Investigation of all solid state end-pumped Nd:YAG Q-switched laser

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Abstract. High energy 1064 nm Q-switched laser output is obtained by LD array end pumping Nd:YAG. For different divergence angles of fast axis and slow axis of LD array, cylindrical lens and spherical lens are used for beam shaping of LD array. The laser properties of high energy 1064 nm Q-switched laser with pump energy is investigated with different Nd3+ ion doping concentration and different LD temperature. The results indicate that the extremely high gain formed at the end of the laser is easy to generate self-excited oscillation with the increasing of Nd3+ ion doping concentration and the increasing of LD temperature, which eventually results in the saturation of Q-switched laser pulse energy and makes it difficult to improve further. In view of saturation phenomenon of Q-switched laser output, Nd3+ ion doping concentration and LD temperature adjustment is proposed to reduce the absorption rate of laser medium to the pump light, which provides an effective technical means for obtaining high energy end pumped Q-switched pulsed laser. A 77.8mJ and 10 ns 1064 nm laser is generated with the LD temperature of 20 ℃ and the Nd3+ ion doping concentration of 0.8%, and the corresponding optical conversion efficiency is 13.9%.

1. INTRODUCTION

High-energy Q-switched lasers with low repetition frequency have been widely used in the fields of mass spectrometry, laser lidars and laser indication for the characteristics of high peak power and narrow pulse width [1-5]. The high energy Q-switched 1064 nm laser and its frequency conversion generated 532,355 nm laser are widely used in atmospheric monitoring of the lidar [6,7]. All solid state lasers pumped by semiconductor laser diodes (DPL) have the advantages of small size, long lifetime, high efficiency and good beam quality. The LD spectral line can be well matched with the absorption spectral line of the gain medium, because the LD spectral line of the pump source is narrow and the central wavelength is controllable. So the energy conversion efficiency is high, and the waste heat in the process of laser generation is less, so the wave front distortion caused by heat is reduced, which is conducive to the output of laser with high beam quality. In addition, the heat can be derived by thermoelectric cooler (TEC), which greatly improves the reliability and environmental adaptability of the system, so DPL has become a research hotspot for obtaining high energy Q-switched lasers. The LD side-pumped Nd:YAG crystal lasers are primarily studied for obtaining high energy 1064 nm Q-switched laser due to their absorption equality and low cost. E. Armandillo et al. designed a Z-shaped geometric optical path based on slab and a Gauss unstable resonator to reduce wave-front distortion and improve laser beam quality. Under the condition of LD pumping energy 750 mJ, a 1064-nm pulsed laser with 100 mJ and 20 ns was produced, and the corresponding light-to-light conversion efficiency was 13.3%[3]. The Chen Weibiao research group of Shanghai Institute of Optics and Machinery of Chinese Academy of Sciences used Z-shaped Nd:YAG slab cut by Brewster angle
to conduct the laser beam. LD and laser crystal waste heat are derived by cooling method, and Q-switched by KD*P is used to obtain 1064 nm laser output of 100 mJ and 10 ns. The corresponding light-to-light conversion efficiency is 13%[8]. In 2011, the project group used unstable resonators and two Z-shaped Nd:YAG slabs for laser amplification, and obtained 450 mJ, 10 ns laser output [9]. In 2017, Li Chaoyang presented a 2.36 J, 50 Hz, 9.4 ns laser with a diode side-pumped Nd:YAG MOPA system[10].

Compared with side-pumping form, end-pumping structure owns the superiority of high efficiency, good mode matching, and good wavelength matching, and so on. Meantime, the laser structure in end-pumped is more compact, which is conducive to reducing the volume and weight of the laser. Liu Xiaojuan et al. obtained 1064 nm laser output with pulse width of 7 ns and peak power of 3.4 kW in the Pulsed laser diode array pumped Nd:YVO4/GaAs laser[11]. L. Goldberg et al. generated 60 mJ of 1064 nm Q-switched laser, corresponding to optical conversion efficiency of 17%[3]. Using LD end-pumped Z-shaped Nd:YAG slabs, Paul R. Styssley et al. obtained 107 mJ laser output with an optical efficiency of 24%[12]. It can be seen that the optical conversion efficiency of end pump is better than that of side pump. However, the extremely high gain formed at the end of the laser is easy to generate self-excited oscillation, which eventually results in the saturation of Q-switched laser pulse energy and makes it difficult to improve further.

In this paper, the laser properties of high energy 1064 nm pulse laser with pump energy is investigated with different Nd3+ ion doping concentration and different LD temperature. High energy Q-switched laser is obtained by adjusting Nd3+ ion doping concentration and LD temperature, which can reduce the absorption rate of the laser medium to the pump light. When the temperature of LD is 20 ℃ and the doping concentration of the crystal rod is 0.8%, a 77.8 mJ and 10 ns 1064 nm laser is generated and the corresponding optical conversion efficiency is 13.9%.

