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High Repetition Wavelength-locked 878.6 nm LD Dual-end-pumped Nd:YVO$_4$ 1064 nm Laser

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A Nd:YVO$_4$ laser dual-end-pumped by a wavelength-locked 878.6 nm laser diode is presented. At the repetition rate of 500 KHz, the absorbed pump power of 58 W, an output power of 26.1 W at 1064 nm is obtained, corresponding to an optical-optical efficiency of 45%. The pulse width is 44.2 ns. Meanwhile, the effects of traditional 808 nm pumping and 878.6 nm dual-end-pumping on the output laser beam quality and pulse width are compared and analyzed in an experiment.

Keywords : Dual-end-pumped, Wavelength-locked 878.6 nm, Q-switch, 500 kHz
OCIS codes : (140.202) Diode lasers; (140.3480) Lasers, diode-pumped; (140.3540) Lasers, Q-switched

I. INTRODUCTION

High-repetition-rate acousto-optic Q-switched lasers are widely used in military fields, laser ranging, and laser radar for their good pulse stability and high output power [1-3]. However the serious thermal effect in a traditional 808 nm pumped acoustic-optically Q-switched laser is the source of the deteriorating output laser beam quality, and leads to output laser pulse width increases, which are not conducive to the application of a high repetition rate laser. How to reduce the heat generated in the laser medium effectively during the pumping process and laser emission, improve the conversion efficiency of the laser and the quality of the output laser beam, even reduce the pulse width of the laser are among the main problems during the research process of all-solid-state high-repetition lasers [4-6]. In order to solve the thermal effect of the laser fundamentally, an in-band pumping technique has been proposed in recent years. It has a good effect in reducing the thermal problems of the laser [7, 8].

In recent years, there have been numerous reports on high-repetition lasers in different pump wavelengths. In 2009, Xavier Helen *et al*. compared the thermal effects and output characteristics of 808 nm pumped and 914 nm pumped acoustic-optically Q-switched lasers at 10~20 kHz. Compared with the traditional 808 nm pump, the 914 nm pump has obvious advantages in reducing thermal effects and has a stable pulse output [9]. In the same year, Yan Xingpeng of Tsinghua University reported a 73.2 W 1064 nm laser output at 650 kHz under 808 nm pumping by using a dual Nd:YVO$_4$ crystal. The pulse width was increased from 17.5 ns to 80 ns at 80 kHz to 650 kHz [10]. In 2011, Hong Hailong *et al*. achieved a 888 nm pumped 1064 nm laser with 57 W and optical-to-optical conversion efficiency of 51.8% when the pump power was 110 W and the repetition rate was 200 kH. The pulse width was 50 ns. When the repetition rate varied from 30 kHz to 250 kHz, the laser had a stable pulse output and the beam quality $M^2 < 1.30$ [11]. In 2016, Liu Qiang and others from Tsinghua University reported a wavelength-locked 878.6 nm pumped acoustic-optically Q-switched Nd:YVO$_4$ laser. In the Master Oscillator Power-Amplifier (MOPA) structure, a maximum output power of 120.8 W and the optical-to-optical conversion efficiency of 47% was obtained at 100 kHz [12].

It is known from the above results that the high frequency operation above 500 kHz can be achieved by a traditional 808 nm pumped pulse laser, but the severe

