# LD-pumped passively $Q$-switched red laser at 660 nm

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A laser diode (LD) pumped Nd:YAG red pulse laser at 660 nm was presented by V:YAG passively $Q$-switching and LBO intracavity frequency doubling. With 1.6-W incident pump power, average output power of 46-mW, pulse duration (FWHM) of 23.3 ns, pulse repetition rate of 21.6 kHz, peak power of 91.4 W, and single pulse energy of 2.13 $\mu$J were obtained. The beam quality factor $M^2$ was less than 1.2. The fluctuations of pulse energy and repetition rate were less than 3% in 4 hours. The pulsed laser at 660 nm is expected to be used as the pump source of $Cr^{3+}$:doped crystal to obtain the gain-switched tunable laser.

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In recent years, LD-pumped continuous-wave (CW) or pulsed red laser has been developed by intracavity or extracavity doubling the 1.3-$\mu$m laser of $Nd^{3+}$-doped crystal[1−3]. In the case of the pulsed red light output, the fundamental wave was actively $Q$-switched[2,3], thus the laser was complex and expensive. Saturable absorber passively $Q$-switching is proved to be a simpler and lower cost way because of no high-voltage and radio frequency (RF) drivers[4]. When the doubler is included into the cavity, pulsed second harmonic wave can be generated[5−7]. Saturable absorber Cr:YAG has been widely used in $Q$-switched and intracavity frequency doubling green and blue lasers[4−7], but it is not suitable for 1.3-$\mu$m wave band. The saturable absorber V:YAG has been proved to be an effective passively $Q$-switched crystal for this wave band[8−10]. It has the properties of large ground-state absorption cross section, small ratio of excited- and ground-state absorption cross section, short recovery time, low saturable energy density, and high damage threshold.

In this paper, a compact and low cost LD-pumped red pulse Nd:YAG laser at 660 nm was demonstrated simultaneously by V:YAG passively $Q$-switching and LBO intracavity frequency doubling. The combination of Nd:YAG and V:YAG was analysed theoretically for passive $Q$-switching. The parameters of pulsed red laser as a function of pump power were studied experimentally. The fluctuations of red pulse energy and repetition rate were less than 3% in 4 hours at last.

The properties of V:YAG was extensively studied in Ref. [8]. The linear absorption spectrum of V:YAG between 350 and 1600 nm is shown in Fig. 1. It is very suitable for the line of 1319 nm of Nd:YAG $Q$-switching. For 1319 nm, the absorption cross sections of ground- and excited-state are $\sigma_{\rm gsa} \approx 7.2\times10^{-18}$ and $\sigma_{\rm esa} = 7.4\times10^{-19}$ cm$^2$, respectively. The ratio of $\beta = \sigma_{\rm esa}/\sigma_{\rm gsa} \approx 0.1$ is small, which indicates that the exited-state absorption (ESA) loss is low. The saturable energy density is about 0.05 J/cm$^2$, corresponding saturable power density is 7 MW/cm$^2$, which means that it can be used in lower pump power level. The recovery time is short (22±6 ns). When proper resonator was adopted, $Q$-switching and mode-locking can be realized[9].

The stimulated emission cross section $\sigma_{\rm em}$ is $8.7\times10^{-20}$ cm$^2$ for Nd:YAG at 1319 nm. The important parameter $\alpha$ for passively $Q$-switching is $\sigma_{\rm gsa}\omega_{\rm l}^2/\sigma_{\rm em}\omega_{\rm s}^2 \approx 80$ (assuming the beam radius $\omega_{\rm l}$ in Nd:YAG is equal to the one $\omega_{\rm s}$ in V:YAG), which guarantees that saturation in the absorber occurs before the gain saturation in the laser crystal (the second threshold condition). As shown in Fig. 2, when the gain is equal, the efficiency increases as the parameter $\alpha$ increases, so the combination of Nd:YAG and V:YAG is a better one. It can be regarded as a rapid $Q$-switched laser[11].

