LD-pumped high repetition rate Q-switched Nd:YVO_4 laser by using $La_3Ga_5SiO_{14}$ single crystal electro-optic modulator

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A diode-end-pumped electro-optic (EO) Q-switched Nd:YVO_4 laser operating at repetition rate of 10 kpps (pulses per second) was reported. A block of $La_3Ga_5SiO_{14}$ (LGS) single crystal was used as a Q-switch and the driver was a metal oxide semiconductor field effect transistor (MOS-FET) pulser of high repetition rate and high voltage. At continuous wave (CW) operation, the slope efficiency of the laser was 46%, and maximum optical-to-optical efficiency was 38.5%. Using an output coupler with transmission of 70%, a 10-kpps Q-switched pulse train with 0.4-mJ monopulse energy and 8.2-ns pulse width was achieved, the optical conversion efficiency was around 15%, and the beam quality M^2 factor was less than 1.2.

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High repetition rate and high beam quality Q-switched solid-state lasers pumped by laser diode arrays (LDAs) are important new source of high-peak-power radiation for a wide range of applications such as laser ranging, remote sensing, diagnosis, micromachining, material processing, nonlinear optics, and so on[1,2]. Passive Q-switch[3,4] and acousto-optic (AO) Q-switch[5,6] can work at high repetition rate easily, but the passive Q-switch is limited in many fields due to its poor stability, while the AO Q-switch has a tendency to produce long pulse (typically several tens to one hundred nano-seconds). Electro-optic (EO) Q-switch can overcome the shortcomings of passive and AO Q-switches, to get stable short pulses less than 10 ns due to its fast loss change, but the repetition rate obtained is low.

Though difficult, it is possible for EO Q-switch to work at high repetition rate with high-gain medium and small insert-loss EO elements. In recent years, high repetition rate Q-switched lasers based on EO elements have been researched widely. Several EO crystals such as beta-barium borate (BBO), periodically poled lithium niobate (PPLN) and $RTiOPO_4$ (RTP) are used for EO Q-switches at tens kilohertz repetition rate[7−9]. BBO crystal has excellent optical properties and high damage threshold, but it is slightly hygroscopic and must be carefully protected from moisture, like as KD*P, which brings many inconveniences into the fabrication and application; PPLN has a large EO coefficient and a very low quarter wave voltage, but the capability of resisting optical damage is quite feeble; RTP maybe a good choice as high repetition rate EO Q-switch because of low work voltage, high damage threshold, hydrolysis-repellent, and absence of piezoelectric ringing, but RTP is natural birefringent crystal, a same size crystal has to be doubled to compensate for the temperature variation.

In 2003, a novel EO Q-switch based on $La_3Ga_5SiO_{14}$ (LGS) single crystal was reported[10]. LGS has the advantages of large EO coefficient, high optical damage threshold, no water-solubility in air, and so on. Furthermore, its low insert loss at 1064-nm wavelength, stable physical and chemical behaviors, high electric resistivity, and low dielectric constant etc are all excellent properties for EO elements[10]. So it is promising to make EO Q-switch with LGS crystal in the medium power. Recently, based on this LGS single crystal, some EO Q-switched lasers have been reported[11−15], but the repetition rates are all limited at a much low level.

In this paper, we present a high repetition rate Nd:YVO_4 laser Q-switched by LGS single crystal. Nd:YVO_4 is chosen as the laser material because of his high stimulated emission cross-section and relatively short lifetime, which enables the production of relatively short Q-switched pulses with modest pump power. Especially, at high repetition rate operation, the very low oscillation threshold of Nd:YVO_4 is an extraordinary virtue. In addition, Nd:YVO_4 is natural birefringent crystal, the output of which is well polarized. This is an important advantage over the other materials such as Nd:YAG for EO Q-switching, where the polarized beam is needed. The polarized output of Nd:YVO_4 reduces redundant thermal induced birefringence, which compensates its low thermal conductivity partially. At present, almost all of the high repetition rate EO Q-switched solid state lasers are based on Nd:YVO_4 materials.

In our experiments, the EO Q-switched Nd: YVO_4 laser was designed for a sample linear cavity. The cavity length was about 150 mm. The experimental setup is shown in Fig. 1. A planar mirror M_1 with high

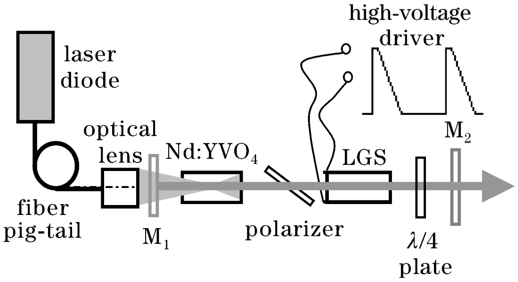

Fig. 1. Schematic diagram of LD end-pumped EO Q-switched Nd:YVO_4 laser.

