Self-Q-switching in bulk Yb:KGd$(WO_4)_2$ laser

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Received December 24, 2014; accepted April 23, 2015; posted online May 28, 2015

Self-Q-switching is observed in a bulk Yb:KGd$(WO_4)_2$ oscillator without any additional modulating elements. The output power reaches 434.4 mW at a pump power of 13.67 W, corresponding to pulse repetition rate of 125 kHz and a pulse duration of 2.5 μs, respectively. The mechanism of self-pulse formation is explained by the re-absorption effect of the Yb^{3+} ion in Yb:KGd$(WO_4)_2$.

OCIS codes: 140.3580, 140.3480, 140.3615, 140.3538.

doi: 10.3788/COL201513.061407.

The Yb^{3+}-doped KGd$(WO_4)_2$ (Yb:KGW) crystal has the advantages of a broad gain bandwidth, high-emission cross-sections, and good thermal conductivity, as well as small quantum defects[1,2], which makes it one of the most important diode-pumped lasers for high-power and high-energy applications[3–5]. Lasers with pulse widths in the nanosecond to microsecond range are required in fields of material processing, remote sensing, and nonlinear frequency conversion[6], etc. Pulsed Yb:KGW lasers have been reported by quite a few publications through Q-switching[7–9] or mode locking[10–13], in which modulators or saturable absorbers were employed to start the Q-switching or mode locking. Recently, some studies have reported that lasers under the quasi-three level may realize self-Q-switching due to the significant re-absorption loss produced by a high thermal population at a lower laser level[14–16]. This could help clarify the mechanism of self-Q-switching and aid in the construction of a laser oscillator with moderating pulse energy without additional modulators, as well as reducing the cost of such systems.

In this Letter, stable self-Q-switching was observed in a bulk Yb:KGW laser operation near 1030 nm. Pulses as short as 2.5 μs were obtained, with an average output power of 434.4 mW. The experimental results were briefly explained by the re-absorption loss effect. To our knowledge, this is the first report on a diode-pumped Yb:KGW bulk laser for self-Q-switching formation.

The experimental setup of the self-Q-switched Yb:KGW laser is shown in Fig. 1, where the pump source was a pure, continuous wave (cw), 976 nm fiber-coupled diode laser with a maximum output power of 25 W. The beam of the pump laser was focused into the crystal by two coupling lenses. The gain medium was a 5 at.% (the corresponding Yb^{3+} concentration is $\sim 3.16 \times 10^{20}$ ions/cm^3, and the peak absorption coefficient near 980 nm is up to 40 cm^{-1}); the Yb:KGW crystal size was 3 mm × 3 mm × 10 mm and cooled with water down to the temperature of 13.6°C. M_1 was a plane mirror that was high-transmission coated at 976 nm and highly reflective around 1030 nm. OC was an output coupler (radius of curvature: 100 mm) with a transmission of 3%. The resonator configuration was plano-concave with a length of 90 mm.

After fine collimation, the laser would oscillate, and the pump threshold was measured to be 3.7 W. When the output power was lower than 100 mW, the laser oscillated in a continuous wave. However, when the output power exceeded 100 mW (and the corresponding pump power was 5 W), the laser turned to the pulsed state. Note that no modulator in a self-Q-switching state was used in the resonator. With the increase in the pump power, self-Q-switching was sustained until the pump power reached 13.67 W. When the pump power was higher, the self-Q-switching would disappear. The cw and the self-Q-switched output power were measured with respect to pump power and are shown in Fig. 2, where a quasi-linear increase in the output power with the pump power can be seen. The maximum cw output power was about 823 mW at a pump power of 13.67 W, and the corresponding slope efficiency was 11.9%. The maximum self-Q-switched output power was about 434.4 mW at a pump power of 13.67 W, and the corresponding slope efficiency was 3.8%. The low slope efficiency is mainly due to the misalignment of the cavity mirrors.

