

Research Article

LD-pumped Nd: YAG Electro-optic Q-switched Laser and Its KTP Extra-cavity Frequency-doubling Characteristics

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Abstract

An Nd: YAG electro-optic Q-switched laser side-pumped by a laser diode and its extra-cavity frequency-doubling characteristics are reported in this paper. The laser employs a KD*P crystal as the electro-optic Q-switch and uses a combination of a 1/4 wave plate and a polarizer to achieve precise Q-switch control. Under the operating conditions of the pump power of 80W, the 1064 nm laser output with a pulse width of 10ns and a single-pulse energy of 3μJ was obtained, with a peak power of 300W. By inserting a 15mm long KTP frequency-doubling crystal outside the cavity, a 532nm single-pulse green of 1.75μJ was achieved with a frequency-doubling conversion efficiency of 58.3%. This experiment achieved high peak power pulsed output from an all-solid-state electro-optic Q-switched laser, with excellent pulse stability and energy fluctuations of less than ±1%. The results demonstrate that the KD*P crystal, as an electro-optic Q-switch, enables precise Q-switching control and generates laser output with narrow pulse width. Furthermore, the frequency-doubling crystal KTP is highly suitable for frequency doubling 1064nm laser radiation, achieving high conversion efficiency at moderate power densities. This study also effectively addressed potential thermal effects during laser operation by implementing a water-cooling system and optimized heat sink design, which successfully controlled the temperature of the Nd: YAG crystal, KD*P electro-optic crystal, and KTP frequency-doubling crystal.

Keywords

Side-pumping, Electro-optic Q-switching, Nd: YAG Laser, Extra-cavity Frequency-doubling, KTP Crystal

1. Introduction

Diode laser (LD) pumped solid-state lasers (DPSSL) have become a research hotspot in modern laser technology due to their advantages such as high efficiency, long lifespan, and compact structure [1-5]. Among these, Q-switching technology is one of the key methods for generating high peak power pulsed lasers. Compared with acousto-optic Q-switching, electro-optic Q-switching technology can achieve higher loss modulation depth (close to 100%), thereby obtaining higher

peak power and narrower pulse widths. Nd: YAG crystal, as a commonly used laser gain medium, has a high gain cross-section at the 1064 nm wavelength and good thermo-mechanical properties, making it generally suitable for the design of high peak power lasers [6-11]. For many application fields, green lasers (532nm) possess unique advantages: the shorter green wavelength and higher photon energy enable longer transmission distances in water and high sensitivity to

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the human eye, leading to widespread applications in laser medicine, underwater communication, spectral analysis, and precision machining. Through nonlinear frequency conversion technology, particularly second harmonic generation (SHG), near-infrared laser radiation can be converted into visible green light. In applications involving nonlinear optical frequency conversion, KTP (KTiOPO₄) crystal is one of the preferred crystals for frequency doubling 1064 nm laser radiation due to its high nonlinear coefficient, suitable transmission range, and high damage threshold. Currently, researchers domestically and internationally have conducted extensive studies on LD-pumped Q-switched green lasers. Northwest University in China investigated an LD side-pumped Nd: YAG/LBO extra-cavity frequency-doubled electro-optic Q-switched green laser, achieving a green light output of 8.12mJ at a repetition rate of 100Hz [12]. However, systematic research on LD side-pumping combined with KD*P Q-switching and KTP extra-cavity frequency doubling remains relatively scarce, especially regarding performance optimization at high repetition rates. This experiment designed and constructed an LD side-pumped Nd: YAG electro-optic Q-switched laser system and conducted experimental research on extra-cavity frequency doubling. Under a pump power of 80W, a 1064nm laser output with a pulse width of 10ns and a single pulse energy of 3μJ was obtained. Furthermore, by frequency doubling with a KTP crystal, a 532nm green light output with a single pulse energy of 1.75μJ was achieved. The experimental scheme used can provide an experimental basis for the design of high peak power green lasers. This research also represents an extension and improvement of the research group's previous work [13-21], and the design scheme of this laser can serve as a reference for the study of similar laser devices.

