LD-pumped acousto-optic Q-switched Pr:YLF pulsed laser at 604 nm

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We demonstrated an actively acousto-optic Q-switched pulsed laser based on Pr:YLF at 604 nm. A 604 nm continuous-wave (CW) laser with maximum output power of 3.84 W was achieved for the first time. The Q-switched laser with a maximum average output power of 0.384 W, a narrowest pulse duration of 44.5 ns, a maximum single pulse energy of ~64.1 μJ, and a maximum peak power of ~1.44 kW were obtained at a repetition rate of 6 kHz. To the best of our knowledge, this was the first report of such narrow pulse duration, high power and high energy Q-switched pulsed laser at 604 nm. The beam quality M2 x and M2 y factors were measured to be 2.87 and 2.40 respectively. The results shown that acousto-optic Q-switching was a promising method to obtain pulsed lasers.

Keywords: 604 nm; Acousto-optic; Q-switched; pulsed laser; Pr :YLF crystal.
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1. Introduction

In recent years, visible lasers have a wide range of applications in many fields [1-4]. Among them, lasers with wavelengths of around 600 nm have been used in biomedicine, astronomy, lasers, metal processing, deep ultraviolet generation, communications [5-10]. Based on the characteristics of lasers with a wavelength of around 600 nm, such as: high absorption efficiency of blood proteins [5], we believe that a high-performance 604 nm laser with narrow pulse duration and high energy will promote its applications in medical treatment.

The CW 604 nm laser has been mentioned many times in previous reports. In 2014, under the action of a linearly polarized 2ω-OPSL pump source with an output power of 5 W at 479 nm, Metz et al. obtained a CW 604 nm laser based on Pr:YLF crystal, whose maximum output power was 1.5 W [11]. In 2016, Luo et al. obtained a CW 604 nm laser with a maximum output power of 0.6 W, the pump source was a commercially available InGaN blue LD with a wavelength of 444 nm [12]. In the same year, Fibrich et al. demonstrated a CW 604 nm laser with output power exceeding 1 W, the pump source used was a fiber-coupled blue laser diode module from Necsel company [13]. In 2022, the maximum output power of 3.28 W was obtained at wavelength of 604 nm based on a ~0.12 at. % doping Pr:YLF crystal [14]. To the best of our knowledge, this was the maximum output power reported so far for a CW 604 nm laser.

There were two main methods to obtain lasers with narrow pulse duration and high pulse energy: mode-locking and Q-switching. Among them, Q-switching includes passive Q-switching and active Q-switching [15,16]. Passively Q-switched praseodymium-doped (Pr^{3+}) all-fiber pulsed lasers at 604 nm have been reported. In 2016, Li et al. proposed a passively Q-switched praseodymium (Pr^{3+})-doped all-fiber pulsed laser at 604 nm based on saturable absorbers of WS_2 and MoS_2, the narrowest pulse durations of the corresponding pulsed lasers were 435 ns and 602 ns respectively. The maximum average output power were 0.7 mW and 0.6 mW respectively, and the maximum pulse energy were 6.4 nJ and 5.5 nJ respectively [17]. In 2017, Lin et al demonstrated a passively Q-switched 604 nm praseodymium (Pr^{3+})-doped all-fiber laser pulsed laser, with a Bi_2Se_3 as saturable absorber. The narrowest pulse duration, the maximum average output power and the maximum pulse energy of the pulsed laser were 494 ns, 0.5 mW and 3.1 nJ respectively [18].

