Short pulse eye-safe laser with a stimulated Raman scattering self-conversion based on a Nd:KGW crystal

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We present the results of a solid self-Raman laser based on a Nd:KGW crystal that is transversely pumped by laser diode bars. A beam of an eye-safe laser with a 31.8 mJ output energy and a 2.0 ns pulse width was obtained by applying a special *s*-polarized reflective resonator configuration in which the length of the Raman resonator was shorter than that of the fundamental radiation resonator. The eye-safe laser has the highest output energy and the shortest pulse width among the Nd:KGW lasers ever reported. © 2007 Optical Society of America

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Potassium gadolinium tungstate crystal doped with neodymium ions [$\mathrm{Nd:KGd(WO_4)_2}$ (Nd:KGW)] can be used as an active medium for efficient lasing in the near-IR spectrum region. Compared with a Nd:YAG crystal, a Nd:KGW crystal can be doped with $\mathrm{Nd^{3+}}$ ions up to 10% of the atomic concentration without an evident decrease of the fluorescence lifetime or deterioration in the optical quality, which permits us to optimize this parameter and obtain the maximum lasing efficiency. Nd:KGW is also a Raman crystal with a high third-order nonlinear susceptibility $\chi^{(3)}$, which provides the efficient stimulated Raman scattering (SRS) conversion of the fundamental emission of neodymium ions to the Stokes components of different orders. Among those Stokes components, a 1538 nm laser beam converted from 1351 nm fundamental radiation is arresting, because the emission at this wavelength is eye safe.[1–3] A problem of the Nd:KGW crystal is its relatively low heat conductivity, which is only one third of that for the Nd:YAG crystal.[4] This leads to serious deterioration in the beam quality and a decrease of the output energy when the average pump power is increased. The problem can be solved by pumping a Nd:KGW crystal with laser diode (LD) bars.

In this Letter, we studied experimentally a Nd:KGW laser transversely pumped by LD bars. A beam of an eye-safe laser with 31.8 mJ output energy and a 2.0 ns pulse width was obtained by applying a special *s*-polarized reflective resonator configuration in which the length of the Raman resonator was shorter than that of the fundamental radiation resonator. This laser has the highest output energy and the shortest pulse width among the ever-reported Nd:KGW lasers pumped by LD bars or Xe lamps.

LD bars used in this experiment were manufactured by the Institute of Semiconductor, Chinese Academy of Sciences, with an output pulse power of no less than 100 W each. The pump module was composed of 32 LD bars, which were combined in four sections and pumped the active medium symmetrically from eight directions. The maximum pump power was 3200 W. The Nd:KGW crystal rod mounted in a quartz chamber was cooled by water.

To optimize the $\mathrm{Nd^{3+}}$ ions concentration, we first tested the output energy of a 1351 nm Nd:KGW laser in the free-running experiment. Five Nd:KGW crystal rods grown by our research group were prepared for the optimization in this step. The parameters of the crystal rods were as follows: (1) $\phi 3.5\times 63$ mm, $C=1.5\%$; (2) $\phi 3.5\times 61$ mm, $C=2\%$; (3) $\phi 3.5\times 61$ mm, $C=3\%$; (4) $\phi 3.5\times 64$ mm, $C=3\%$; (5) $\phi 3.5\times 63$ mm, $C=5\%$ (where C is the concentration of neodymium ions). Both end faces of each crystal rod were antireflection coated to have $<0.2\%$ reflectivity at 1351 nm and $<3\%$ reflectivity at 1067 nm. The pulse repetition frequency was 10 Hz while the pump pulse width was 230 μs. The plane-concave cavity configuration was applied with a cavity length of 17 cm. The highly reflective mirror was 0.5 m radius of curvature with a high-reflection coating at 1351 nm ($R>99.8\%$) and an antireflection coating at 1067 nm ($T>95\%$). The output coupler was a plane mirror with 30% transmissivity at 1351 nm and $>85\%$ transmissivity at 1067 nm. The energy parameters of the 1351 nm Nd:KGW laser measured in our experiment are presented in Fig. 1. The laser energy was detected by a LPE-1A power–energy meter, which was manufactured by Beijing Physcience Optoelectronics Company Limited.