2. Experimental Scheme

The experimental setup is shown in Figure 1. The LD side-pumped Nd: YAG electro-optic Q-switched extra-cavity frequency-doubling laser mainly consists of three parts: the LD side-pumping module, the resonator and Q-switching module, and the extra-cavity frequency-doubling module. The pump source is an LD array with a peak power of 100W (wavelength 808nm), which irradiates the Nd: YAG crystal (dimensions Φ6×100mm, Nd³⁺-doping concentration 1at.%) via side-pumping. The two ends of the Nd: YAG crystal are coated with a 808nm anti-reflection coating and a 1064nm high-reflection coating, respectively. It is packaged in a copper heat sink and equipped with a water cooling system to maintain the operating temperature at 20±0.3 °C. The resonator employs a plane-concave cavity design with a cavity length of 300mm. The total reflector is a plane mirror coated with a 1064nm high-reflection coating (R > 99.9%). The output coupler is a concave mirror with a radius of curvature of 1000mm, having a transmittance of 80% for the 1064nm laser. The Q-switching system consists of a KD*P elec-

tro-optic crystal, a quarter-wave plate, and a polarizer. The KD*P crystal dimensions are 6×6×20 mm, with both ends coated with a 1064nm anti-reflection coating (single-surface residual reflectivity <0.2%). The quarter-wave voltage applied is approximately 3000V. The quarter-wave plate and polarizer are used to control the laser polarization state and achieve polarized output, respectively. The extra-cavity frequency-doubling system uses a Type-II critically phase-matched KTP crystal (dimensions 3×3×15mm), cut for the beam propagation direction (θ=90°, φ=23.5°). Both ends of the KTP crystal are coated with anti-reflection coatings for 1064nm and 532nm (single-surface residual reflectivity <0.2%). The KTP crystal is mounted on a precision three-dimensional adjustment stage to ensure accurate achievement of phase matching and alignment with the laser beam. A dichroic mirror is placed at the laser output end. As shown in Figure 1, the fundamental wave is transmitted directly through dichroic mirror 9 for output, while the frequency-doubled wave is reflected by dichroic mirror 9 and then further reflected by the upper mirror 10 for output.

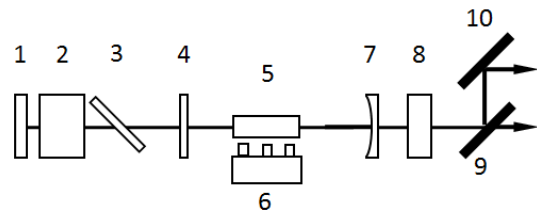


Figure 1. LD Side-pumped Nd: YAG Electro-optic Q-switched Extra-cavity Frequency-doubling Laser: (1) Total Reflector, (2) Electro-optic Q-switch Crystal Kd*P, (3) Polarizer, (4) Quarter-wave Plate, (5) Gain Medium Nd: YAG, (6) Ld Array, (7) Output Coupled Reflector, (8) Frequency-doubling Crystal Ktp, (9) Dichroic Mirror, (10) Mirror.

3. Results and Discussions

3.1. Output Characteristics of the Fundamental Wave

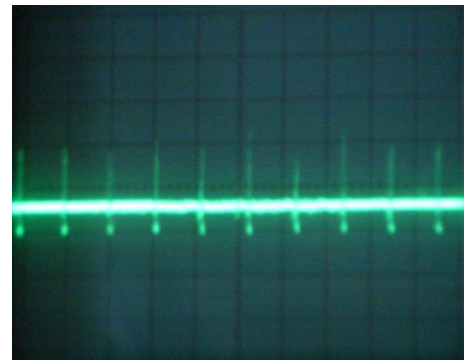


Figure 2. Waveform of the Pulse Train from the LD Side-pumped Nd: YAG Electro-optic Q-Switched Laser.