Passively Q-switched Pr:YLF pulsed lasers at 604 nm have been reported. In 2017, using a topological insulator (TI) Bi_2Se_3 nanosheet material as a saturable absorber, Cheng et al. proposed a passively Q-switched 604 nm pulsed laser based on Pr:YLF. The narrowest pulse duration, the maximum average output power and the maximum pulse energy of the pulsed laser were 802 ns, 26 mW and 0.2 μJ respectively [19]. One year later, Luo et al. proposed passively Q-switched dual-wavelength (607 nm/604 nm) pulsed laser based on Pr:YLF, with a saturable absorber of a few-layer Bi_2Se_3. The narrowest pulse duration, the maximum pulse energy and peak power were 263 ns, 0.19 μJ and 0.71 W respectively [20]. In 2019, Tian et al. demonstrated passively Q-switched dual-wavelength (607 nm/604 nm) pulsed laser and dual-wavelength pulse vortex laser, The narrowest pulse duration and maximum average output power of dual-wavelength pulsed laser were 409 ns and 63 mW respectively. The narrowest pulse duration and maximum average output power of dual-wavelength pulse vortex laser were 545 ns and 13 mW respectively [21]. Actively Q-switched Pr:YLF dual-wavelength pulsed lasers have been reported. In 2023, Jin et al. proposed a mechanism to obtain dual-wavelength (604 nm/639 nm) pulsed laser based on Pr:YLF with an F-P etalon and an acousto-optic modulator (AOM). The pulse duration, the energy of single pulse and the maximum output power at the PRF of 10 kHz were 100 ns, 4.9 μJ and 98 mW respectively [22].

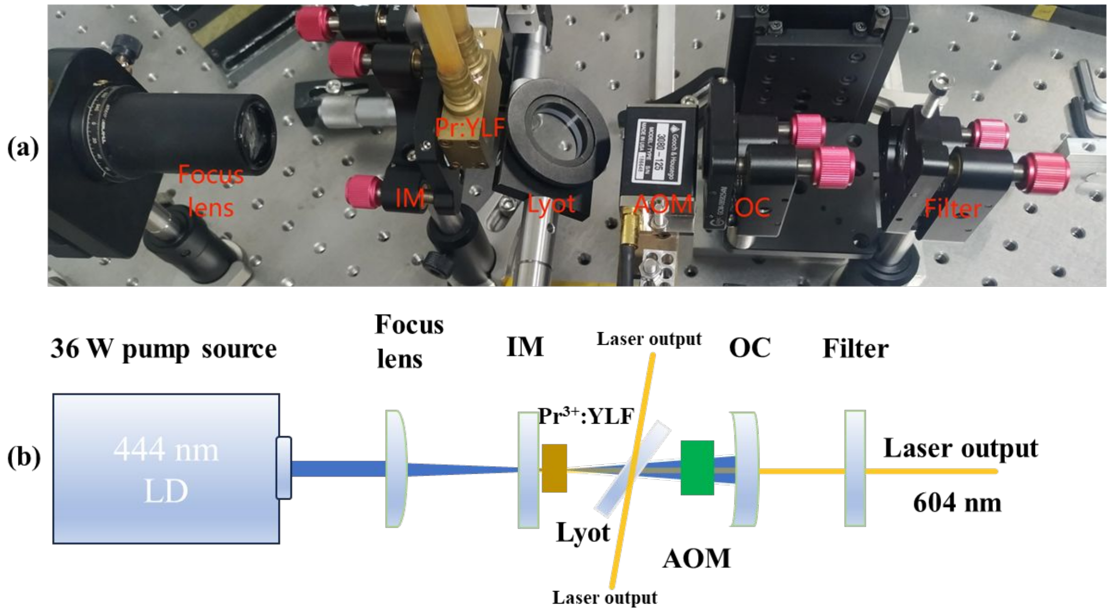

Fig. 1. (a) Physical diagram of experimental setup (pump source omitted), (b) Schematic diagram of experimental setup

However, Q-switched 604 nm pulsed laser with narrower pulse duration, higher power, and higher energy have not yet been reported.

In this work, we proposed an actively Q-switched Pr:YLF laser at single wavelength of 604 nm with an AOM for the first time. A Lyot filter was used to select the oscillating laser in the resonant cavity. In CW laser operation, we achieved the maximum output power of 3.84 W at 604 nm. We obtained the maximum average output power, narrowest pulse duration, maximum single pulse energy and peak power at repetition rates of 6 kHz (0.384 W, 44.5 ns, 64.1 μJ, 1.44 kW), 20 kHz (0.408 W, 56 ns, 20 μJ, 0.36 kW) and 50 kHz (0.454 W, 88 ns, 9.1 μJ, 0.1 kW) in Q-switched operation. The beam quality M^2 factors were measured to be 2.87 (horizontal direction) and 2.40 (vertical direction).