The spectrum of the self-Q-switching and the cw was detected by a spectrometer (S2000, Ocean Optics). The results are shown in Fig. 3, where a small blue drift represents the central wavelength, and shows a decrease in the full width at half maximum (FWHM) of the spectrum with a corresponding increase in the pump power. This can possibly be attributed to the accumulated thermal effect and mode competition of the oscillating modes.

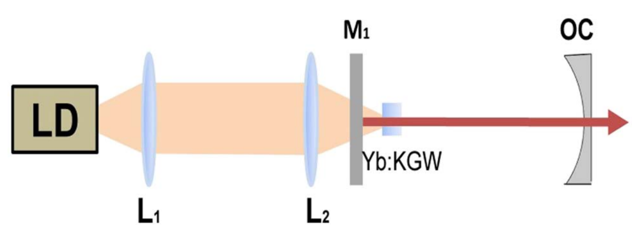

Fig. 1. Schematic of the self-Q-switched Yb:KGW laser.

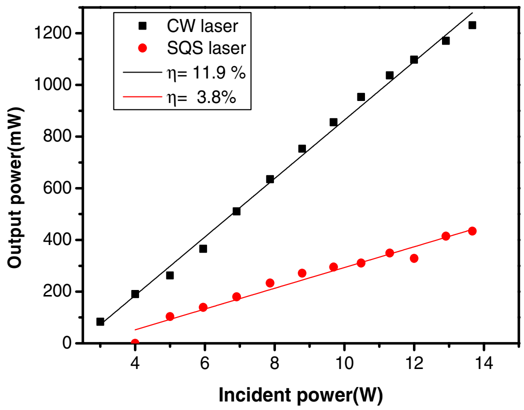

Fig. 2. Output power in the cw and self-Q-switched state with respect to the pump power.

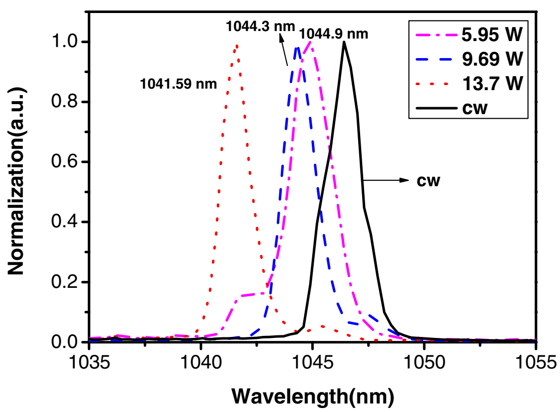

Fig. 3. Typical spectra for cw and self-Q-switching at pump powers of 5.95, 9.69, and 13.7 W.

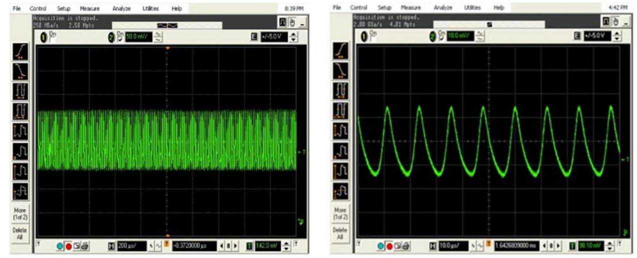

Fig. 4. Self-Q-switched pulse trains at a pump power of 7.87 W. (a) Long-term pulse trains. (b) Short-term pulse trains.

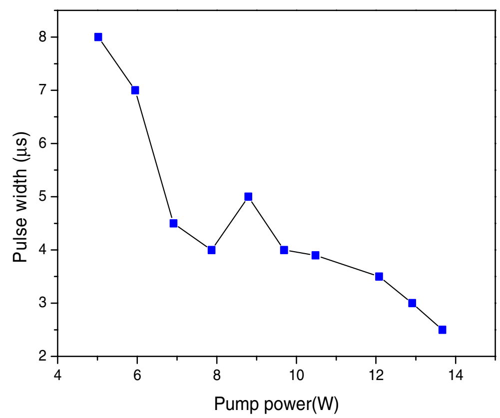

Fig. 5. The pulse width as a function of the incident pump power.

