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# Acousto-Optically Q-Switched Operation of Yb:CNGG Disordered Crystal Laser *

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*We report the repetitively Q-switched laser operation of the Yb-doped calcium niobium gallium garnet disordered garnet crystal, achieved with an acousto-optic modulator in a compact plano-concave resonator that is end-pumped by a 935-nm diode laser. An average output power of 1.96 W is produced at pulse repetition rate of 50 kHz at emission wavelengths around 1035 nm, with a slope efficiency of 16%. The highest pulse energy of 269 μJ is generated at pulse repetition rate of 1 kHz, with pulse width 12.1 ns and peak power 20.53 kW.*

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Ytterbium (Yb)-doped calcium niobium gallium garnet (Yb:CNGG), a disordered Yb-ion garnet crystal, was developed first in 2007.[1] As a disordered laser crystal, it possesses, to some extent, the advantages of laser glasses such as broad absorption and emission bands, and the advantages of ordinary laser crystals such as relatively high thermal conductivities. Disordered laser crystals are therefore attractive for some applications, particularly in tunable lasers or in mode-locked lasers.

During the past decade, numerous investigations were carried out experimentally into the laser performance of the Yb:CNGG disordered garnet crystal, when it was utilized in various operational modes including continuous-wave (cw),[1–5] mode-locked,[6] passively Q-switched lasers with $Cr^{4+}$:YAG crystal,[4,7,8] with GaAs semiconductor crystal plate,[9] or with single-layer graphene sheet as saturable absorbers.[10] The maximum cw output power produced from Yb:CNGG lasers was in the level of 5–6 W;[3–5] while the highest pulsed output amounted to about 2.0 W, which was generated in passively Q-switched operation with a $Cr^{4+}$:YAG saturable absorber.[4]

Despite the extensive studies on Yb:CNGG lasers operating in different modes, the acousto-optic Q-switching laser performance of this disordered garnet still remains unknown. In fact, research work on actively Q-switched Yb-ion lasers as a whole also seems quite insufficient if compared with the situation of passive Q-switching; the relevant work conducted so far was merely limited to garnets including Yb:YAG,[11] Yb:GGG,[12] Yb:YSGG,[13] and Yb:GAGG,[14] disordered crystal of Yb:CLB,[15] and the rare earth calcium oxyborates of Yb:YCOB and Yb:GdCOB.[16,17] Compared with passive Q-switching, the most pronounced advantage of acousto-optic Q-switching is that the pulse repetition rate can be precisely controlled by an external modulating signal, making it possible to adjust the repetition rate over a very wide range, and eliminating time jitters which usually exist in passively Q-switched laser action. In general, the technique of acousto-optic Q-switching is applicable only to those low-gain laser materials, due to the relatively low diffraction losses which it can provide. By contrast, the suitability of passive Q-switching seems to be much wider, and a higher gain can be accounted for simply by reducing the initial transmission ($T_0$) of the saturable absorber.

In this Letter, we report the active Q-switching laser performance of Yb:CNGG disordered crystal, demonstrated by use of an acousto-optic Q-switch in a plano-concave laser resonator. Stable repetitively Q-switched laser operation is achieved with the pulse repetition frequency (PRF) changed from 50 kHz down to 1 kHz, producing a maximum average output power of 1.96 W, which proves to be very close to the highest output generated from passively Q-switched Yb:CNGG lasers.[4,9]

The acousto-optically Q-switched Yb:CNGG crystal laser was fabricated by employing a compact plano-concave cavity, as schematically illustrated in Fig. 1. The plane mirror (M1) was coated for high reflectance at 1020–1200 nm (>99.9%) and high transmittance at 820–990 nm (>98%). The concave mirror M2 with a radius of curvature of 50 mm, served as the output coupler, which had a transmission (output coupling) of $T = 30\%$ at 1030 nm. The Yb:CNGG crystal sample was cut along its [111] crystallographic direction, with a square aperture of 3.3 mm × 3.3 mm and a length of 3.5 mm, and no antireflection (AR) coatings were made on its end faces. During the laser operation, the crystal sample was cooled with cycling water that was kept at a temperature of 7℃. To actively Q-switch the Yb:CNGG laser, an acousto-optic Q-switch (33080-16-7-I-TB, Gooch & Housego) was utilized, whose inter-

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action length was 20 mm, with AR coating on its end faces for 1.06 µm. It was driven at 80 MHz with an rf power of 16 W during its operation. In the experimental laser setup shown in Fig. 1, the laser crystal (denoted as LC) was positioned near the plane mirror M1, while the acousto-optic Q-switch (denoted as AO) was inserted between the Yb:CNGG crystal and the output coupler M2, leaving a geometric cavity length of 60 mm. The pump source employed was a high-brightness fiber-coupled diode laser emitting at 935 nm with a bandwidth of less than 1 nm, with the fiber core diameter and NA being 200 µm and 0.22, respectively. Through a focusing optics, the pump radiation was coupled into the laser crystal, with a pump spot radius of approximately 100 µm.

