{\text{par,rt}} + \gamma_{\text{op}})$ is the ratio of saturable to
unsaturable cavity losses, where $\gamma_{\text{sat,rt}}$ is the round-trip saturable-loss constant, $\gamma_{\text{par,rt}}$ is the round-trip unsaturable intracavity parasitic loss constant, and $\gamma_{\text{op}}$ is the output-coupling loss constant. The round-trip saturable losses were estimated to be 2%. The round-trip unsaturable intracavity parasitic losses were estimated from laser-threshold measurements to be 3%. The energy-extraction efficiency of the laser pulse was calculated to be 0.58. Taking $t_t = 0.34$ ns, we calculated $t_p = 70$ ns for $T_{\text{out}} = 1.1\%$. One can assume that the experimental pulse width can be slightly shortened in the same cavity configuration with more-powerful pumping when the pulse width of the laser reaches asymptotic value.

In the $Q$-switched mode we observed Raman conversion of the fundamental emission in the laser crystal. The Stokes shift with the largest gain for the KGd(WO$_4$)$_2$ crystal is 901.5 cm$^{-1}$.$^8$,9,10 Stimulated Raman emission was observed at 1139 nm (the first Stokes of the fundamental 1033 nm) at 370 mW of absorbed pump-power threshold, which corresponds to 1360 W of intracavity peak power at 1033 nm. The output-coupling transmission was 1.1% at the fundamental laser wavelength and 7% at 1139 nm. We obtained 0.4-$\mu$J pulses at 1139 nm with a pulse width of 20 ns, resulting in a peak power of 20 W at a repetition rate of 17 kHz. A summary of the experimental results for the fundamental and the Raman laser emission of the $Q$-switched Yb:KGW laser is given in Table 2.

In conclusion, what is to our knowledge the first realization of a diode-pumped passively $Q$-switched Yb:KGW laser with a Cr$^{4+}$:YAG saturable absorber has been reported. Raman conversion of fundamental laser emission in a Yb:KGW laser crystal has been demonstrated. $Q$-switched 3.4-$\mu$J pulses with a pulse width of 85 ns were obtained at the 1033-nm fundamental wavelength, and 0.4-$\mu$J pulses with a pulse width of 20 ns were produced in a first Stokes at 1139 nm. Peak powers and Raman conversion efficiencies are expected to be enhanced as a result of optimization of the laser-cavity configuration and the parameters of the saturable absorber at more-powerful diode pumping.

A. A. Lagatsky's e-mail address is aal@ilc.unibel.by.

References