Figure 3 shows the configuration of pulsed red laser at 660 nm. A laser diode with maximum output of 2 W, central emitting wavelength of 807.5 nm at 25°C, emitting bandwidth of 1.8 nm, and divergent full angle of 10×36° were used as pump source. A set of coupling optics with 90% efficiency was used to re-image the pump light into the laser crystal. The average pump spot radius

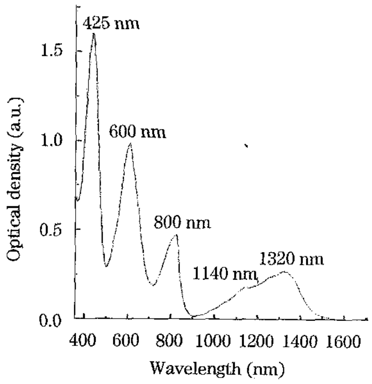

Fig. 1. Linear absorption spectrum of V:YAG.

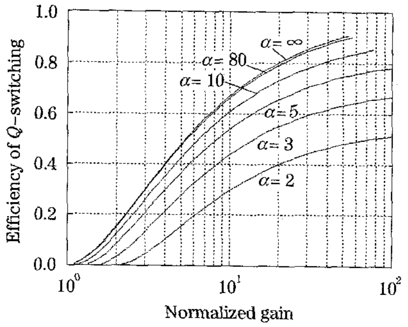

Fig. 2. Efficiency of passive $Q$-switching versus normalized gain. The parameter is $\alpha = \sigma_{\rm gsa}/\sigma_{\rm em}$.

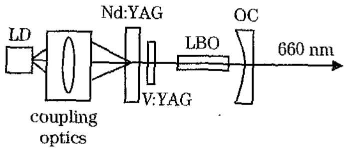

Fig. 3. Schematic of the experimental setup.

$\omega_p$ was 85 $\mu$m. Its ellipse was better than 0.9. The active medium was a 1.0 at.-% doped Nd:YAG crystal. Its size was $\phi$4×3 mm. The left side acting as one mirror of resonator was high transmission (HT) coated at 808 nm ($T$ > 95%) and high reflectivity (HR) coated at 1319 nm ($R$ >99.9%). The right side was antireflection (AR) coated at 1319/1064 nm. For the possible parasitic oscillation will affect the energy storage in the active medium, the remaining reflection of this side was as small as possible to suppress the effect of Fabry-Perot (F-P) etalon that will affect the efficiency of $Q$-switching. The reflection of 808 nm was not considered for double pass through the laser medium at this face. Measurement indicated that more than 85% pump light was absorbed. The resonator was plano-concave. The radius of curvature (ROC) of output coupling mirror was 50 mm. It was HR coated at 1319 nm ($R$ >99.9%), HT coated at 1064 ($T$ >90%) and 660 nm ($T$ >98%). Its plane face was HT coated at 660, 1064, and 1319 nm ($T$ >98%).

A piece of V:YAG with thickness of 0.46 mm and small signal transmission of 89% was used to switch the fundamental laser at 1.3 $\mu$m. Both sides were broad AR coated at this wave band. LBO (2×2×10 mm$^3$) with type-I critical phase matching ($\theta$=85.9°, $\phi$=0° at 27°C) was used to intracavity frequency doubling. The effective nonlinear coefficient was 0.818 pm/V. The walk-off angle at 660 nm was 0° according to the doubling frequency process of 1319.0(e) + 1319.0(e) = 659.5(o), which was favorable to circular light spot. Both sides were AR coated at 660/1319 nm ($R$ <0.2%). For the pulse duration was direct proportion to the length of the resonator, the length of the cavity was set as short as possible. Geometry length of 18 mm was adopted at last. The linear cavity mode radii in Nd:YAG ($\omega_l$), V:YAG ($\omega_s$), and LBO ($\omega_n$) were about the same as 98 $\mu$m. Thus the resonator did not affect the parameter $\alpha$ calculated above. Red pulses were measured by a TDS1012 digital oscilloscope (100-MHz bandwidth) and a fast Si PIN photodiode with a rise time of less than 0.5 ns.