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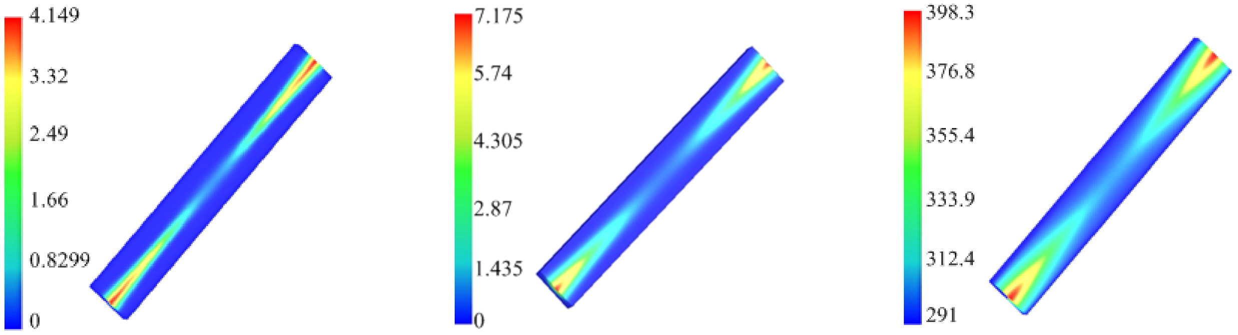
thermal effect leads to the greater pulse width of the output laser. Compared with the traditional pumping mode, the in-band pumped technology can greatly reduce the heat released during the laser production process. It is an effective solution to fundamentally solve the thermal effect of the all-solid-state laser, but the repetition rate cannot reach a stable pulse output above 200 kHz. In this paper, the advantages of wavelength-locked 878.6 nm dual-end pumped mode and 808 nm traditional pumping for thermal effects are compared and the output characteristics of high-repetition acoustic-optical Q-switched lasers in wavelength-locked 878.6 nm pumping mode are studied. Simulating the thermal effect of the laser, designing the resonant cavity rationally, using the acoustic-optical Q-switched signal generator modified in house, adjusting the trigger time of the TTL level, the laser still has a stable pulse output at 500 kHz repetition rate. Compared with traditional 808 nm pumping, it has the advantages of high beam quality and narrow pulse width at high repetition rate.

II. THEORY AND SIMULATION

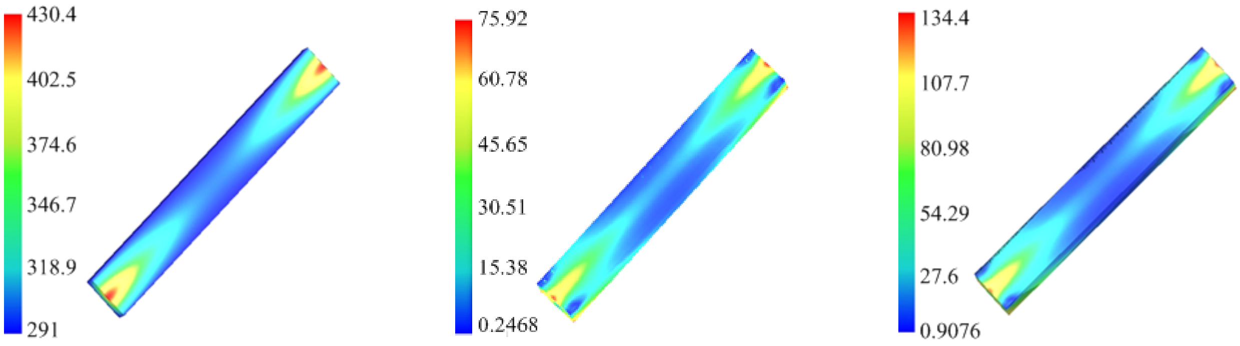
In the traditional 808 nm pumping Nd:YVO_4 four-level system, Nd^{3+} absorbs the pump photon and then transitions from the ground state $^4I_{9/2}$ to the excited state $^4F_{5/2}$, then relaxes to the laser upper state $^4F_{3/2}$. In the process, the thermal relaxation process of $^4F_{5/2} \rightarrow {}^4F_{3/2}$ increases the quantum loss between pump photons and laser photons, reduces the conversion efficiency of pump energy, and increases the thermal load. The wavelength-locked 878.6 nm direct pumping method directly pumps Nd^{3+} from the ground state to the laser upper level $^4F_{3/2}$, which reduces the quantum loss, reduces the heat generation, and effectively improves the quantum efficiency.

We conducted the simulation of the Nd:YVO_4 crystal by using LASCAD software. The thermal load, temperature and thermal stress distribution of the crystal under 878.6 nm and 808 nm pumping were compared through the software, as shown in Fig. 1. The parameters in the simulation are shown in Table 1.