2. Experimental setup

As shown in Fig. 1, a LD array with a peak wavelength of 444 nm and a maximum output power of 36 W was used as pump source. In our experiments, we measured an absorbed pump power efficiency of about 50%, with the maximum absorbed pump power of 18.06 W. The Focus lens was an aspherical plano-convex lens with a focusing length of 75 mm. Under the action of the Focus lens, the pump beam was focused into the crystal. The linear resonant cavity consists of an input mirror (IM) and an output coupling mirror (OC). The IM was an end-coated plane mirror, and the OC was an end-coated plano-concave mirror with a curvature radius of 100 mm. The Pr:YLF crystal was encased in a copper block cooled with 18 ℃ circulating water. The Pr:YLF was an a-cut crystal, with a 0.2 at. % doping concentration of Pr^{3+} ions, and it has a length of 15 mm, with 3×3 mm^2 polished facets.

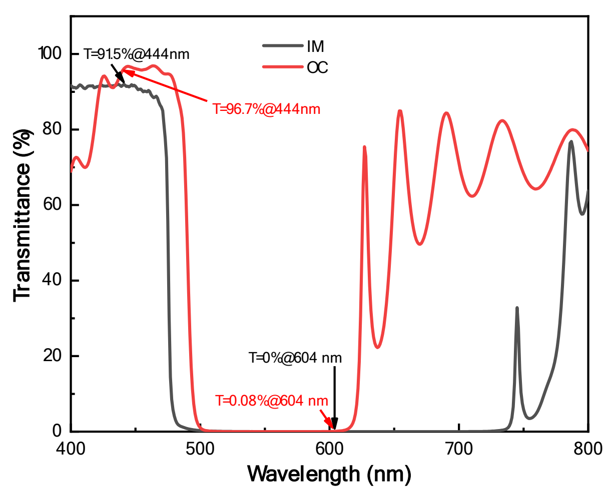

Fig. 2. Optical transmittance properties of IM and OC.

In CW laser operation, there was serious competition between the 604 nm laser in π-polarization direction and the 607 nm laser in σ-polarization direction, it was difficult for the coupling mirrors (IM and OC) to suppress the output of 607 nm laser efficiently. In order to solve this problem, we inserted a Lyot filter with thickness of 2 mm at Brewster's Angle ~56° in the resonant cavity for the selection of the 604 nm laser.

The AOM used in the experiment was the 3080-125 from Gooch & Housego, which has a modulation range of 400 nm to 850 nm. Filter was used to filter out pump laser, which has a reflectivity of about 100% at 444 nm and a transmittance of about 90% at 604 nm.

As can be seen from Fig. 2, the transmittance of IM at 444 nm was 91.5%, and the transmittance at 604 nm was almost 0%. The transmittance of OC at 444 nm was about 96.7%, and the transmittance at 604 nm was about 0.08%.

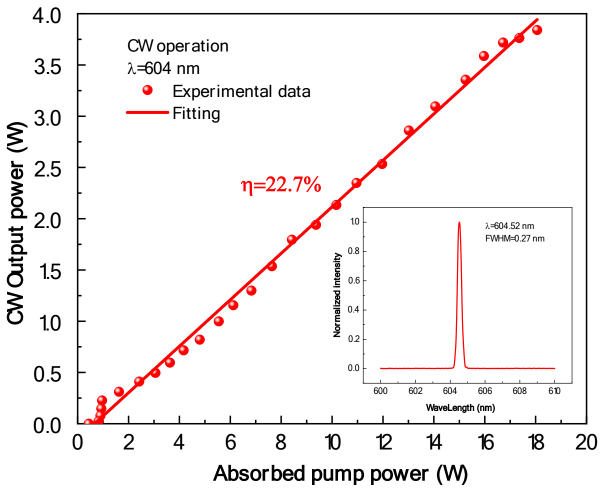

Fig. 3. CW output laser characteristics at 604 nm.