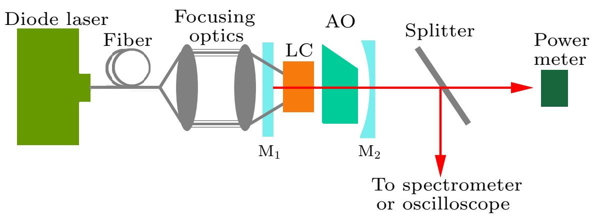


**Fig. 1.** Schematic diagram of the experimental laser setup. LC stands for the laser crystal, and AO denotes the acousto-optic Q-switch.

With the resonator configuration described above, we achieved repetitively Q-switched laser operation of the Yb:CNGG disordered garnet crystal, with the PRF changing over a range from 50 to 1 kHz. The transmission of output coupler employed was chosen to be 30%, which is proven to be the best to obtain high average output power and to restrain the occurrence of multi-pulse operation.

Figure 2 shows the output characteristics of the laser in terms of average output power ($P_{avr}$) versus absorbed pump power ($P_{abs}$), for four different PRFs of 50, 20, 5, 1 kHz in cw operation. The value of $P_{abs}$ was estimated from the incident pump power ($P_{in}$), by $P_{abs} = \eta_p P_{in}$, where $\eta_p$ is the small-signal absorption of the laser crystal for the pump radiation. For the 3.5 mm long Yb:CNGG crystal, $\eta_p$ was measured to be 0.85. Under the conditions of PRF = 50 kHz, the threshold for Q-switched laser operation was reached at $P_{abs}$ = 3.80 W. In this case, the maximal output power reached 1.96 W at $P_{abs}$ = 16.69 W, with a slope efficiency of 16.2%, and the optical-to-optical efficiency was 11.8%. As can be noted, the Q-switched operation would become less efficient with the amount of $P_{abs}$ increasing above 14 W, which could be attributed to the thermally induced losses. In the case of PRF = 50 kHz, one can see that the average output power was close to that obtained in cw operation when the thermal losses were not significant.

From Fig. 2 one can see that the average output power would become reduced as the pulse repetition rate was lowered. In the case of PRF = 20 kHz, the maximum output power, achievable before the onset of multi-pulse operation, was 1.47 W, generated at $P_{abs}$ = 14.20 W. When the laser was operated at a lower repetition rate of 5 kHz, the highest average output power obtainable was 1.06 W. With the lowest PRF of 1 kHz utilized in the experiment, the average output power could only reach 0.27 W at $P_{abs}$ = 7.12 W. Under conditions of low repetition rates, the switching time of the AO Q-switch could become longer than the pulse build-up time.[18] When this situation occurred in the Q-switched operation, a second laser pulse was able to develop.

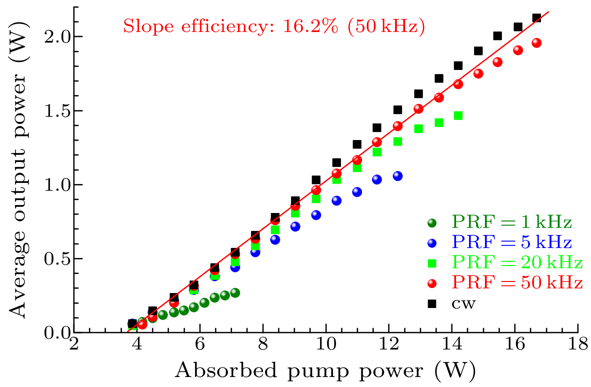


**Fig. 2.** Average output power versus absorbed pump power, measured in the cases of PRF = 50, 20, 5, 1 kHz and cw operation.