Under operating conditions of a pump power of 80W, the laser achieved stable 1064nm laser output. Figure 2 shows a typical Q-switched pulse train. The pulse amplitude exhibits good uniformity with energy fluctuations of less than $\pm 3\%$. The single pulse profile is of high quality, with a pulse width of 10ns and good symmetry. No significant pedestal or spiking is observed, indicating a normal Q-switching process without relaxation oscillation phenomena.

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Figure 3 shows the output spectrum of the fundamental wave from the LD side-pumped Nd: YAG electro-optic Q-switched laser. The output laser exhibits central wavelength of 1064nm with a spectral width of approximately 2nm.

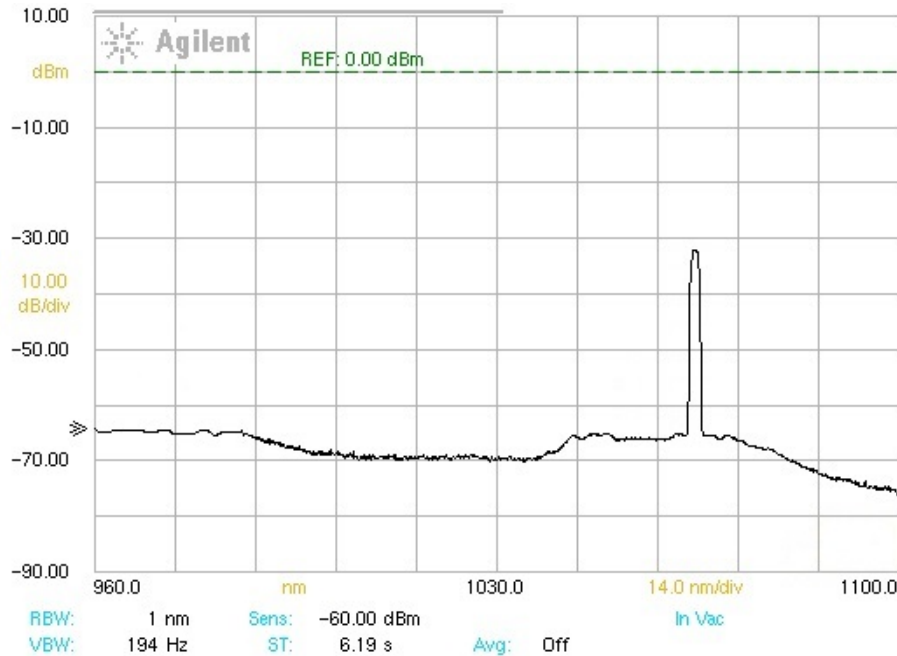


Figure 3. Output Spectrum of the LD Side-pumped Nd: YAG Electro-optic Q-switched Laser.

During the experiment, when the pump power was below 4W, the laser remained below the threshold, and no laser output was observed. Once the pump power exceeded the threshold, the output energy increased linearly with the pump power. At a pump power of 80W, the maximum average output power of the fundamental wave reached 60W, corresponding to an optical-to-optical conversion efficiency of 75%.

3.2. Output Characteristics of the Frequency-Doubled Wave

After injecting the fundamental wave into the KTP frequency-doubling crystal, 532nm green laser output was obtained. Experiments showed that when the fundamental wave energy was low, the frequency-doubled wave energy increased with the square of the fundamental wave energy, consistent with the frequency-doubling theory under the small-signal approximation. As the fundamental wave energy increased further, the frequency-doubling conversion efficiency gradually saturated, aligning with theoretical predictions.

At the fundamental wave energy of $3\mu\text{J}$, a green light energy of $1.75\mu\text{J}$ was achieved, corresponding to a fre-

quency-doubling conversion efficiency of 58.3%. This efficiency is lower than the theoretically predicted value (approximately 70%), potentially attributable to the following factors: (i) slight phase mismatch in the KTP crystal, induced by temperature variations or angular misalignment; (ii) degradation of power density due to imperfect beam quality; (iii) inhomogeneity in the nonlinear coefficient of the crystal.