These Nd:KGW crystal rods used in the above experiment had different optical qualities, while the optical quality for the rod with $C=5\%$ was the worst. Obviously, we can see from Fig. 1 that the slope efficiency of the two crystal rods with $C=3\%$ is higher than the others and reaches 16.8% and 12.2%, respectively, whereas the slope efficiency was only 1% for the crystal rod with $C=5\%$. The poor result for the rod with $C=5\%$ was mainly induced by its awful optical quality. In the next step, we performed the

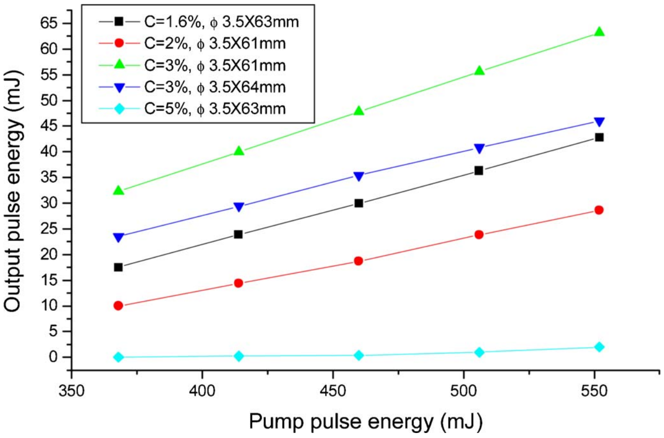

Fig. 1. (Color online) Energy of the free-running Nd:KGW laser.

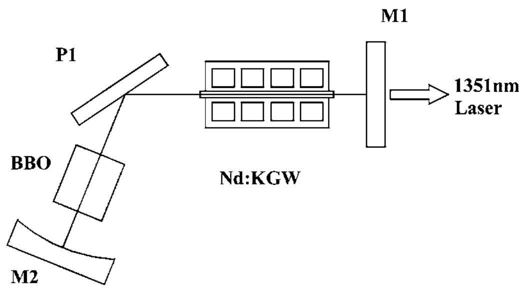

Fig. 2. Schematic of the experimental setup.

Q-switched Nd:KGW laser experiment with the No. 3 crystal rod that provided the highest laser efficiency.

The experimental setup is shown in Fig. 2. All mirrors were arranged compactly with a total resonator length of only 14.5 cm. The special s-polarized reflective resonator was employed, because the s-polarized reflectivity ($R_s > 99\%$) of the polarizer (P1) was higher than the p-polarized transmissivity ($T_p < 96\%$). This configuration can well reduce the resonator loss and improve the output pulse energy. The Q-switched experiment was performed with the help of an electro-optical gate based on the β-barium borate (BBO) crystal,[5–8] which was cut along the Z axis with 1351 nm antireflection coatings ($R < 0.2\%$) at both surfaces. The highly reflective mirror (M2) with a 0.2 m radius of curvature had a high-reflection coating at 1351 nm ($R > 99.8\%$). The output coupler (M1) was a plane mirror with 90% transmissivity at 1351 nm. Both surfaces of the Nd:KGW crystal had antireflection coatings at 1351 nm ($R < 0.1\%$). In addition, compared with the radiation at 1351 nm, the other fundamental radiation of the Nd:KGW crystal at 1067 nm can oscillate easily for its bigger cross section. So all surfaces of mirrors and crystals were antireflection coated at 1067 nm ($T > 95\%$) to suppress the laser oscillation at 1067 nm.

The energy parameters of the Q-switched 1351 nm Nd:KGW laser presented in Fig. 3 was measured under the circumstances of different pump durations at the pulse repetition frequency of 10 Hz. Although the fluorescence lifetime of the Nd:KGW crystal is only 110 μs, the output energy increases obviously as the pump duration increases at the same LD current. A beam of laser with a maximum output energy of 52 mJ and a pulse width of 33 ns was achieved when the maximum input energy was 1.23 J at the maximum pump duration of 385 μs.