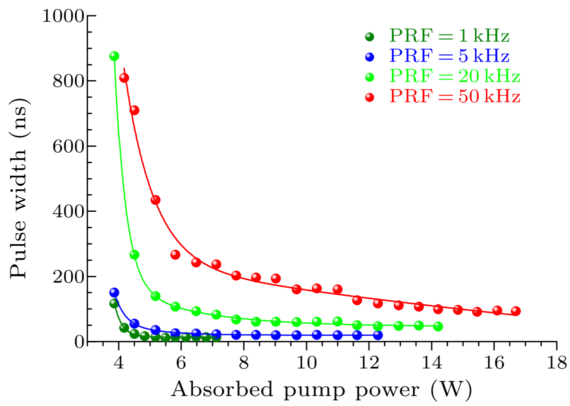


**Fig. 3.** Dependence of pulse duration on pump power for PRF = 50, 20, 5, and 1 kHz.

Figure 3 shows the measured pulse duration (FWHM) as a function of $P_{abs}$ under different pulse repetition rates from 50 to 1 kHz. The pulse duration was found to be dependent upon both pump power and pulse repetition rate. In the case of PRF = 50 kHz, the pulse width was measured to be 809 ns near the oscillation threshold ($P_{abs}$ = 4.18 W); then it dropped rapidly with the increase of the absorbed pump power, eventually reaching a magnitude of approximately 100 ns kept to be roughly unchanged. In addition, at a given pump power, the pulse width would be reduced greatly as the repetition rate was decreased.

In the case of PRF = 1 kHz, the shortest pulse width $t_p = 12.1$ ns was measured.

Figure 4 presents two oscilloscope traces showing a typical laser pulse train, which were recorded at $P_{abs} = 5.49$ W for the case of PRF = 1 kHz, and at $P_{abs} = 15.45$ W for the case of PRF = 50 kHz, respectively. The temporal profile of an individual pulse is also shown as an inset for each case. The amplitude fluctuations were estimated to be about 10% for the case of PRF = 1 kHz, and the values amounted to 16% under the highest repetition rate conditions of PRF = 50 kHz.

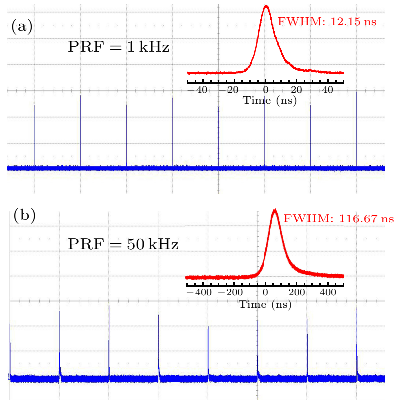


**Fig. 4.** Oscilloscope traces showing typical pulse train, which were measured at $P_{abs} = 5.49$ W for PRF = 1 kHz (a), and at $P_{abs} = 15.45$ W for PRF = 50 kHz (b). The insets illustrate the profile of an individual laser pulse.

Figure 5 depicts the laser emission spectra for different PRFs and cw operation, which were measured at $P_{abs} = 7.12$ W. The laser emission covered a wavelength range of 1031–1037 nm. In comparison with the case of the Yb:GGG ordered garnet crystal laser,[19] the laser emission band obtained here proves to be much broader. One can also note that the detailed structures of the laser emission spectrum for different PRFs are different to some extent. The physical mechanism underlying this behavior can be understood as follows: firstly, the effect of longitudinal mode discrimination turns out to be very weak in actively Q-switching process, which is in sharp contrast to the situation of passively Q-switching.[20] This implies that the active Q-switching itself can have only very limited effects on the laser emission spectrum. As a consequence, the emission spectrum of a quasi-three-level laser operating in actively Q-switching mode will be determined, just as in the free-running case, by the effective gain cross-section curve for the laser medium, namely, $\sigma_g(\lambda) = \beta\sigma_{em}(\lambda) - (1-\beta)\sigma_{abs}(\lambda)$, where $\sigma_{em}$ and $\sigma_{abs}$ denote the emission and absorption cross-sections, respectively, while $\beta$ is the fraction of Yb ions that have been excited to the upper manifold ($^2F_{5/2}$). In general, laser emission will occur at those wavelengths where $\sigma_g(\lambda)$, and hence the overall gain of the laser reaches its maximum. For the Yb:CNGG disordered crystal, the $\sigma_g(\lambda)$ curves for different $\beta$ levels are proved to be very smooth (lack of pronounced peaks),[1] which is the physical reason for the broad laser emission band observed. Evidently, when the laser was operated at different PRFs, the dynamical process of laser emission and other related thermal effects experienced by the Yb:CNGG crystal will be distinct, giving rise to different thermally induced losses and thus different overall losses for the laser resonator. As a result, the amounts of $\beta$ required for maintaining laser operation at a given pump level for different PRFs will be different. Considering the strong and sensitive dependence of the maximum of $\sigma_g(\lambda)$ on the magnitude of $\beta$ for the Yb:CNGG crystal,[1] distinct laser emission spectra would be expected for different PRFs.