reflectivity at 1064 nm and high transmission at 808 nm was used as the rear mirror, the transmission of output-coupler (OC) M_2 was variable for obtaining optimal output. The pump source was a fiber coupled 30-W continuous wave (CW) diode laser, the output from the fiber pig-tail was coupled into the rod via a collimating and focal lens combining with a magnification of 1, the coupling efficiency was more than 98%. The Nd:YVO_4 crystal used in the experiments was a $4 \times 4 \times 8$ (mm) quadrate sample with 0.8 at.-% Nd^{3+} doping concentration, which was placed 5 mm from M_1. The absorption coefficient of the sample at 808.5 nm is 31.4 cm^{-1} and the fluorescence lifetime is about 100 μs. The sample was cooled by water through coppery heat-sinkers. The EO LGS single crystal Q-switched was placed between a polarizer and a $\lambda/4$ plate. The LGS single crystal was made in Shandong university, with dimensions of $8 \times 8 \times 37.5$ (mm). The insertion loss of LGS was less than 2%. The transverse EO effect of LGS single crystal was utilized to make a Q-switch and the calculated quarter-wave voltage $V_{\pi/2}$ was 3600 V, but because of the influences of circuit loss and contacting resistance, the effective work voltage was about 4000 V. The EO driver was a homemade 0—20 kHz metal oxide semiconductor field effect transistor (MOS-FET) pulser with a rise time less than 10 ns, the high adjustable voltages were 0—4.5 kV. However in our experiments, the maximum repetition rate limited by the high voltage source used, could be reached 10 kpps at 4000 V.

At first we studied the output performance of this laser without any inserting elements. With the optimal OC with a transmission of 21.6%, we obtained 10.8 W output at pump power of 28 W (output from the fiber pig-tail), the slope efficiency and optical conversion efficiency were 46% and 38.5%, respectively. Figure 2 shows the CW output power as a function of the pump power when the transmission of OC takes variable values.

To successfully actualize pulse increased Q-switching operation, a polarizer and a $\lambda/4$ plate was needed to restrain the laser oscillation before the high voltage pulses were added on the LGS crystal though the output of Nd:YVO_4 was polarized. When the polarizer and LGS crystal were inserted in the cavity orderly, the laser threshold increased and the output decreased slightly by comparison with the results of the empty cavity, as shown in Fig. 3, where, to achieve optimal Q-switching output, the OC with transmission of 70% was used. These results showed that the inserted losses of polarizer and LGS crystal were small due to the linear polarized output of Nd:YVO_4 and high transmission of LGS crystal. The low insert loss and almost absence of thermal induced depolarization were excellent advantages for high repetition rate EO Q-switched lasers. At Q-switched operation, by use of OC with 70% transmission, a maximum output average power of 4.2 W with the shortest pulse width (full-width at half-maximum (FWHM)) of 8.2 ns was obtained at 10 kpps when the pump power output from the fiber pig-tail reached 28 W, corresponding monopulse energy and peak power were 0.42 mJ and 50 kW, respectively, which also was shown in Fig. 3. The slope efficiency was 23%, the maximum optical conversion efficiency was 15%, and the maximum dynamic-static ratio was around 75%.

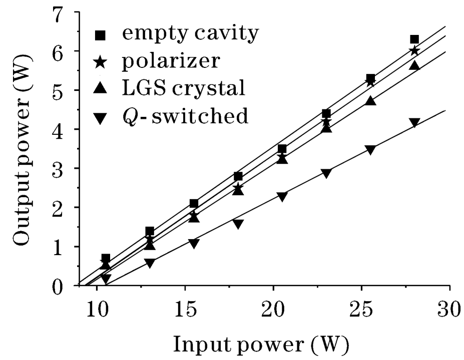

Fig. 3. Q-switched output power as a function of input power in Nd:YVO_4 laser with transmission of 70%.

At lower repetition rate, higher monopulse energy and higher peak power could be obtained due to the longer energy storage time, but the average power decreased correspondingly. Figure 4 shows the Q-switched output performance at different repetition rates, where the pump power is 28 W. From Fig. 4, we can see that the average power increased with the increase of the repetition rate under 8 kpps, above 8 kpps, the average power no longer increased. On the other hand, the pulse energy decreased rapidly with the increase of the repetition rate about above 3 kpps (when the repetition rate lower than 3 kpps, the pulse energy was almost invariable), because the pulse width changed very slightly, the peak power behaved a change tendency similar to the pulse energy.

Furthermore, this Q-switched laser also presented a good beam quality, at maximum output power and 10-kpps repetition rate, the beam size close to the output coupler was about 1.2 mm measured by edge method and

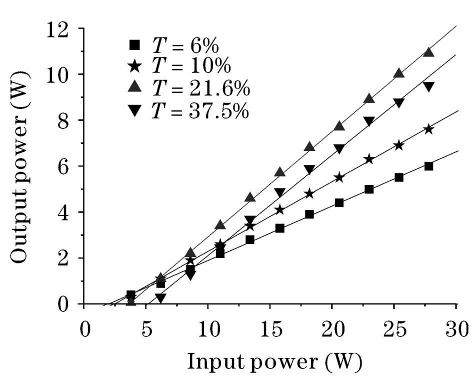

Fig. 2. CW output power versus input power of Nd:YVO_4 laser with variable OC transmissions.