The frequency-doubling conversion efficiency can be further improved by optimizing the phase-matching angle and enhancing the temperature control of the KTP crystal. Additionally, methods such as focusing the fundamental wave beam to increase power density could help improve the efficiency, although care must be taken to avoid damaging the frequency-doubling crystal due to excessively high power density.

3.3. Pulse Stability Analysis

The laser exhibited good stability during prolonged operation. Measurements of the output energy over 30 minutes showed that the green light energy fluctuation was less than $\pm 1\%$, indicating excellent thermal and mechanical stability of the laser system. The pulse width remained stable during extended operation, with fluctuations within $\pm 0.5\text{ns}$. The

pulse profile also showed no significant distortion, suggesting effective thermal management of both the Q-switch crystal and the frequency-doubling crystal, with no significant observable effects such as thermal lensing or thermally induced phase mismatch.

3.4. Analysis of Thermal Effects Management

Thermal management is a critical factor in ensuring stable output performance for LD side-pumped solid-state lasers. Among these, the thermal lensing effect in the Nd: YAG laser crystal is one of the main factors affecting beam quality and output power. In this work, the temperature rise of the laser crystal was effectively controlled, and the thermal lensing effect was mitigated by employing a water-cooling system and an optimized heat sink design. The KD*P electro-optic crystal is highly sensitive to temperature changes, requiring a constant operating temperature to prevent performance degradation. This system utilized an independent temperature control system to maintain the KD*P crystal temperature at $25 \pm 0.1^\circ\text{C}$, ensuring Q-switching stability. Temperature variations in the KTP crystal can cause phase mismatch and reduce frequency-doubling efficiency. By monitoring changes in the frequency-doubling efficiency, the temperature variation of the crystal can be inferred. In this experiment, the KTP crystal employed passive heat dissipation, resulting in a temperature increase of approximately 2°C during operation, which had a minor impact on the frequency-doubling efficiency.

4. Conclusions

This experiment successfully developed an LD side-pumped Nd: YAG electro-optic Q-switched laser and investigated its extra-cavity frequency-doubling characteristics. Under operating conditions of the pump power of 80W, a 1064nm laser output was achieved with a pulse width of 10ns and a single pulse energy of 3 μJ . By frequency doubling using the KTP crystal, a 532nm green laser output with a single pulse energy of 1.75 μJ was obtained, and the frequency-doubling conversion efficiency reached 58.3%. In the experimental study, the combination of LD side-pumping and the electro-optic Q-switching scheme enabled high peak power output, exhibiting excellent stability with energy fluctuations of less than $\pm 1\%$. The KD*P crystal, serving as the electro-optic Q-switch, provided precise Q-switch control and generated laser output with narrow pulse width. The KTP crystal proved suitable for frequency doubling the 1064nm laser, achieving high conversion efficiency at moderate power densities. Effective thermal management was crucial for ensuring the long-term stable operation of the laser, particularly the temperature control of the Nd: YAG crystal, the KD*P electro-optic Q-switch crystal, and the KTP frequency-doubling crystal. This laser system offers advantages such as compact structure, good stability, and high peak power,

indicating broad application prospects in fields including laser processing, medical therapy, spectral analysis, and scientific research. Subsequent research by the team will focus on optimizing the system structure to improve conversion efficiency, exploring operational characteristics at higher repetition rates, and extending frequency conversion to other wavelengths.

Abbreviations

LD	Diode Laser
DPSSL	Diode Laser Pumped Solid-state Lasers
SHG	Second Harmonic Generation

Author Contributions

Lianju Shang: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing

Zhenzhong Cao: Data curation, Formal Analysis, Methodology, Software, Supervision, Validation, Visualization

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Conflicts of Interest

The authors declare no conflicts of interest.

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