As the pump power was increased, more laser modes would obtain enough gain to surpass the loss and begin to oscillate; thus, the spectral width was broadened. Furthermore, gain competition had been always present in a linear cavity, solid-state laser. With the increase in the pump power, more heat would accumulate in the crystal. As a result, the thermal load of the crystal would change its gain curve and the oscillation modes in the resonators; thus, the central wavelength may shift. However, the self-Q-switching could be sustained, regardless of the change in the central wavelength and the spectral width.

A small portion of the output laser was injected into a photodiode, and then the pulse trains were recorded by a digital oscilloscope (54866A, Agilent Technologies). Figure 4 shows the long-term and short-term pulse trains at a pump power of 7.87 W. From Fig. 4(a), one can see that the self-Q-switched pulse trains had little modulation, which demonstrated that the pulse energy was very stable. From Fig. 4(b), it can be seen that the pulse width was about 3.9 μs.

The pulse widths at different pump powers were determined, and Fig. 5 shows the results. While the self-Q-switching was being sustained, the pulse width would decrease from 8 to about 2.5 μs, with the increase in the pump power. This pulse width appeared to be larger than that of Q-switched[17–19] and mode-locked pulses with modulators[6,10]. We believe this was due to the weak modulation effect of the Yb:KGW crystal, rather than the functional modulators. In our experiment, we tried to enhance the modulation by realigning the intra-cavity optical elements to achieve a shorter pulse width, but it was very difficult to obtain stable self-Q-switching with a shorter pulse width. However, since the oscillator did not require additional modulators, it was still a cost-effective laser with moderate pulse energy.

In Fig. 6, the self-Q-switched repetition rate with respect to pump power was plotted. The repetition rate was increased from 43.5 to 125 kHz by raising the pump power from 5 to 13.67 W, which was similar to the passive Q-switching behavior. Upon further raising the pump power, the self-Q-switching would vanish.

Some researchers have modeled the self-Q-switched action as a simple, saturable absorber based on the standard passive Q-switching theory, and then used the experimental pump-dependent repetition rate data to determine the small-signal saturable loss. In the presence of a saturable absorber with a small-signal loss of Q_0 (modulation depth), the repetition rate f_{rep} of the pulse train can be determined from the Eq. (1)[20–23], where τ_f is the fluorescence lifetime of the gain medium (275 μs

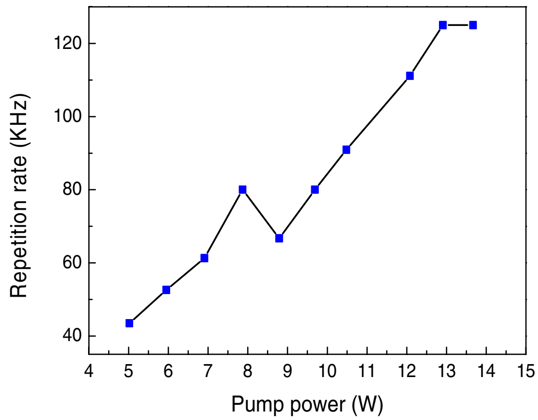

Fig. 6. The pulse repetition rate as a function of the incident pump power.

for Yb:KGW)[24] and G_0 is the round-trip, small-signal gain:

$$f_{\mathrm{rep}} = \frac{1}{\tau_f}\frac{G_0}{Q_0}. \tag{1}$$

By the theoretical calculations from the above equation, we get the repetition frequency of the self-Q-switching versus the modulation depth, as shown in Fig. 7.