From the simulation results, compared with the 808 nm conventional pump, the highest local thermal load of the crystal drops from 7.1 (W/mm^3) to 4.1 (W/mm^3), the maximum temperature of the end face is reduced 430 K to 398 K, and the maximum thermal stress is reduced from 134.4 (N/mm^2) to 75.9 (N/mm^2). The temperature distribution in the crystal at wavelength-locked 878.6 nm pump is more uniform, while the heat load of the crystal at 808 nm pumping is mainly concentrated on the end face of the crystal which could easily lead to thermal cracking. The wavelength-locked 878.6 nm directly pumping method can



(a) Wave-locked 878.6 nm pump heat load (W/mm^3) (b) 808 nm pump heat load (W/mm^3) (c) Wave-locked 878.6 nm pump temperature (K)



(d) 808 nm pump temperature (K) (e) Wave-locked 878.6 nm pump stress intensity (N/mm^2) (f) 808 nm pump stress intensity (N/mm^2)

FIG. 1. Heat load, temperature and stress intensity in crystal at wave-locked 878.6 nm and 808 nm.

TABLE 1. Parameters used in the LASCAD simulation

Parameters	Wave-locked 878.6 nm pump	808 nm pump
Pumping power	58 W	58 W
Pumping radius	0.7 mm	0.7 mm
Stimulated emission cross section	12.0×10^{-19} cm^2	12.0×10^{-19} cm^2
Lasing wavelength	1064 nm	1064 nm
Fluorescent lifetime	100 μs	100 μs
Boundary temperature	291 K	291 K
Absorption coefficient	0.4 mm^{-1}	0.6 mm^{-1}
Thermo-optical coefficient	$dn_e/dT = 2.9 \times 10^{-6}$/K	$dn_e/dT = 2.9 \times 10^{-6}$/K
Thermal conductivity coefficient	0.066 W/cm/K	0.066 W/cm/K
Thermal expansion coefficient	11.37×10^{-6} K	11.37×10^{-6} K
Absorbed-pump-power-heat conversion efficiency	30%	50%
Poisson ratio	0.3	0.3
Dimension of the crystal	3 × 3 × 20	3 × 3 × 20

significantly reduce the thermal load in the laser crystal, reduce the influence of the thermal effect on the laser, and provide an effective way to achieve high-repetition, narrow-pulse-width acoustic-optical Q-switched lasers.

Under the LD end-pumping conditions, the temperature and thermal stress are different within the crystal, which results in different refractive indices in the crystal, causing the thermal lensing effect. At high power, the thermal focal length of the crystal can be expressed is as follows:

$$f = \frac{\pi\omega_p^2 K_c}{P_{ph}\dfrac{dn}{dT}}\left[\frac{1}{1-\exp(-\alpha l)}\right] \tag{1}$$

where P_{ph} is the power of the thermal deposition of pump light in the crystal, K_c is the thermal conductivity, ω_p is the average pump spot diameter, dn/dT is the change rate of the crystal refractive indice, α is the crystal absorption coefficient, for the crystal with 20 mm length. Figure 2 shows the relationship between the thermal lens focal length of the laser crystal and the pump power at different pump wavelengths simulated by Matlab software. The simulation parameters are the same as for LASCAD. Simulation result shows that the thermal effect of the crystal becomes severe with the increase of the pump power, the corresponding equivalent thermal focal length is also shorter. Meanwhile, at the same absorption pump power, the thermal lens focal length of the 808 nm pump crystal is shorter and the thermal effect is more serious.

According to the four-level rate equation of the Q-switched laser, the expression of the pulse width is given by:

$$\Delta t = \frac{E}{P_{out(p)}} = \tau_c \frac{\Delta n_i - \Delta n_f}{\Delta n_i - \Delta n_t\left[\ln\left(\Delta n_i / \Delta n_t\right)+1\right]} \tag{2}$$

Figure 3 shows the variation of pulse width with repetition rate at two pump wavelengths. It can be seen from the curve that the pulse width gradually widens with

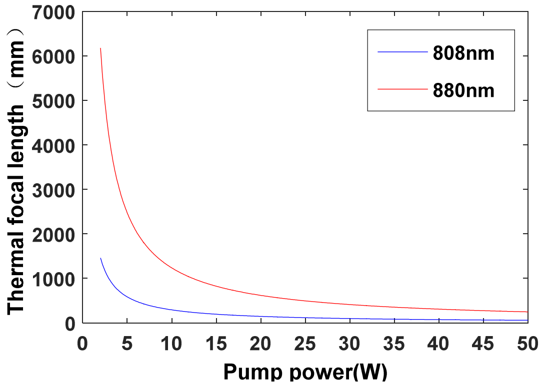


FIG. 2. Curves of thermal lens focal length of the laser crystal and the pump power at different pump wavelengths.