3. Results and discussions

In CW laser operation, we inserted no Lyot into the resonant cavity in the previous experiments. when the absorbed pump power was low, only 604 nm laser was output. as the absorbed pump power increased, 604 nm and 607 nm laser were output simultaneously, and finally only 607 nm laser was output. The emission cross sections at wavelength of 604 nm and 607 nm were ~1.96×10^{-19} cm^2 and ~1.57×10^{-19} cm^2 respectively [23], which was one of the possible reasons for the experimental results. The CW output power versus absorbed pump power with no AOM in experimental setup was presented in Fig. 3. No significant CW output power saturation was observed. The threshold absorbed pump power was 0.436 W, and the slope efficiency was 22.7%. The maximum CW output power at 604 nm was 3.84 W at maximum absorbed pump power. The inset shown the spectrum of CW laser at 604 nm, the central wavelength was 604.52 nm, and the full width at half maximum (FWHM) was about 0.27 nm. We measured the power and spectrum by an Thorlabs S425C-L (detection sensitivity > 2 mW) and an Advantest Q8384 Optical Spectrum Analyzer respectively.

We recorded the experimental results in actively Q-switched operation, which showed that the range of experimental tunable repetition rates were 6 kHz to 50 kHz. The average output power versus absorbed pump power at different repetition rate of 6 kHz, 20 kHz and 50 kHz were presented in Fig. 4. With the same absorbed pump power, the average output power became gradually larger as the repetition rate within the range of tunable repetition rate increased, and no saturation of the average output power was observed. Under the maximum absorbed pump power, the maximum average output powers at repetition rates of 6 kHz, 20 kHz and 50 kHz were 0.384 W, 0.408 W and 0.454 W respectively. At different repetition rates of 6 kHz, 20 kHz and 50 kHz, the corresponding slope efficiencies were 2.22%, 2.51% and 2.77% respectively. We believe that a better coupling system (mirrors) and a crystal with anti-reflection coating on end faces in experiment will improve the output power, as a result, a high slope efficiency will be obtained.

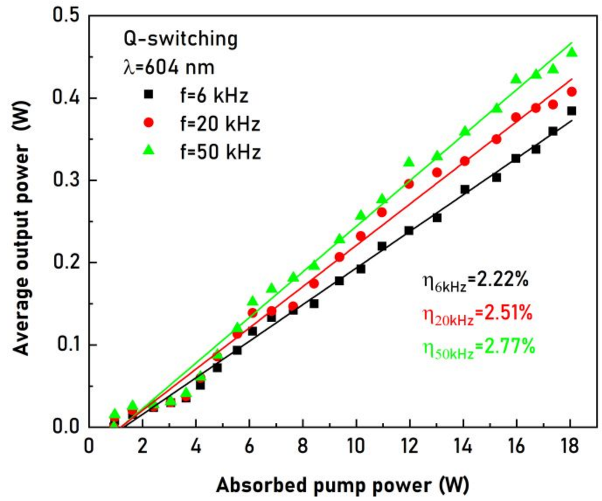

Fig. 4. Average output power versus absorbed pump power under different repetition rates of 6 kHz, 20 kHz and 50 kHz.

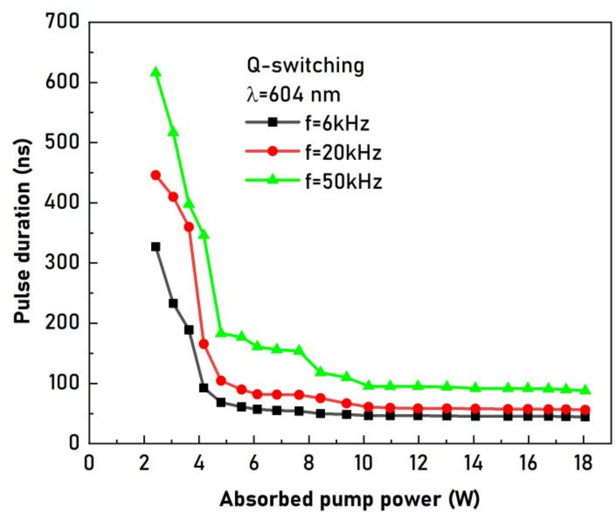

Fig. 5. Pulse durations versus absorbed pump power under different repetition rates of 6 kHz, 20 kHz and 50 kHz.