Several attempts to explain the self-Q-switching formation have been made and possible reasons contributing to the self-Q-switching were proposed, such as Brillouin scattering[25], stimulated scattering[26], Kerr lensing[27], saturable absorption in a gain medium[28], and relaxed oscillation[29]. Brillouin scattering, stimulated scattering, and Kerr lensing are closely related to the peak power of a pulse, and typically accompany a new frequency generation. However, in our experiment, the peak power was relatively low, which made it very difficult to excite Brillouin scattering, stimulated scattering, or Kerr lensing. Furthermore, we had not observed a new frequency in the spectra. Relaxed oscillation often occurred near the threshold, and most lasers had irregular, undamped spikes in their pulse trains. However, in our laser, the self-Q-switching only occurred beyond 100 mW, and the pulse trains had nearly

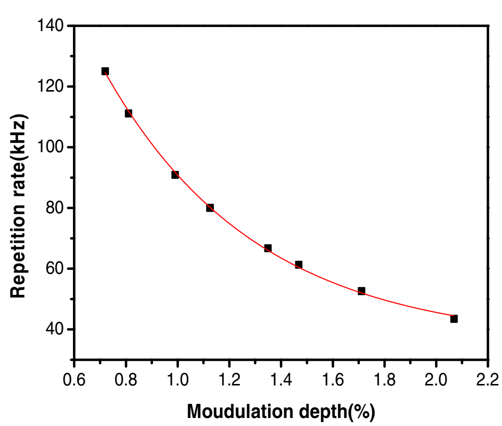

Fig. 7. The pulse repetition rate of the self-Q-switching versus the modulation depth.

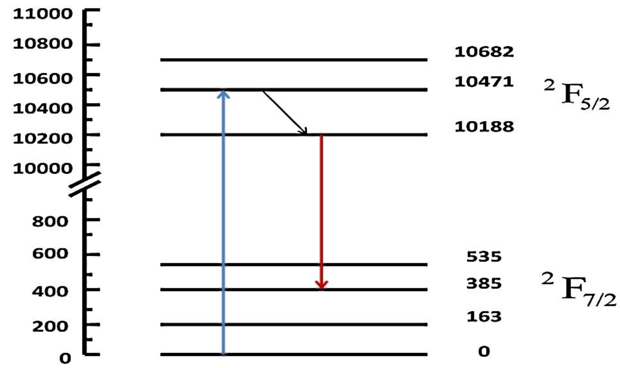

Fig. 8. Energy level of the $^2F_{5/2}$ and $^2F_{7/2}$ manifolds of Yb^{3+} in KGW.

equal intensity. In Ref. [14], self-Q-switching was observed in a solid-state Nd:YVO_4 laser, and it was attributed to the re-absorption effect. We noted that the Yb:KGW had a similar energy level when compared to Nd:YVO_4. Figure 8 shows the energy level of Yb:KGW, which was a typical quasi-three-level structure. A number of lines observed in the absorption and the emission spectra were assigned to vibronic sidebands that coupled with the electronic transition between the ground state $^2F_{7/2}$ and the excited state $^2F_{5/2}$ levels. This was because of the high absorption and emission cross sections of the Yb:KGW crystal, along with its useful Stark-level splitting and comparatively low re-absorption at the laser wavelength[2]. The saturation of the re-absorption loss resulting from the thermal population at the lower laser level induced self-Q-switching. Since our experimental results were similar to those in Ref. [14], we believe the self-Q-switching can also be attributed to the re-absorption effect of the Yb:KGW crystal.

In conclusion, we demonstrate a diode-pumped, self-Q-switched Yb:KGW laser near 1044 nm. The shortest pulse width of 2.5 μs is obtained at a pump power of 13.67 W, with a repetition rate of 125 kHz. The maximum output power is 434.4 mW at 125 kHz, corresponding to a pulse energy of 3.48 μJ. The self-Q-switching can be explained by the reabsorption effect of Yb:KGW between its energy levels. This experiment presents more evidence for self-Q-switching in solid-state lasers, and the modulator-free oscillator can meet the demand for a cost-effective laser source with moderate output power and pulse energy rather than pulse width.

This work was supported by the National Natural Science Foundation of China (Grant No. 61177047), the Beijing Municipal Natural Science Foundation (Grant No. 1102005), and the Basic Research Foundation of Beijing University of Technology (Grant No. X3006111201501).

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