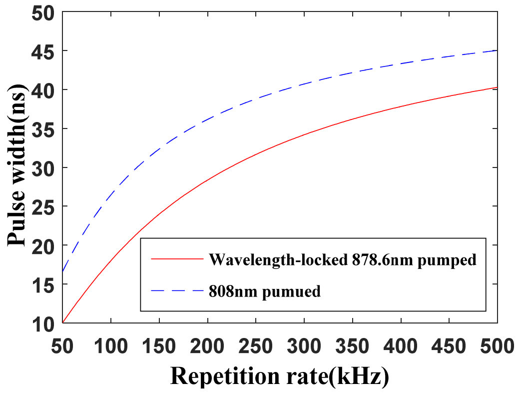


FIG. 3. The pulse width varies with repetition rate curve.

the increase of the repetition rate, at the same repetition rate the output laser pulse width is narrower when pumped by wavelength-locked 878.6 nm. In theory, it is more advantageous to obtain a narrow pulse width output.

II. EXPERIMENTAL SETUP

Figure 4 illustrates the experimental setup of the wavelength-locked 878.6 nm dual-end-pumped Nd:YVO$_4$ acoustic-optically Q-switched laser. The two pumping sources were high-power semiconductor laser systems with P10 fiber bundle coupling output produced by the nLIGHT company. The output laser wavelength was 878.6 nm, 0.17 in numerical aperture, and 75 W maximum output power. Compared with the 880 nm pumping, in the temperature range of 10~40°C, the output power fluctuation of wavelength-locked 878.6 nm pumped was small and the output stability was good. Therefore, the wavelength-locked 878.6 nm pumped source had lower temperature control requirements than the 880 nm pump laser, which was advantageous for achieving stable power output. The coupling system was two 1:2 coupling systems. The cavity was a flat-flat cavity and its geometric length was approximately 245 mm. M$_1$ was a plane mirror with high-reflectivity coating at 1064 nm. M$_2$ was a plane output coupler with a transmittance of 60% at 1064 nm. The two 45°mirrors with both surfaces anti-reflection coated at 878.6 nm and the surface close to the laser crystal high-reflectivity coated at 1064 nm. The laser crystal was 0.5at.% doped Nd:YVO$_4$ with a dimension of 3 mm × 3 mm × 20 mm and both ends anti-reflection coated at 878.6 nm and 1064 nm. The side of the crystal was wrapped in an indium foil and placed in a copper sink, which was kept at a temperature of 18°C by Leybukco SHP-50 cooling water.

The stability within the cavity can be calculated by the ABCD matrix theory, whereby the transformation matrix of the medium in the cavity is written as:

$$M=\begin{bmatrix} A & B \\ C & D \end{bmatrix}=\begin{bmatrix} 1 & l_2 \\ 0 & 1 \end{bmatrix}\cdot\begin{bmatrix} 1 & 0 \\ -1/f & 1 \end{bmatrix}\cdot\begin{bmatrix} 1 & l_1 \\ 0 & 1 \end{bmatrix}$$
$$=\begin{bmatrix} 1-l_2/f & l_1+l_2-l_1 l_2 . f \\ -1/f & 1-l_1/f \end{bmatrix} \tag{3}$$

where $M_l=\begin{bmatrix} 1 & 0 \\ -1/f & 1 \end{bmatrix}$ is the transmission matrix of the thin lens. The g parameter of the cavity can be expressed as:

$$\begin{aligned} g_1 &= A-\frac{B}{R_1}=1-\frac{l_1+l_2}{R_1}+\left(\frac{l_1 . l_2}{R_1}-l_2\right)\cdot\frac{1}{f} \\ g_2 &= A-\frac{B}{R_2}=1-\frac{l_1+l_2}{R_2}+\left(\frac{l_1 . l_2}{R_2}-l_2\right)\cdot\frac{1}{f} \end{aligned} \tag{4}$$

