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Single longitudinal mode Q-switched operation of Pr:YLF laser with pre-lase and Fabry–Perot etalon technology

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HIGHLIGHTS

- First demonstration of a SLM Q-switched Pr:YLF laser operating at 639.5 nm.
- The output energy was 3.94 μJ, with pulse width of 81.1 ns and PRF of 10 kHz.
- The SLM emission linewidth was 33 MHz at the maximum output.

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Q-switching
Single-longitudinal mode
Pre-lase
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ABSTRACT

This letter presents a visible light direct oscillation Q-switched single-longitudinal-mode Pr:YLF laser output at 639.5 nm by using the Q-switching pre-lase technology combined with the Fabry–Perot etalon. The experimental results show that the single-longitudinal-mode oscillation can be generated in a low-energy injection state. The proposed laser overcomes the problem associated with the Q-switched Pr:YLF laser, which cannot produce high-efficiency single longitudinal mode owing to the high loss of inserted elements. With the proposed laser, a Q-switched single-longitudinal-mode pulsed laser output has been achieved with 3.94 μJ energy and 81.1 ns pulse duration at a repetition of 10 kHz. The spectral linewidth of single-longitudinal-mode pulse laser was approximately 33 MHz.

1. Introduction

Owing to their narrow spectral linewidth output with low phase noise, single-longitudinal-mode lasers have been embraced in many fields such as in the laser Doppler velocimetry, gravitational wave detection, Doppler Lidar, and optical communication [1–4]. The single-longitudinal mode pulsed radiation in the visible part of a spectrum may have great potential for light sources as well as spectroscopy and medicine. Currently, there are several methods used to realize the single-longitudinal-mode output of solid-state laser, such as: inserting two Fabry–Perot (F-P) etalons, circular cavity, and twisted-mode cavity [5–7]. However, these lasers have larger insertion losses that lead to serious energy losses compared to other technologies. The pre-lase Q-switching technology was a unique one in which the "injected seed signal" was provided by itself and the Q-switched single-longitudinal mode pulse was built up from a relaxation oscillation "seed pulse" [8]. Sooy suggested that a slowly opening Q-switch will reduce the number of longitudinal-mode oscillations [9]. The selection of single-longitudinal-mode in pre-lase technology was realized by the above method. Currently, this technique is being widely used in many lasers for research [10–13].

The most efficient lasing in the visible region was achieved with Pr^{3+} doped fluoride materials, particularly Pr^{3+} doped YLF (LiYF4), that provide rich laser emission in optical spectrum (479, 522, 604, 639, and 720 nm) [14–18]. However, no reports currently exist for visible high-repetition Q-switched single-longitudinal-mode lasers using Pr:YLF crystals. Based on our information, there was only one research which uses continuous-wave (CW) single-longitudinal-mode laser at 640 nm with Pr:YLF crystal [19]. Recently, the development of Pr^{3+} doped lasers was mainly limited by the lack of high-power pump sources. In the case of low output power, more mode selection elements were inserted into the laser cavity resulting in high losses in the cavity and a great reduction in the final output power of the Q-switched single-longitudinal mode. Therefore, it is significant to research the high repetition Q-switched single-longitudinal mode Pr:YLF laser in low-energy injection. In this study, we obtained a diode-pumped acousto-optic Q-switched single-longitudinal-mode laser at a pulse repetition rate of 10 kHz. The corresponding single pulse energy, pulse

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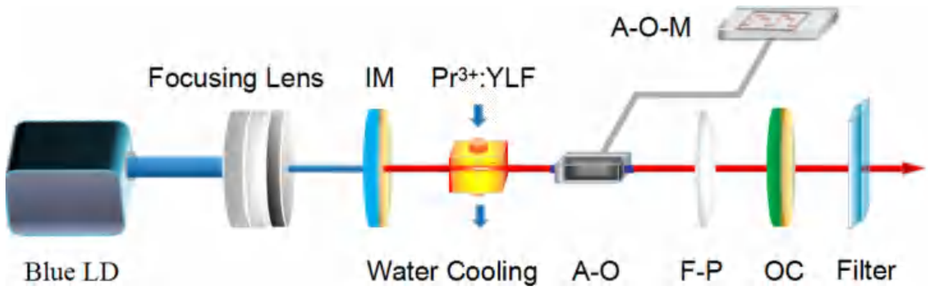

Fig. 1. Schematic of pre-lase single-longitudinal mode Pr:YLF laser.

