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# LD-pumped passively Q-switched Nd:$YVO_4$/LBO red laser with V:YAG

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**Abstract**

An LD-pumped Nd:$YVO_4$ passively Q-switched by V:YAG and intracavity frequency doubled by LBO red pulse laser at 671 nm was presented. With 1.6 W incident pump power, average output power of 53 mW, pulse duration (FWHM) of 29.5 ns, pulse repetition rate of 37.2 kHz, peak power of 48.3 W and single-pulse energy of 1.43 μJ were obtained. The stability of pulse energy and repetition rate was better than 3% for 4 h.
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*Keywords:* LD-pumped; Passively Q-switched; Red laser; V:YAG; LBO

## 1. Introduction

In recent years, LD-pumped cw or pulse red lasers have been developed by intracavity or extracavity doubling the 1.3 μm line of $Nd^{3+}$ [1–3]. In the case of pulse 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 simpler and has a lower cost because there are no high-voltage and RF drivers [4]. When the doubler is included into the cavity, pulse 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 was not suitable for 1.3 μm wave band. The saturable absorber V:YAG was proved to be an effective passively Q-switched crystal for this wave band [8–10]. It has 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:$YVO_4$ laser at 671 nm was demonstrated by simultaneously V:YAG passively Q-switched and LBO intracavity frequency doubling. The parameters of pulsed red laser as a function of pump power were studied. Red pulses with energy and repetition rate stability less than 3% were obtained.

## 2. V:YAG Q-switched properties for 1342 nm

The linear absorption spectrum of V:YAG is between 350 and 1600 nm as shown in Fig. 1. It is very suitable for the line of 1342 nm of Nd:$YVO_4$ Q-switching. For 1342 nm, the absorption cross sections of ground- and excited-state are $\sigma_{gsa} = (7.2 \pm 2.6) \times 10^{-18}$ and $\sigma_{esa} = (7.4 \pm 2.8) \times 10^{-19}\,cm^2$, respectively. The ratio of $\beta = \sigma_{esa}/\sigma_{gsa} \approx 0.1$ is small, which indicates that the excited-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 it can be used in lower pump power level. The recovery time is short (22 ± 6 ns) [8]. When proper resonator was adopted, Q-switching and mode-locking can be realized [9].

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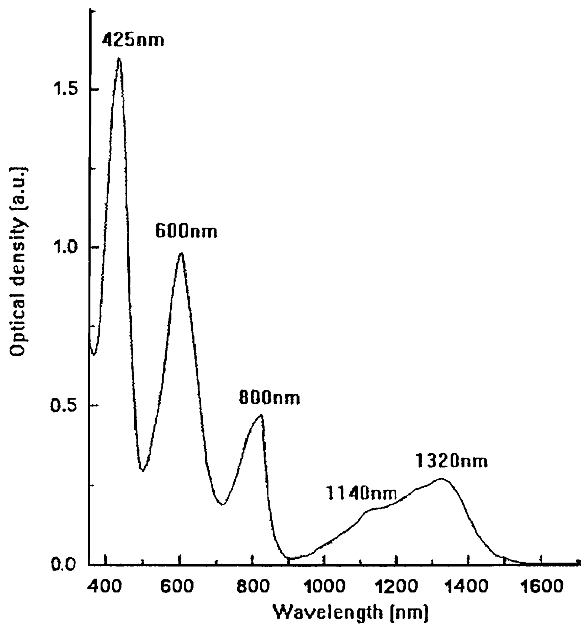


Fig. 1. Linear absorption spectrum of V:YAG.

The stimulated emission cross section ($\sigma_{em}$) is $6.0 \times 10^{-19}\,cm^2$ for a-cut $Nd:YVO_4$ at 1342 nm. The important parameter (α) for passively Q-switching is $\sigma_{gsa}/\sigma_{em} \approx 10$, which guarantees that saturation in the absorber occurs before the gain saturation in the laser crystal (the second threshold condition). So the combination of $Nd:YVO_4$ and V:YAG is a better one. It can be regarded as a rapid Q-switched laser [11].