For a flat cavity, $R_1=\infty$, $R_2=\infty$, set $l_1=0$, through the stability condition of the cavity $0<g_1g_2<1$ can be known the cavity was in the stable region when $l_2<f$. According to the previous theoretical simulation, the focal length of the crystal thermal lens was 193.9 mm at the absorption pump power of 60 W. As the Q-switched crystal should be inserted into the resonant cavity, the cavity length should not be too short, so the cavity length was selected to be 220 mm. Good mode matching can be maintained between the pump light and the cavity mode to ensure TEM$_{00}$ output under high power conditions.

The above experimental device adopted an acoustic-optically Q-switching element with a working length of 33 mm, both surfaces anti-reflected coated at 1064 nm and the diffraction loss greater or equal to 85%. The modulation repetition rate was adjustable from 1~500 kHz, driven by a center frequency at 40.68 MHz, and an electric power of 20 W. The electrical pulse rise time was 100 ns and the fall time was 50 ns. The acoustic-optically Q-switched component was placed close to the Nd:YVO$_4$ crystal and the air cooling system was used to control temperature.

III. EXPERIMENTAL RESULTS AND ANALYSIS

Figure 5 shows the relationship between the output power and the absorbed pump power in the continuous state. When the dual-ended injection current is 5 A and the L30A-V1 SENSOR with a 150 W range, the RoHs laser power meter measures the average power P$_{av}$ of the output pulsed laser. The output power is 26.4 W, with crystal absorbed power of 58 W, and optical-optical efficiency is 45.5%.

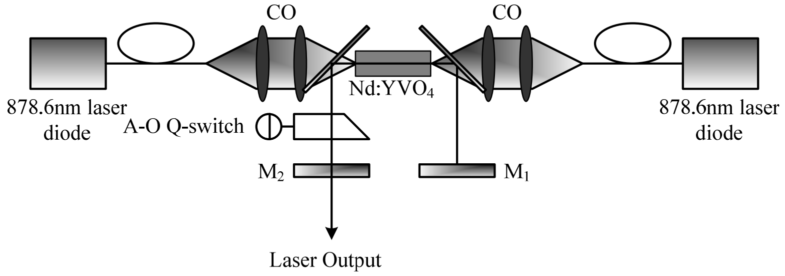


FIG. 4. The experimental device of dual-end-pumped A-O Q-switched pumped by wavelength-locked 878.6 nm.

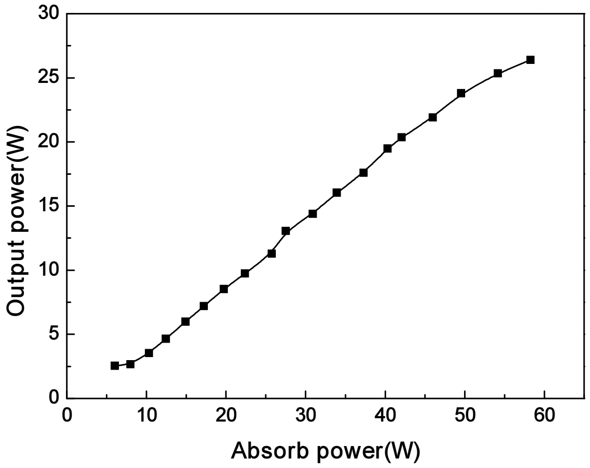


FIG. 5. Output power varies with absorb power curve.