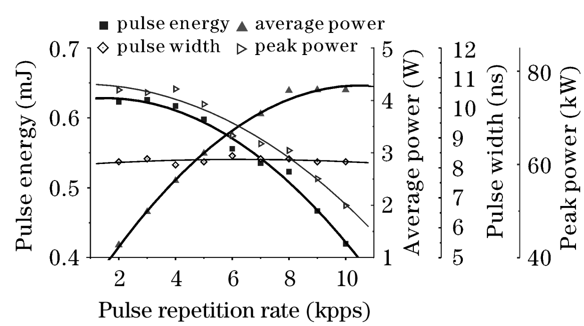

Fig. 4. Q-switched output average power and pulse energy at different repetition rates with pump power of 28 W.

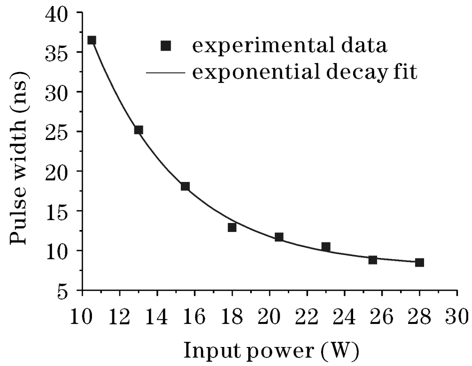

Fig. 5. Q-switched pulse width (FWHM) as a function of input power in Nd:YVO_4 laser.

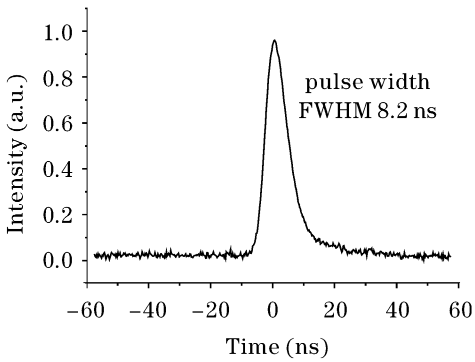

Fig. 6. Q-switched pulse waveform recorded by an oscillograph at 28-W input power.

beam divergence was less than 1.2 mrad, corresponding beam propagation factor M^2 can be derived approximately by the equation $M^2 = D_0\Theta\pi/4\lambda$[16], the value was about 1.13.

Figures 5 and 6 show the pulse width as a function of the input power and the pulse waveform is recorded by an oscillograph, respectively. When the laser overcame the threshold, the average output power increased linearly and the pulse duration decreased according to an exponent law approximately. From Fig. 6, we can see that the pulse fall time is longer than the rise time and a small tail come forth, this is due to the finite relaxation time of the low energy level[17,18]. In addition, noticed in Fig. 3, the threshold of Q-switching operation was slightly larger than that of static state, this can attribute to the damp vibration occurring at the front edge of the high-voltage pulse as shown in Fig. 7. At the beginning of Q-switch, the high voltage was rolling around $V_{\pi/2}$, and then tended to fixedness about 100 ns later, so an inherent loss was introduced, which enlarged the threshold and made the output decline. When designing an EO Q-switch driver, one should take method to minish the amplitude of relaxation oscillation and shorten the relaxation time.

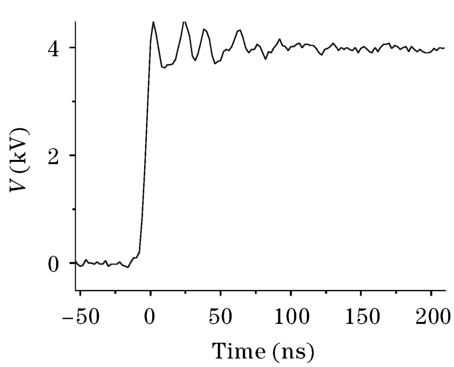

Fig. 7. Damp vibration at the rising edge of the Q-switch high-voltage driving pulse.

In conclusion, we reported a high repetition rate (up to 10 kpps) EO Q-switched Nd:YVO_4 laser based on pulse increased LGS single crystal, using homemade series MOS-FET driver, a pulse train with 0.42-mJ monopulse energy and 8.2-ns pulse width was obtained at maximum input power of 28 W, the optical-optical efficiency was 15% and the dynamic-static ratio was 75%. At repetition rate of 10 kpps, the piezoelectric ringing was almost absent, so Q-switching at higher repetition rate with this LGS crystal is possible with larger power high voltage source.

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