By adopting the intracavity Raman configuration, we achieved the first Stokes component of 1538 nm, which was SRS converted from 1351 nm fundamental radiation. The Raman experiment was performed based on the 1351 nm Q-switched experiment. The M1 mirror in Fig. 1 was substituted by the 1538 nm output coupler, a plane mirror with 90% transmissivity at 1538 nm, 97% transmissivity at 1067 nm, and 99.9% reflectivity at 1351 nm. For the sake of shortening the Raman resonator length, one surface of the Nd:KGW crystal near the M1 mirror had an antireflection coating at 1538 nm ($R < 0.2\%$), 1351 nm ($R < 0.2\%$), and 1067 nm ($R < 2\%$), while the other surface had a high-reflection coating at 1538 nm ($R > 99.9\%$) and an antireflection coating at 1351 nm ($R < 0.1\%$) and 1067 nm ($R < 2\%$). In this experiment, the length of the Raman resonator was shortened to 7 cm, while the total length was the same as the 1351 nm laser experiment. In this way, the Raman loss was decreased, and the power density on the surfaces of the BBO crystal and the highly reflective mirror (M2) was also reduced correspondingly.

Figure 4 shows the results of the Raman experi-

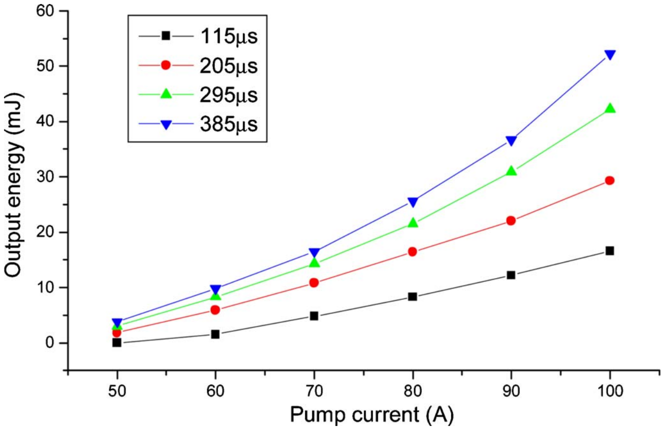

Fig. 3. (Color online) Energy of the 1351 nm Q-switched laser versus LD current at different pulse durations.

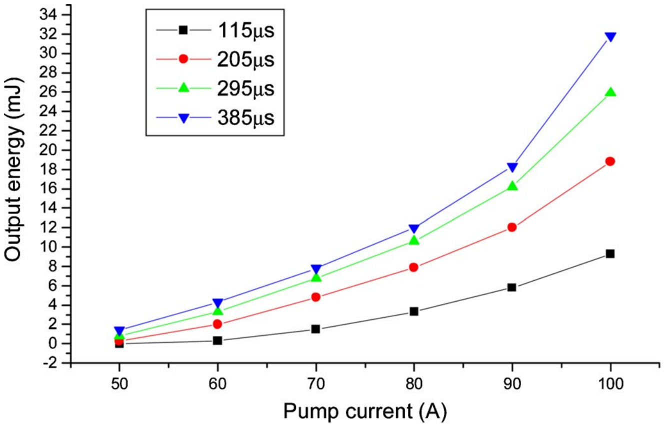

Fig. 4. (Color online) Energy of the 1538 nm Q-switched laser versus LD current at different pulse durations.

ment. The pulse repetition frequency was also 10 Hz. As seen from Fig. 4, upon increasing the LD current, the efficiency of the Raman laser was improved, which improved the power density of the 1351 nm fundamental radiation. When the pump energy was up to 1.23 J, a beam of the eye-safe laser was achieved with a 31.8 mJ output energy and a 2.0 ns pulse width. The laser temporal profile was recorded by a Tektronix TDS3052B oscillograph and THORLABS D400FC fiber photodetector.

We have successfully demonstrated an eye-safe Raman laser of a Nd:KGW crystal pumped by LD bars. With the help of a BBO electro-optical *Q* switcher, a beam of an eye-safe laser was obtained by applying a special *s*-polarized reflective resonator configuration in which the length of the Raman resonator was shorter than that of the fundamental radiation resonator. Under the condition of a 10 Hz repetition rate, a beam of laser was achieved with a 31.8 mJ output energy and a 2 ns pulse width. To the best of our knowledge, the eye-safe laser has the highest output energy and the shortest pulse width among the ever-reported Nd:KGW lasers pumped by LD bars or Xe lamps. In the future, we intend to further improve the beam quality and the output energy of the Raman laser.

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