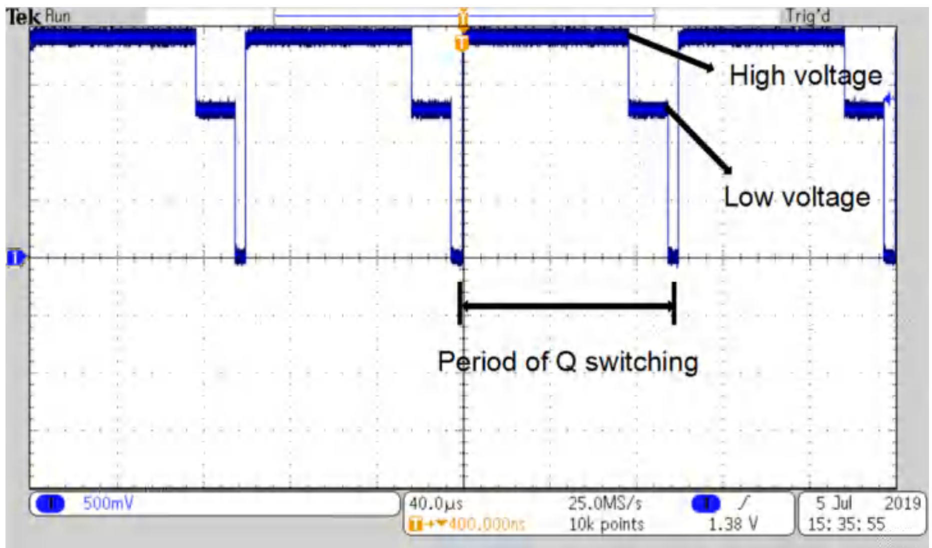

Fig. 2. Two step signal diagram produced by signal modulator.

peak power, and pulse width were 3.94 μJ, 48.5 W, and 81.1 ns, respectively.

2. Experimental setup

Fig. 1 shows the schematic of the single-longitudinal-mode Pr:YLF Q-switched laser. The resonator cavity was composed of an input mirror (IM), an a-cut Pr:YLF crystal as the gain medium, a F-P etalon, an acousto-optic crystal, and an output coupler (OC). The pump source was an InGaN laser diode with an emission wavelength of 443 nm and a maximum output power of about 8 W; the diameter beam waist was 200 μm. The pump beam from the laser diode was collimated using a focusing lens system. The laser resonator was a plano-concave cavity. The highly reflective mirror IM was coated for a reflectivity of 99.8% at 639.5 nm and has a maximum transmission at 443 nm. The OC was employed with transmissions of 2% at 639.5 nm and the curve radius was 100 mm. The laser active medium was an uncoated a-cut 0.5 at.% Pr^{3+}:YLF crystal (3 mm × 3 mm × 5 mm). Both end faces of the Pr:YLF crystal were polished and uncoated. The laser crystal was wrapped with indium foil to improve its thermal contact and mounted in a water-cooled copper holder. The water-cooling system maintained its temperature at about 22 °C. The Q-switch employed an acousto-optic quartz crystal, and the signal was generated by the acousto-optic modulator. The acousto-optic modulator produces a two-step signal comprising high-and low-voltage signals, whose voltage and duration were controllable. A glass plate with a thickness of 0.3 mm, acting as a F-P etalon, was inserted in the cavity to improve single-longitudinal-mode selection. The filter was used to block the pump light. Through experiments and theoretical calculations, the effective cavity length between input mirror and output mirror was found to be approximately 95 mm.

3. Experimental results and discussion

When no mode-selection element was introduced, free-running operation of the multi-longitudinal -mode CW output was carried out with emission at 639.5 nm with a maximum output power of 789 mW. As shown in Fig. 3(a), multi-longitudinal-mode oscillations were observed with a scanning Fabry–Perot interferometer (SA210-5B, Thorlabs) with a free spectral range of 10 GHz. The minimum finesse was 150 and resolution was 67 MHz. According to the cavity length, the longitudinal-mode spacing was about 1.57 GHz. It can be seen that there were about six oscillation longitudinal modes in the optical system. To suppress the multi-longitudinal-mode oscillation and achieve the single- longitudinal-mode Q-switched operation, the acousto-optic Q-switch, the two step signal modulator, and a F-P etalon were inserted. The single-longitudinal-mode selection of the pre-lase Q-switching technology resulting from a slow build up from the pre-pulse that underwent N passes through the F-P etalon, had its bandwidth significantly narrowed [9]. The key for achieving the single-longitudinal-mode output laser was the two-step signal modulator. There were some details that needed to be noted in the investigation. The first was that partially opening the Q-switch, which was set at a level such that the laser operates at just above the threshold makes the longitudinal mode of the near-center frequency start oscillating. This part was controlled by the low-voltage Q-switch loss. Second, extending the pre-pulse lengthens the duration of longitudinal-mode selection until the single-longitudinal mode was established. This part was controlled by the low-voltage Q-switch turn-on time. After setting the parameters of the two step signal modulator and the angle of F-P etalon, the Q-switched