When the V:YAG was not inserted into the cavity, the laser was operated in CW at 660 nm with low noise. Maximum output power of 182 mW was obtained at the pump power of 1.6 W. When the V:YAG was inserted, red pulse was achieved. The average power of 46 mW, pulse duration (FWHM) of 23.3 ns (see Fig. 4), pulse repetition rate of 21.6 kHz were obtained. The corresponding peak power and single pulse energy were 91.4 W and 2.13 $\mu$J, respectively. The threshold was 1.06 W.

Experiments showed that average power, pulse repetition rate, peak power, and single pulse energy increased linearly as the pump power increased. Pulse duration decreased as the pump power increased, so one can obtain different interesting results easily by varying the pump power from near threshold to 1.6 W.

As shown in Fig. 4, time symmetry of the pulse was good. The phenomenon of pulse duration being longer than that of without LBO with fundamental wave output mirror ($T$ = 7%) instead of the red output mirror was not observed as reference. This is because the red output was not overcoupled[5]. For the temperature fluctuation in the environment, thermal gradient in the crystals (Nd:YAG, V:YAG and LBO), absorption of the remained pump light and 660-nm laser by V:YAG, or fluctuation of the diode pump power and spectrum, repetition rate and energy instabilities of the red pulses were about 10%. By carefully adjusting the pump power near 1.6 W and the temperature of the crystals, stable pulse traces were obtained. The instabilities of energy and repetition rate were measured to be less than 3% in 4 hours by the statistics function of the oscilloscope.

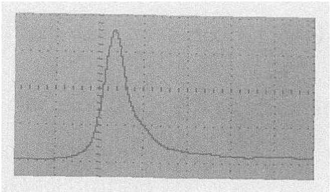

Fig. 4. Oscilloscope trace of a single pulse at 660 nm.

In summary, a compact and low cost LD-pumped all-solid-state simultaneously intracavity passively $Q$-switched by V:YAG and frequency doubling with LBO red pulse laser at 660 nm was obtained. Average output power of 46 mW, pulse duration (FWHM) of 23.3 ns, pulse repetition rate of 21.6 kHz, peak power of 91.4 W, and single pulse energy of 2.13 $\mu$J were obtained when the pump power was 1.6 W. Pulses with stable energy and repetition rate were achieved when the pump power and the temperature of the crystal were adjusted simultaneously. The pulsed laser at 660 nm is expected to pump Cr:$^{3+}$-doped crystal to obtain the gain-switched laser.

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## References

1. A. Agnesi, A. Guandalini, G. Reali, S. Dell'Acqua, and G. Piccinno, Opt. Lett. **29,** 56 (2004).
2. L. J. Qin, X. L. Meng, C. L. Du, L. Zhu, Z. S. Shao, and B. C. Xu, Opt. & Laser Technol. **35,** 257 (2003).
3. G. Z. Luo, S. N. Zhu, J. L. He, Y. Y. Zhu, H. T. Wang, Z. W. Liu, C. Zhang, and N. B. Ming, Appl. Phys. Lett. **78,** 3006 (2001).
4. Y. F. Chen, IEEE Photon. Technol. Lett. **9,** 1481 (1997).
5. N. Pavel, J. Saikawa, and T. Taira, Opt. Commun. **195,** 233 (2001).
6. Q. Zheng, L. Zhao, Z. Q. Ye, and L. S. Qian, Opt. & Laser Technol. **34,** 425 (2002).
7. C. W. Wang, Y. L. Weng, P. L. Huang, H. Z. Cheng, and S. L. Huang, Appl. Opt. **41,** 1075 (2002).
8. A. M. Malyarevich, I. A. Denisov, K. V. Yumashev, V. P. Mikhailov, R. S. Conroy, and B. D. Sinclair, Appl. Phys. B **67,** 555 (1998).
9. A. Agnesi, A. Guandalimi, G. Reali, J. K. Jabczynski, K. Kopczynski, and Z. Mierczyk, Opt. Commun. **194,** 429 (2001).
10. A. V. Podlipensky, K. V. Yumashev, N. V. Kuleshov, H. M. Kretschmann, and G. Huber, Appl. Phys. B **76,** 245 (2003).
11. J. J. Degnan, IEEE J. Quantum Electron. **31,** 1890 (1995).