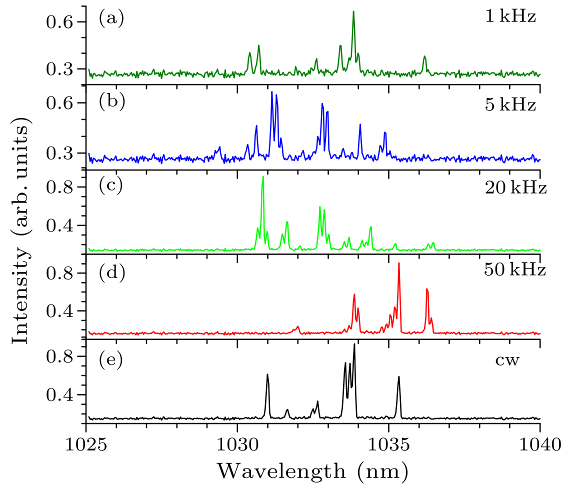


**Fig. 5.** Laser emission spectra measured at $P_{abs} = 7.12$ W for PRF = 50, 20, 5, and 1 kHz, and for cw operation.

Table 1 summarizes the primary parameters characterizing the acousto-optically Q-switched Yb:CNGG laser operating at different PRFs, including maximum average output power ($P_{avr}$), maximum pulse energy ($E_p$), pulse width ($t_p$), highest peak power ($P_p$), and slope efficiency ($\eta_s$). To give a direct comparison, the results for a passively Q-switched (PQS) Yb:CNGG/$Cr^{4+}$:YAG laser under operating conditions of $T = 30\%$, $T_0 = 93.8\%$,[4] are also listed (the last row). One sees that, when the highest output power achievable through the two Q-switching modes was comparable, the slope efficiency for passive Q-switching was proved to be higher than active Q-switching by a factor of greater than three, and the pulse duration of passive Q-switching was also considerably shorter at similar PRFs. On the other hand, stable pulsed operation at very low PRF ($\leq$2 kHz) or at very high PRF ($\geq$35 kHz) seemed to be difficult to achieve through passive Q-switching.[4] It is therefore, from a point of view of practical applications, desirable to utilize acousto-optic Q-switch to generate pulsed laser radiation at PRF$\leq$2 kHz or at

PRF≥35 kHz; whereas the passive Q-switching would be more preferable for producing pulsed radiation with PRF ranging from 2 to 35 kHz.

**Table 1.** Parameters of the acousto-optically Q-switched Yb:CNGG laser.

| PRF (kHz) | $P_{\rm avr}$ (W) | $\eta_{\rm s}$ (%) | $E_{\rm p}$ (μJ) | $t_{\rm p}$ (ns) | $P_{\rm p}$ (kW) |
|---|---|---|---|---|---|
| 50 | 1.96 | 16.2 | 39.2 | 93.0 | 0.42 |
| 20 | 1.47 | 15.1 | 73.3 | 46.0 | 1.59 |
| 5 | 1.08 | 12.8 | 211.4 | 19.3 | 10.95 |
| 1 | 0.27 | 6.6 | 269.0 | 12.1 | 20.53 |
| 12 (PQS) | 2.0 | 56.0 | 166.7 | 9.5 | 17.50 |

In summary, actively Q-switched laser operation has been demonstrated for the Yb:CNGG disordered garnet crystal over a range of pulse repetition rate from 50 to 1 kHz, with an acousto-optic Q-switch in a simple plano-concave resonator that was end-pumped by a 935-nm diode laser. An average output power of 1.96 W can be generated around emission wavelengths of 1035 nm at pulse repetition rate of 50 kHz, with a slope efficiency determined to be 16%. In the operation at the lowest repetition rate of 1 kHz, the pulse energy produced could be scaled to 0.27 mJ, with pulse duration and peak power being 12.1 ns and 20.53 kW, respectively.

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