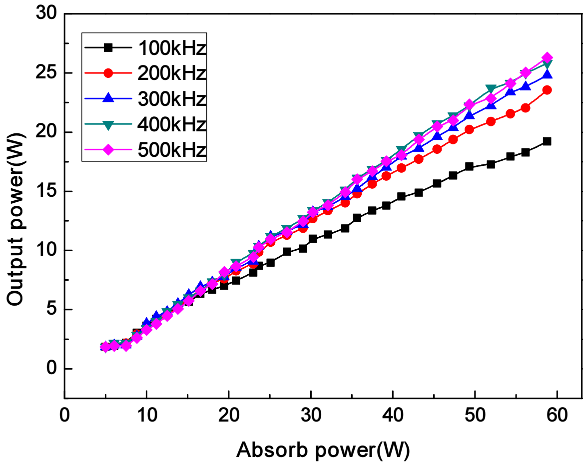
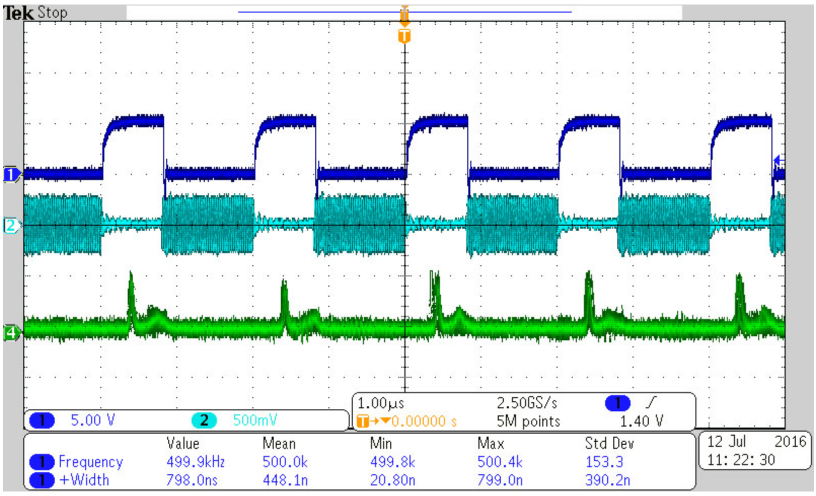


FIG. 6. Wavelength-locked 878.6 nm pumping Nd:YVO$_4$ laser output power varies with the repetition rate of 100~500 kHz.

After inserting the acoustic-optically Q switch, set the repetition rate at 100~500 kHz and set the TTL high-level duration to 0.8 μs. In the experiment, when the cavity length was 245 mm and the output mirror transmittance was 60%, combined with theoretical simulation analysis, the effect of wavelength-locked 878.6 nm direct pumping on the highest output power at different repetition rates was studied. The maximum output power of the wavelength-locked 878.6 nm pumped Nd:YVO$_4$ laser as a function of repetition rate at 100~500 kHz was plotted in Fig. 6.

The output power of 18.2 W at 1064 nm laser was obtained with total absorption power of the dual-end-pumped of 58 W and optical-optical efficiency of 31.3%; when the repetition rate of was 500 KHz, LD pump power was 58 W, the output power of 26.1 W at 1064 nm was obtained, optical-optical efficiency was 45%. The laser had a stable power output at the repetition rate of 100~500kHz, the maximum output power was 26.1 W at 500 KHz. As far as we know, this is the highest repetition rate that can be achieved under the stable output condition of the end pumped laser using the 880 nm band as the pumping source. The laser pulse signal was measured by a DPO3000 series oscilloscope and a Thorlabs DET01CFC model pulse width probe. Figure 7 is a waveform corresponding to the relationship between the control level of the wavelength-locked 878.6 nm pumping falling edge-triggered Q switch and the radio frequency timing at 500 kHz.

Under the same conditions, the wavelength-locked 878.6 nm pumping source was replaced by the 808 nm pumping source to compare the effect of wavelength-locked 878.6 nm pumping and 808 nm conventional pumping on the output laser beam quality and pulse width. In the 878.6 nm direct pumping experiment, when the repetition rate was 100~500 kHz and the total pump power was 58 W, the pulse width was increased from 15.23 ns to 44.15 ns in Fig. 8. Under the same experimental conditions, the pulse width increased from 24.43 ns to 52.44 ns in the traditional



	Value	Mean	Min	Max	Std Dev
1 Frequency	499.9kHz	500.0k	499.8k	500.4k	153.3
1 +Width	798.0ns	448.1n	20.80n	799.0n	390.2n

FIG. 7. Wavelength-locked 878.6 nm pumping falling edge triggers the waveform corresponding to the control level of the Q switch and the RF timing relationship at 500 kHz.