As shown in Fig. 5, we recorded the pulse durations versus absorbed pump power at repetition rates of 6 kHz, 20 kHz and 50 kHz. Under the same repetition rate, as the absorbed pump power increased, the pulse duration gradually decreased. Under the same absorbed pump power, the smaller the repetition rate within the range of tunable repetition rate, the narrower the pulse duration. At the maximum absorbed pump power, the pulse durations corresponding to 6 kHz, 20 kHz and 50 kHz repetition rates were 44.5 ns, 56 ns and 88 ns respectively. The results were consistent with the law of dynamic evolution of population inversion density and photon density in the cavity at different repetition rates during the Q-switching operation. For example: when the repetition rate was the minimum value of 6 kHz, the population inversion density at upper energy level was largest, and the photon density in the cavity evolved at the fastest speed, and the pulse duration was narrowest.

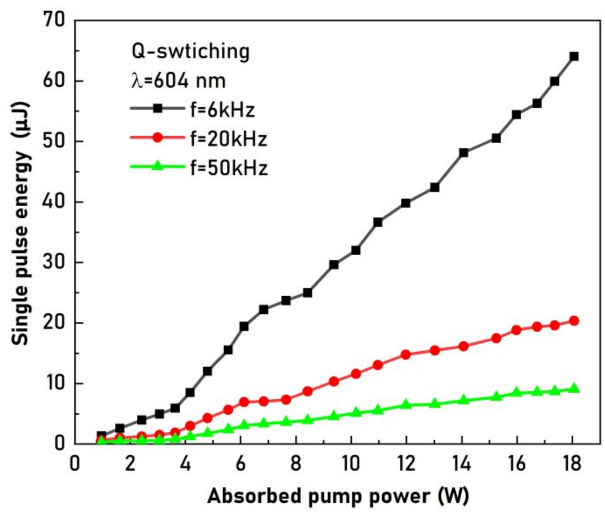

Fig. 6. Single pulse energy versus absorbed pump power under different repetition rates of 6 kHz, 20 kHz and 50 kHz.

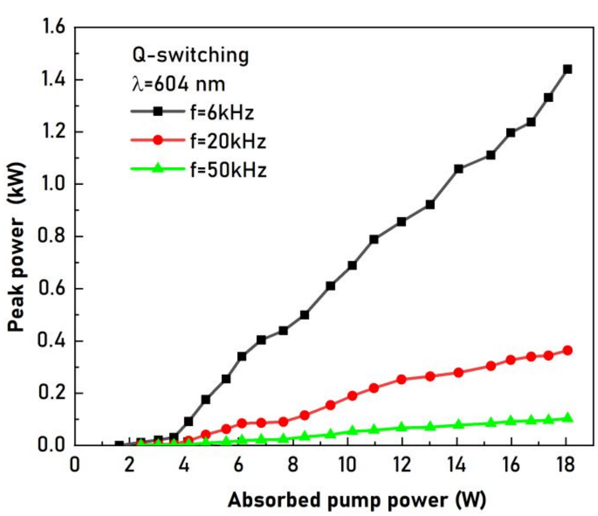

Fig. 7. Peak power versus absorbed pump power under different repetition rates of 6 kHz, 20 kHz and 50 kHz.

According to the equations of $E=P/f$ and $P_{peak}=E/\tau$ [24], where E, P, f, P_{peak} and τ were single pulse energy, average output power, repetition rate, peak power, and pulse duration respectively. As shown in Fig. 6, under the same absorbed pump power, the smaller the repetition rate within the range of tunable repetition rates, the greater the single pulse energy. At the maximum absorbed pump power, the maximum single pulse energy corresponding to repetition rates of 6 kHz, 20 kHz and 50 kHz were 64.1 μJ, 20 μJ and 9.1 μJ respectively.

As shown in Fig. 7, under the same absorbed pump power, the smaller the repetition rate within the range of tunable repetition rate, the greater the peak power. At the maximum absorbed pump power, the maximum peak power reached watt level, which corresponding to repetition rates of 6 kHz, 20 kHz and 50 kHz were 1.44 kW, 0.36 kW and 0.1 kW respectively. The single pulse energy and peak power were maximum values of Q-switched 604 nm pulsed laser reported so far.