2. EXPERIMENT AND ANALYSIS

2.1. Experimental setup

![Fig. 1 Experimental device of end-pumped 1064 nm Q-switched laser](image)

The experimental setup of the end-pumped Nd:YAG Q-switching is shown in Fig. 1, which includes the pump source LD, LD shaping lens F1, F2, laser crystal LC, polarizer PS, quarter-wave plate QW, electro-optic crystal EOC and output coupled mirror OC. LD is a single row vertical array consisting of 10 bars, with maximum output energy of 600 mJ. The bar spacing is 0.43 mm, and the divergence angles of the fast and slow shafts are 5 and 10 degrees, respectively. Due to the different divergence angles, the LD fast and slow axis is shaped by cylindrical lens and spherical lens with focal length 80 mm and 30 mm respectively. The distance between cylindrical lens and LD is 6.8 mm; the distance between cylindrical lens and spherical lens is 25.5 mm; the distance between crystal rod and spherical lens is 17 mm. The Nd:YAG rod was 5 mm in diameter and a 40mm long low-doped region with different Nd3+ ion doping concentration. Pump end of Nd:YAG is coated with 1064 nm high reflectivity film and 800 nm high transmittance film, and the other end is plated with 1064 nm anti reflection coating. PS is a polarizing beam splitter, which makes the vertically polarized s light reflect and horizontally polarized P light transmission. The Q-switched component modulates the Q value of the resonant cavity to produce a pulsed laser output, which concludes polarization beam splitter, quarter-wave plate and electro-optic crystal. The output coupling mirror OC with mirror curvature of 1100 mm and pump end face of Nd:YAG with mirror curvature of -2000 mm form the resonant cavity to generate a 1064 nm laser.
2.2. Experimental results

In the experiment, the output energy of Q-switched 1064 nm laser is measured by energy meter (PE50BF-DIFH-C, Ophir-Spiricon, Inc.) The output energy respect to the pump energy for different Nd3+ ion doping concentration with the LD temperature of 25 °C is shown in Fig. 2. It is found that the 1064 nm laser output energy is saturated when the pump energy is greater than 405 mJ with 0.8% Nd3+ ion doping concentration, and the output energy is 59.6 mJ at the pump energy of 498 mJ. The 1064 nm laser output energy does not appear saturation in the pump energy range 467 mJ with 0.6% Nd3+ ion doping concentration, and the output energy is 54.1 mJ at the pump energy of 498 mJ. The output energy of 1064 nm pulsed laser increases continuously with pumping energy with 0.4% Nd3+ ion doping concentration, and the output energy is 57.1 mJ at the pump energy of 498 mJ, and no saturation occurs. When the laser medium doping concentration is high, such as 0.6% or 0.8%, the extremely high gain formed in the front of the Nd:YAG, which can easily generate self-excited oscillation. This leads to the saturation of Q-switched laser pulse energy, which is difficult to further improve. However, the maximum output energy of 1064 nm pulsed laser with 0.8% Nd3+ ion doping concentration is larger than that with 0.4% and 0.6% Nd3+ ion doping concentration in the pump energy range of 498 mJ.

![Graph](image)

Fig. 2 Variation curves of 1064 nm laser output energy with the pump energy at different Nd3+ doping concentration

The output energy respect to the pump energy for different LD temperature with 0.8% Nd3+ ion doping concentration is shown in Fig. 3. When the LD temperature is 25 °C, it is found that the 1064 nm laser output energy is saturated when the pump energy is greater than 405 mJ. Subsequently, the output energy of 1064 nm pulsed laser at different temperatures is studied. It is found that pumping energy corresponding to the output laser saturates increases continuously as the LD temperature decreases. When the LD temperature is 23 °C, 1064 nm laser output does not appear saturation in the pump energy range of 498 mJ. When the LD temperature is 20 °C, the output energy of 1064 nm pulsed laser increases continuously with the increasing of the pump energy, and a 77.8mJ 1064 nm laser is obtained at the pump energy of 560 mJ, and the corresponding optical conversion efficiency is 13.9%. The laser pulse waveform of the maximum output energy is measured by a fast response silicon photo detector (DET10A, Thorlabs) and an oscilloscope (DPO 4104, Tektronix), as shown in Figure 4, and laser pulse width is about 10 ns.
Fig. 3 Variation curves of 1064 nm laser output energy with the pump energy at different LD temperatures

Fig. 4 Pulse waveform of 1064 nm laser

The LD spectra were measured by spectral analyzer (HR2000+CG, Ocean Optics) in the process of temperature changes for studying the saturation phenomenon of laser output energy. The LD wavelength decreases with the decrease of temperature, as shown in Fig. 5. The peak wavelength of LD changes from 796.1 nm to 799.2 nm when the LD temperature increases from 17.5 °C to 30 °C, corresponding to wavelength variation coefficient of 0.25 nm/°C, and the LD wavelength is shifted away from the absorption peak of laser medium by adjusting the LD temperature. So the absorption rate of the gain medium to pump light decreases with the decreasing of LD temperature. The very high gain formed by end-to-end will easily produce self-excited oscillation with the increase of temperature. As a result, the energy of 064 nm pulsed laser pulse saturates, which makes it difficult to improve further.

Fig. 5 The wavelength of LD at different temperature
3. CONCLUSIONS
The laser properties of 1064 nm pulsed laser with different Nd3+ ion doping concentration and different LD temperature are investigated in this study. For different divergence angles of fast axis and slow axis of LD array, cylindrical lens and spherical lens are used for beam shaping. The laser properties of 1064 nm pulsed laser with pump energy is investigated with different Nd3+ ion doping concentration and different LD temperature. The results indicate that the extremely high gain formed at the end of the laser is easy to generate self-excited oscillation with the increasing of Nd3+ ion doping concentration and the increasing of LD temperature, and finally leads to the saturation of Q-switched laser pulse energy. For the saturation phenomenon of 1064 nm pulsed laser energy output, LD temperature adjustment is carried out to make the pump wavelength to deviate from the absorption peak of Nd:YAG crystal, and reduce the end-face gain of laser medium pumping, which effectively suppress the self-excited oscillation, and provide an effective technical means for obtaining high-energy end-pumped Q-switched laser output. A 77.8 mJ and 10 ns 1064 nm laser is obtained at the pump energy of 560 mJ with the LD temperature of 20 °C and the Nd3+ ion doping concentration of 0.8%, and the corresponding optical conversion efficiency is 13.9%.

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