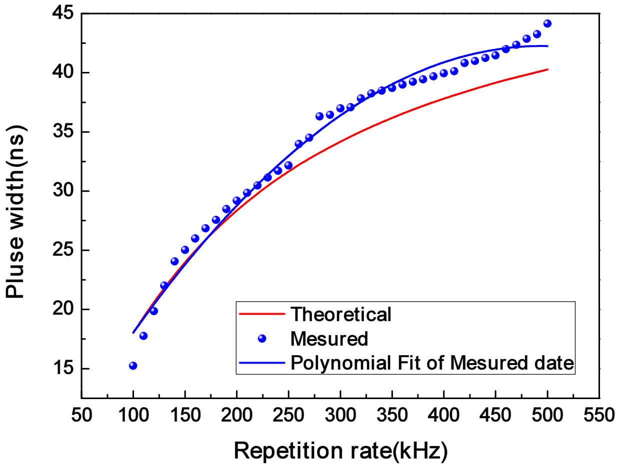
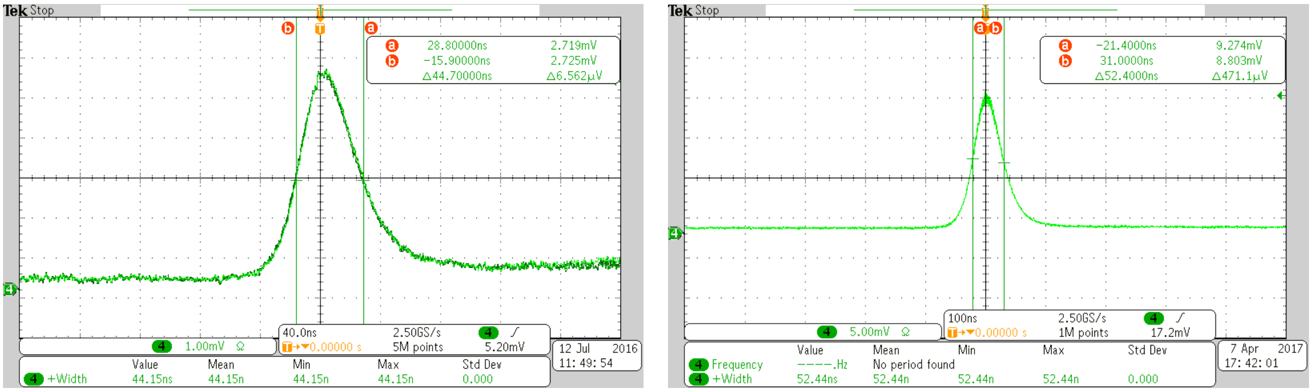


FIG. 8. The curve of pulse width of the wavelength-locked 878.6 nm pumped at repetition rate of 100~500 kHz.

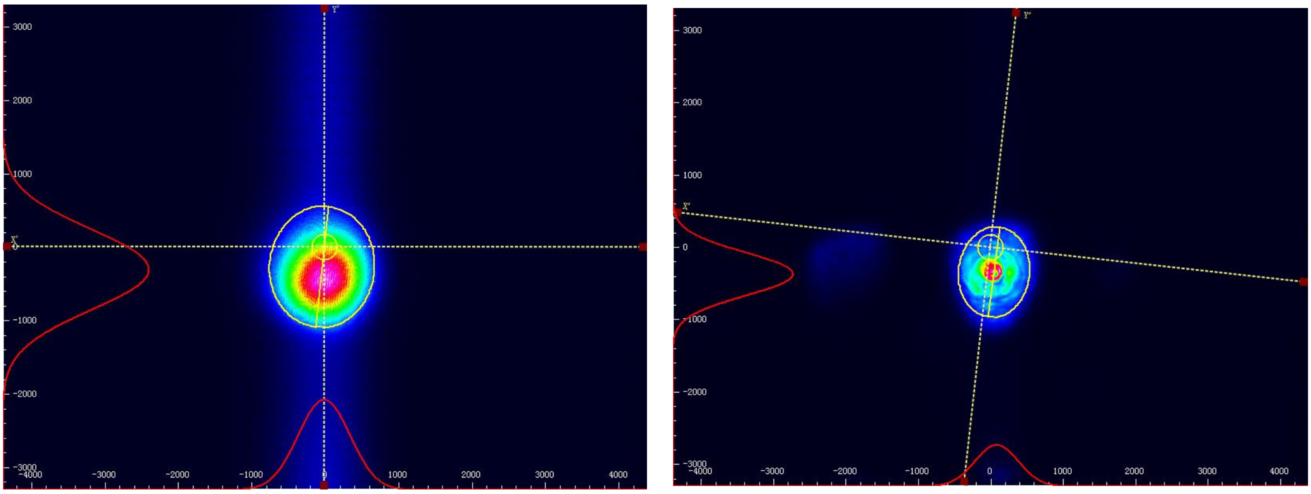
808 nm pumping experiment. Figure 9 was a pulse width diagram of the wavelength-locked 878.6 nm direct pump and the 808 nm conventional pump at 100~500 kHz.