## 3. Experimental setup

Fig. 2 shows the configuration of pulsed red laser at 671 nm. A laser diode with maximum output 2 W, central emitting wavelength of 807.5 nm at 25 °C, emitting bandwidth of 1.8 nm and divergent angle of $10 \times 36^\circ$ was 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 ($\omega_p$) was 85 μm. Its ellipse is better than 0.9. The active medium was a 1.0 at% $Nd^{3+}$ doped, size of $3 \times 3 \times 2$ mm, a-cut $Nd:YVO_4$ crystal. The left side acting as one mirror of resonator was coated AR at 808 nm ($T > 95\%$) and HR at 1342 nm ($R > 99.9\%$). The right side was coated for AR at 1342/1064 nm, the remaining reflection was as small as possible to suppress the effect of F–P etalon. The reflection of 808 nm was not considered to double pass through the laser medium at this face. Measurement indicated that more than 95% pump light was absorbed. The resonator was plane-concave. The ROC of output coupling mirror was 50 mm. It was coated HR at 1342 nm ($R > 99.9\%$), AR at 1064 nm ($T > 90\%$) and 671 nm ($T > 98\%$). Its plane face was coated AR at 671, 1064, and 1342 nm ($T > 98\%$).

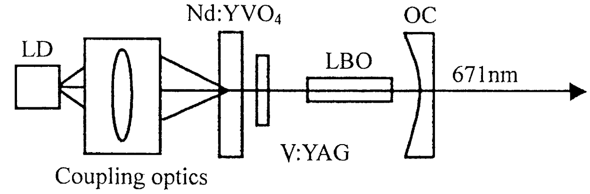


Fig. 2. The setup of experiments.

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 1342 nm. Both sides were coated wideband AR at 1.3 μm. LBO ($2 \times 2 \times 10$ mm) with type-I critical phase matching ($\theta = 86.1^\circ, \phi = 0^\circ$ at 27 °C) was used to intracavity frequency doubling. The effective nonlinear coefficient is 0.817 pm/V. The walk-off angle of 671 nm is 0°, which is favorable to circular light spot. Both sides were coated AR at 671/1342 nm ($R < 0.2\%$). In order to shorten the pulse duration, the length of the cavity was chosen as short as possible. Geometry length of 18 mm was adopted. The linear cavity mode radius in $Nd:YVO_4$ ($\omega_l$), V:YAG ($\omega_s$), LBO ($\omega_n$) was about the same (98 μm). Thus the resonator did not affect the parameter α calculated in Section 2. Red pulses were measured by a TDS1012 digital oscilloscope (100 MHz bandwidth) and a fast Si PIN photodiode with rise time of less than 0.5 ns.

## 4. Results and discussion

When the V:YAG was not inserted into the cavity, the laser was operated in cw at 671 nm with low noise. Maximum output power of 213 mW was obtained at the pump power of 1.6 W.

When the V:YAG was inserted into the resonator, red pulse was achieved. Results of average power of 53 mW, pulse duration (FWHM) of 29.5 ns (Fig. 3), pulse repetition rate of 37.2 kHz (Fig. 4) were obtained at the incident power of 1.6 W. The corresponding peak power and single-pulse energy were 48.3 W and 1.43 μJ, respectively.

Figs. 5–7 showed the relationship between the pulse laser parameters and the pump power. The cw output was also showed in Fig. 5. 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. The minimum duration was 29.5 ns. As observed from these figures, one can obtain different interesting results easily by varying the pump power from near threshold to 1.6 W.

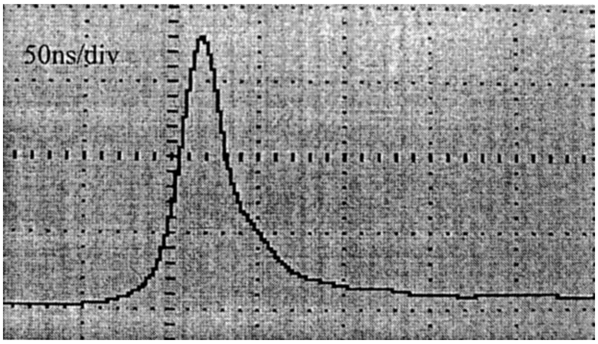


Fig. 3. Oscilloscope trace of a single pulse for red laser at 671 nm.

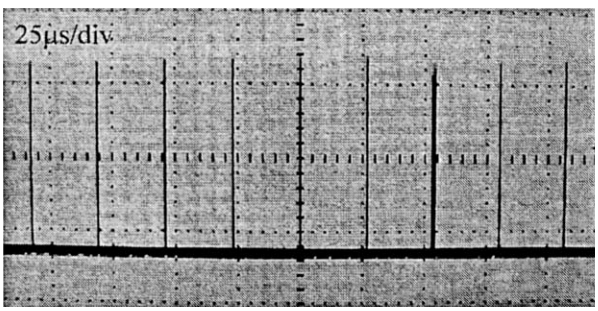


Fig. 4. Oscilloscope traces of a train of pulses for red laser at 671 nm.