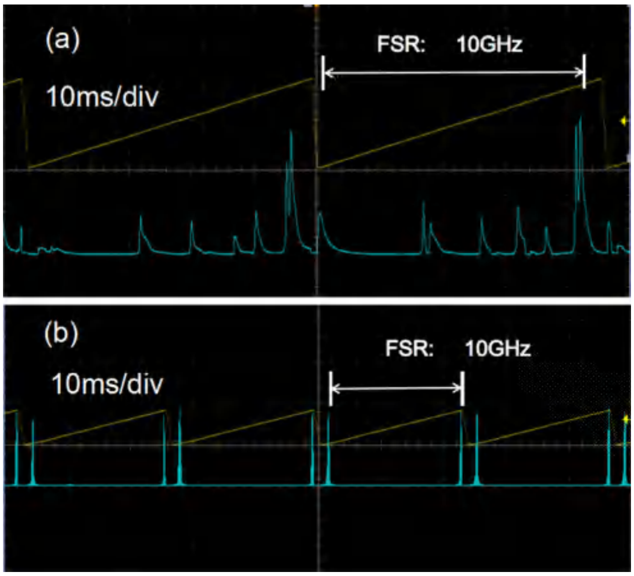

Fig. 3. Measurement results of the Fabry–Perot interferometer. (a) CW laser with the multi-longitudinal -mode; (b) Q-switched laser with the single-longitudinal-mode.

single-longitudinal-mode laser output was achieved. The double step signal diagram of the signal generator is shown in Fig. 2.

The spectral characteristic of the single-longitudinal-mode laser pulse was analyzed by using two scanning F-P interferometers with a free spectral ranges of 10 GHz (SA210-5B, Thorlabs) and 1.5 GHz (SA200-5B, Thorlabs) with minimum finesse of 200 and resolution of 7.5 MHz. Fig. 3(a) and (b) show the measurement results of the CW output and Q-switched single-longitudinal mode pulse output observed with the free spectral range of 10 GHz. For the laser that was operated on a single-longitudinal-mode, it can be seen that there was longitudinal mode oscillation at every free spectral range of the F-P interferometer. The spectral range of 1.5 GHz was used to measure the linewidth of the single-longitudinal-mode pulse laser. According to previous reports, it was assumed that the waveform was Lorentzian spectral which was based on the approximate solution of the linewidth. Using the collected data and processing them to demonstrate, they were all achieved by the software program [19,20]. At the lasing threshold and the maximum output, we calculated spectral linewidths of 28 MHz and 33 MHz as shown in Fig. 4(a) and (b).

Fig. 5 shows the relationship between the input current and pump power as well as absorbed pump power. The crystal absorbed slope efficiency was about 38.4%. The effect of different input current on pulse laser performance was studied on the basis of single-longitudinal-mode operation. Fig. 6 shows the relationship between the output pulse energy and pulse width as well as absorbed pump power which was measured at 10 kHz. In the investigation, we observed single-longitudinal mode operation when the pump power reached the maximum value at 10 kHz. At the absorbed pump power of 2.8 W and repetition frequency of 10 kHz, the maximum single-longitudinal mode output pulse energy of 3.94 μJ was obtained under the single-longitudinal-mode operation. Correspondingly, the pulse width and pulse peak power were about 81.1 ns and 48.5 W. Fig. 7 shows the pulse width with maximum absorbed pump power of 2.8 W at 10 kHz.

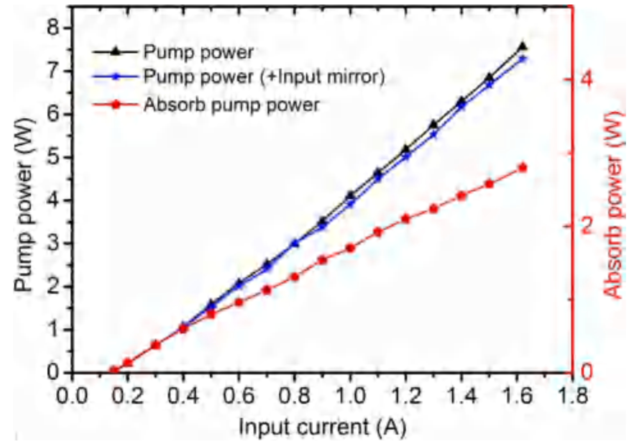

Fig. 5. Relationship between input current and pump power as well as absorb power.

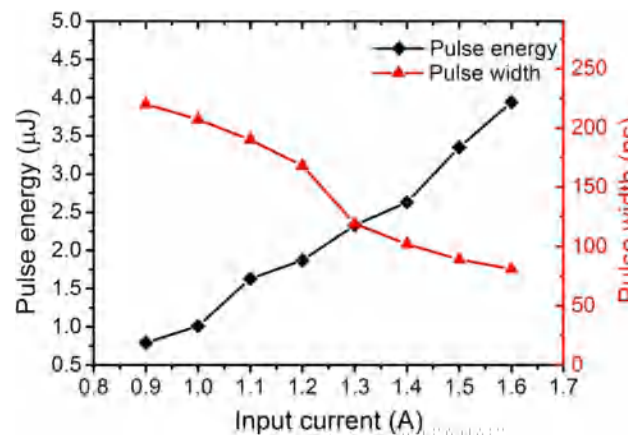

Fig. 6. Pulse energy and pulse width varying form the input current for the Q-switched lasers at 10 kHz.