The light intensity distribution of wavelength-locked 878.6 nm pumping and 808 nm pumping output laser at the repetition of 500 kHz and maximum pumping power are shown in Fig. 10. It can be seen from the comparison of the two figures that the beam profile energy distribution was not very uniform under the condition of 808 nm pumping, while the beam profile distribution was very symmetrical under the wavelength-locked 878.6 nm pumping, and the beam quality was improved. We measured the beam quality factor of the output beam profile by Thorlabs' BC106-VIS beam quality analyzer. The beam quality factors of the output laser under wavelength-locked 878.6 nm pumping and the 808 nm pumping were $M^2 = 1.55$ and $M^2 = 2.92$, respectively. From the experimental data, we can see that under the wavelength-locked 878.6 nm pumping and the 808 nm pumping, the laser has stable pulse output



(a) (b)

FIG. 9. The pulse width diagram of the wavelength-locked 878.6 nm direct pump and 808 nm traditional pump at 500 kHz.



(a) (b)

FIG. 10. In the condition of maximum pump power, the intensity distribution of output laser pumped by wavelength-locked 878.6 nm pumping and 808 nm pumping at 500 KHz.

at the repetition of 500 kHz, but the former had better beam quality and the pulse width of the output laser was narrower at the same repetition rate. Combined with theoretical simulation analysis, under the traditional 808 nm pumping, the severe thermal effect in the laser crystal deteriorated the beam quality and limited the output capability of the laser, resulted in the increase of the pulse width. The thermal effect of the crystal can be reduced effectively by using the wavelength-locked 878.6 nm pumping, the beam quality of the output laser can be improved and the narrower pulse width can be obtained at 1.06 μm laser.

IV. CONCLUSION

In this paper, a wavelength-locked 878.6 nm direct-pumped Nd:YVO_4 acoustic-optically Q-switching technology was proposed, which can effectively reduce the thermal effect of the crystal, and use the acoustic-optically Q-switching signal generator modified in house to adjust the trigger time of the TTL level, then obtain a 500 KHz high-frequency, high beam quality, narrow pulse width laser output. The output power of 24.2 W at 1064 nm laser was obtained with absorption power of 58 W and optical-optical efficiency of 31.3%, the pulse width was 15.2 ns; when the repetitive rate was 500 kHz and the crystal absorbs power at 58 W, a 26.1 W 1064 nm laser was obtained, the optical-optical conversion efficiency was 45%, and the pulse width was 44.2 ns. It had a stable pulse output at the repetition rate of 100~500 KHz. A similar experimental study was carried out under the traditional 808 nm pumping. It was found that under the traditional 808 nm pumping, the pulse width was significantly greater than that of the former at the same repetitive rate, and the beam quality was poor, which was due to the severe thermal effect of the 808 nm pumping. Therefore, using the wavelength-locked 878.6 nm direct pumping Nd:YVO_4 acoustic-optically Q-switching technology can reduce the thermal effect of the crystal and obtain high-frequency, high beam quality, narrow pulse width laser output, which provides an effective way for the practical application of high-repetition laser.

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