The traces of a typical oscilloscope pulse trains and temporal pulse profile corresponding to three repetition rates at maximum absorbed pump power were shown in Fig. 8. It can be seen that the 604 nm pulsed laser was relatively stable at actively Q-switched operation with an AOM at repetition rates of 6 kHz, 20 kHz and 50 kHz. We recorded experiment data by an oscilloscope from Agilent DSO-X 2012A.

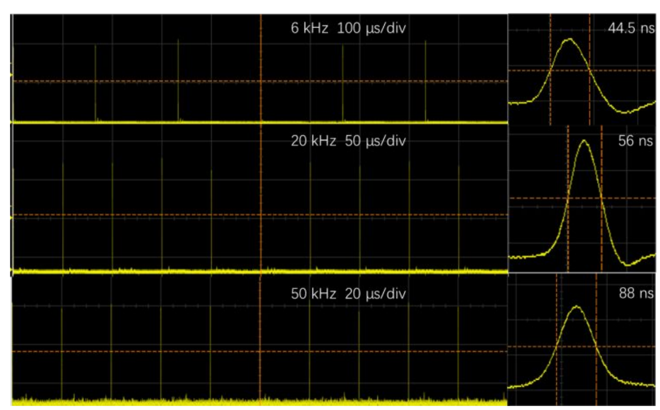

Fig. 8. Typical oscilloscope traces of the pulse trains and temporal pulse profile under different repetition rates of 6 kHz, 20 kHz and 50 k.

Fig. 9 presented the beam quality M^2 factors and beam profile under actively Q-switched operation with an AOM at repetition rate of 6 kHz. The beam quality M^2 factors in the horizontal and vertical directions were 2.87 and 2.4 respectively. The inset was the beam profile captured by a CCD camera, the results showed the formation of a Gaussian-like distribution. We believe that the thermal effects of the crystal has a great impact on the beam quality, and a better control of the crystal temperature will improve the quality factors of the beam.

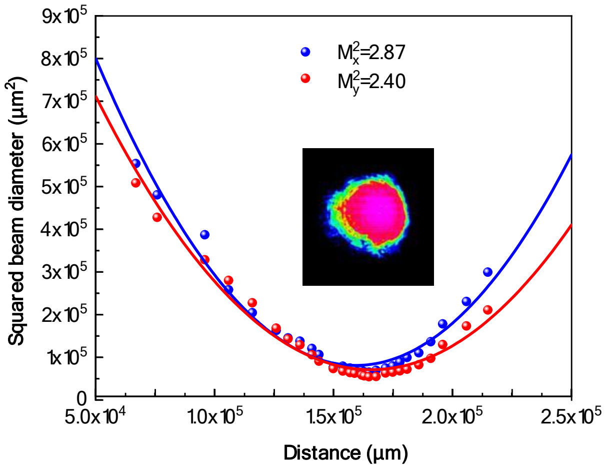

Fig. 9. Beam quality M^2 factors at 604 nm and beam profile captured by CCD camera.

4. Conclusion

We demonstrated an actively Q-switched Pr:YLF laser at single wavelength of 604 nm with an AOM for the first time. In our experiments, we obtained the maximum CW output power of 3.84 W at 604 nm reported so far. The characteristics of Q-switched pulsed laser at different repetition rates of 6 kHz, 20 kHz and 50 kHz was compared. Under the maximum absorbed pump power, the pulse duration, average output power, peak power and single pulse energy in Q-switched operation at repetition rate of 6 kHz were 44.5 ns, 384 mW, 1.44 kW and 64.1 μJ respectively. As far as we know, there was no report on such narrow pulse duration, high power and energy Q-switched pulsed laser at 604 nm. The pulse trains recorded by the oscilloscope were relatively stable. Apart of this, the beam quality M2 x and M2 y of the Q-switched 604 nm laser were 2.87 and 2.4 respectively. This work provided a method to obtain 604 nm pulsed laser with narrow pulse duration, high power and energy, which promoted the application of orange pulsed lasers in various fields. In future work, we believe that a 604 nm pulsed laser with narrower pulse duration, higher power and energy will be achieved by optimizing the experimental setup with a higher power pump source.

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Disclosures. The author declares no conflicts of interest.

Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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