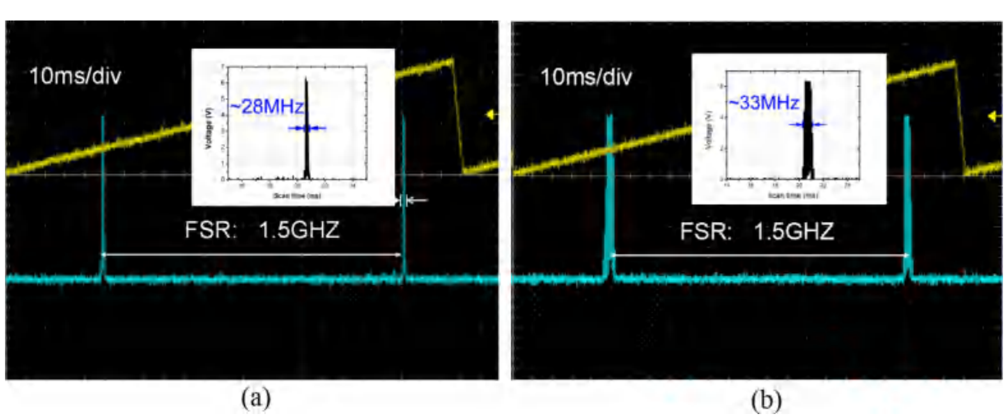

Fig. 4. Measured linewidths of the single-longitudinal-mode laser. (a) At the lasing threshold; (b) at the maximum output.

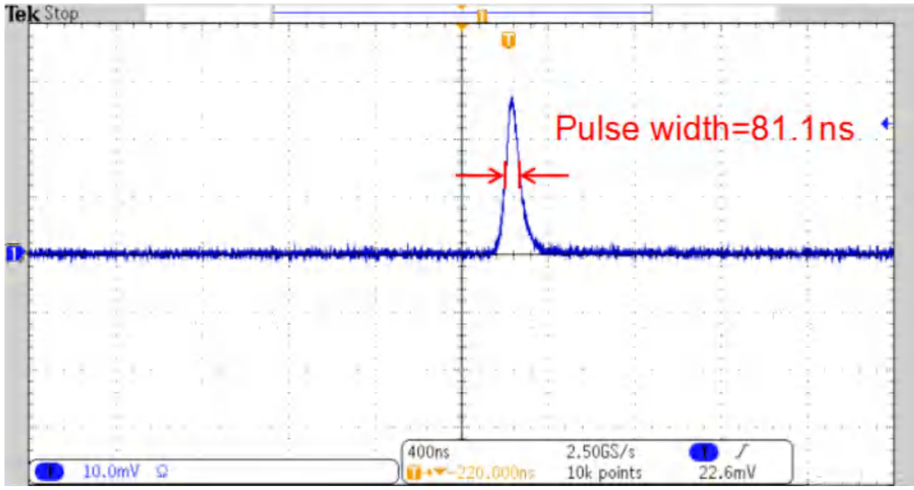

Fig. 7. Oscilloscope trace of the single-longitudinal mode laser pulse at 10 kHz.

4. Conclusion

In conclusion, we demonstrated a single-longitudinal-mode Q-switched operation of Pr:YLF laser with pre-lase and Fabry–Perot etalon technology. The narrow linewidth single-longitudinal-mode operation was achieved and analyzed using scanning F-P interferometer. At the lasing threshold and the maximum output, the measured single-longitudinal mode laser spectral linewidths were 28 MHz and 33 MHz. At a absorbed pump power of 2.3 W and repetition frequency of 10 kHz, the maximum single- longitudinal-mode output pulse energy of 3.94 μJ was obtained. Correspondingly, the pulse width and pulse peak power were about 81.1 ns and 48.5 W, respectively.

CRediT authorship contribution statement

Long Jin: Conceptualization, Methodology, Software, Investigation, Writing - original draft. **WeiCheng Dai:** Validation, Formal analysis, Visualization, Software. **YongJi Yu:** Resources, Writing - review & editing, Supervision, Data curation. **Yuan Dong:** Resources, Writing - review & editing, Supervision, Data curation. **GuangYong Jin:** Resources, Writing - review & editing, Supervision, Data curation.

Declaration of Competing Interest

The authors declared that they have no conflicts of interest to this work. We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.optlastec.2020.106294.

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