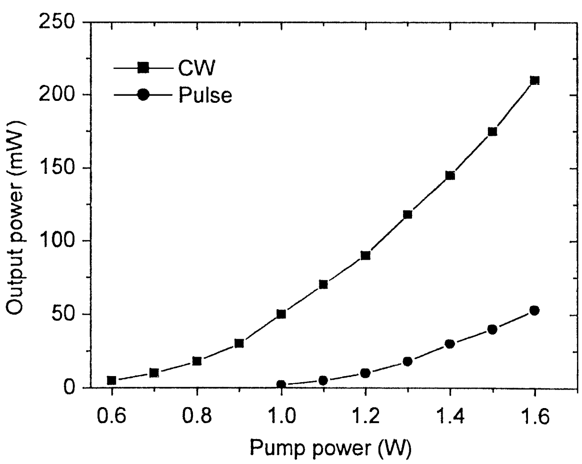


Fig. 5. CW and pulse 671 nm output power versus pump power.

Depolarization by saturable absorber was also observed in the experiments as the Nd:$YVO_4$ pulse green laser passively Q-switched by Cr:YAG and frequency doubling with KTP [4]. When LBO was removed from the cavity, the polarization of fundamental wave changed from about 800:1 to 100:1 by inserting V:YAG into the resonator. Because of the low transmission of the output coupler at 1342 nm, the measurement was not very precise. Despite this, for the total experiments, the polarization of fundamental wave was always parallel to the *c*-axis of Nd:$YVO_4$ independent of the azimuth of V:YAG because of strong linear polarization emission character of birefringent active medium. This is favorable to efficient intracavity frequency doubling.

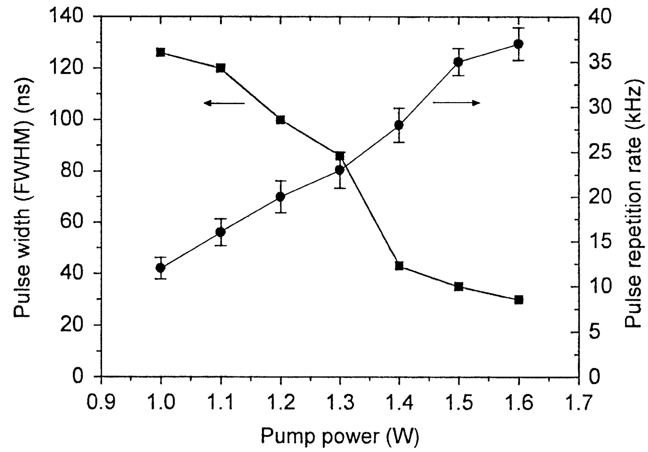


Fig. 6. Pulse duration (FWHM) and repetition rate versus pump power.

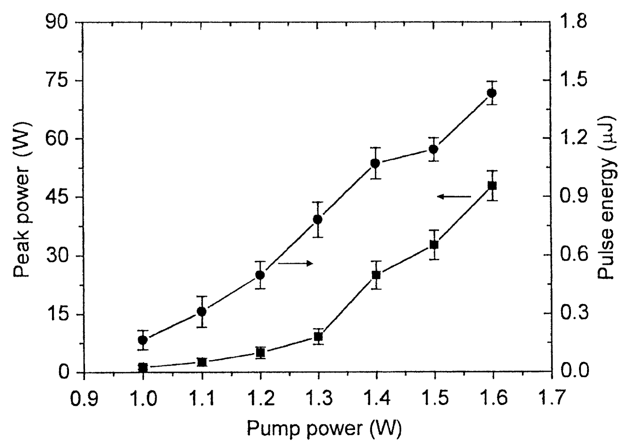


Fig. 7. Pulse peak power and energy versus pump power.

As shown in Fig. 3, 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 Ref. [6]. This is because the red output was not overcoupled. In addition, depolarization was reconfirmed in this structure.

For the fluctuation in the environment, thermal gradient in the crystal (Nd:$YVO_4$, V:YAG and LBO), remaining pump light producing 671 nm laser absorbed by V:YAG, or the diode pump power and spectrum, repetition rate and energy instability of the red pulses were about 10%. By carefully adjusting the pump power near 1.6 W and the temperature of the crystal, stable pulse traces were obtained as shown in Fig. 4. The stability of energy and repetition rate was better than 3% for 4 h.

## 5. Conclusion

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 pulse red pulse laser at 671 nm was obtained. Average output power of 53 mW, pulse duration (FWHM) of 29.5 ns, pulse repetition rate of 37.2 kHz, peak power of 48.3 W and single pulse energy of 1.43 μJ was obtained when the pump power was 1.6 W. Pulses with stable energy and repetition rate was achieved when the pump power and temperature of the crystal were adjusted carefully.

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