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A Laser-Diode-Pumped Acoustic-Optic Q-Switched Nd:YVO_4 Slab Laser with a Hybrid Resonator[1]

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Abstract—A 32.1 W laser-diode-stack pumped acoustic-optic Q-switched Nd:YVO_4 slab laser with hybrid resonator at 1064 nm was demonstrated with the pumping power of 112 W and repetition rate of 40 kHz, the pulse duration was 32.47 ns. The slope efficiency and optical-to-optical efficiency were 37 and 28.7%, respectively. At the repetition rate of 20 kHz and pumping power of 90 W, the average output power and pulse duration were 20.4 W and 20.43 ns, respectively. With the pumping power of 112 W, the beam quality M_2 factors in CW operation were measured to be 1.3 in stable direction and 1.6 in unstable direction.

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Laser-diode pumped all solid state laser with high repetition has a wide range applications in laser processing, laser radar, medicine and so on due to its compact structure, long lifetime and high efficiency. To most LD pumped Q-switched all solid state lasers, Nd:YVO_4 is a favorite crystal owning to its large emission cross section, wide pumping wavelength bandwidth and short upper-state life time [1]. Therefore, a great deal of research have concentrated on Nd:YVO_4 by many structures, such as LD pumped grazing-incidence slab laser [2–4], LD pumped rod oscillator, amplifier [5–9], self-stimulated Raman laser [10], optical parametric oscillator [11] and so on. The three emission lines (1064 [12–15], 914 nm [16, 17], and 1342 nm [18, 19]) of Nd:YVO_4 were also investigated during the past few years.

Compared to electro-optical Q-switched laser, AO Q-switched laser appears easier to get high repetition, because that electro-optic Q-switch need high drive voltage. In 2003, García López et al. [2] achieved a 200 kHz AO Q-switched grazing incidence slab laser with average power of 15.9 W and pulse duration of 15 ns under the pump power of 30 W. After that, Minassian et al. [3] obtained a 400 kHz AO Q-switched Nd:$GdVO_4$ slab laser with average power of 101 W using LD side-pumped bounce MOPA system and the pulse width was 20 ns. By using LD pumped rod laser, in 2008, Yan et al. [5] achieved 35 W average power with an AO Q-switching oscillator and 108 W average power, 500 kHz stable pulse output and a MOPA configuration of two amplifier. The pulse duration was 48 ns and the beam quality M^2 factors were 1.99 and 1.76. In 2009 [6], with the same oscillator and four-stage amplifier, 183.5 W at repetition of 850 kHz was achieved and beam quality was measured to be 1.28 and 1.21 in both directions.

LD partially end-pumped slab laser with hybrid resonator has been proved to be efficient in high power laser operating with excellent beam quality [20–22]. In 2003, with LD pumped electro-optically Q-switched Nd:YVO_4 structure, 83 W of average power at a pulse-repetition rate of 50 kHz with a pulse length of 11.3 ns was achieved and the beam quality $M^2 < 1.5$ was measured with the same pumping power in continuous-wave operation [20]. In 2007, using this structure as amplifier, Zhe et al. [21] obtained a pulse energy of 3.8 mJ and pulse width of 5 ns Q-switched laser at a repetition of 1 kHz with the amplification factor of 11. In this paper, it is the first time that an AO Q-switch was used in this structure to obtain high repetition rate Q-switched laser. A 32.1 W, high repetition rate laser-diode-stack pumped Nd:YVO_4 slab laser was demonstrated under the pumping power of 112 W at the repetition rate of 40 kHz, the pulse duration was measured to be 32.47 ns. At the repetition rate of 20 kHz and pumping power of 90 W, the average output power and pulse duration were 20.4 W and 20.43 ns, respectively.

The experiment arrangement was shown in Fig. 1. The central wavelength of LD stack (including four bars) was 808.6 nm and the emission from each diode laser bar was individually collimated by microlens. After the coupling system, a homogeneous pumping line was generated inside the Nd:YVO_4 slab. The crystal was 12 × 10 × 1 mm and a-cut with the c axis along the 1mm direction. It was dopted 0.3 at % and mounted between two water-cooled heats sinks with two large faces (12 × 10 mm). Indium foil was used for

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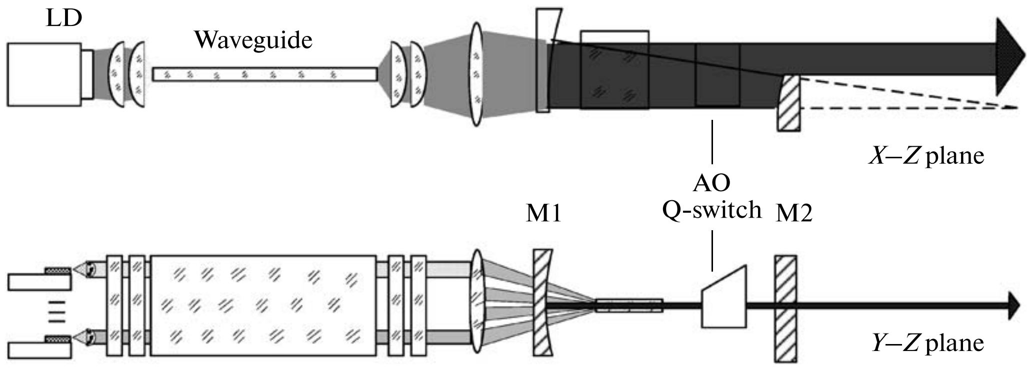

Fig. 1. Experiment arrangement of laser-diode-stack pumped acousto-optic Q-switched NdYVO$_4$ slab oscillator.

effective and uniform thermal contact and cooling. An AO Q-switch was inserted in the cavity with the repetition rate from 1 to 100 K. The size of AO Q-switch along with x-axis was ~9.5 mm, which was shorter than that of Nd:YVO$_4$ slab. Therefore, the pumping power mentioned in this paper was 80% of LD output power and the diffraction of Q-switch will increase the losses and lower the beam quality.

M1 (concave spherical mirror) and M2 (convex cylindrical mirror), with the radius of 500 and 350 mm, respectively, were chosen to be as resonator mirrors. The magnification of unstable direction was $M = -R_1/R_2 = 1.67$ and the equal transmission was $T = 1 - 1/M = 30\%$. As shown in Fig. 1, M1 and M2 built up a concave-flat stable resonator in vertical direction and an off-axis positive confocal unstable resonator in the horizontal direction. While considered as laser crystal and AO Q-switch, the real cavity length should be calculated as (1), where L was the real cavity length, R_1 and R_2 were radius of cavity mirrors, k, l, and n were the number, length and refractive index of elements inserted in the resonator, respectively. In our experiment it was about 110 mm.

$$L = \frac{R_1 + R_2}{2} + \sum_{i=1}^{k}\left(1 - \frac{1}{n_i}\right)l_i. \quad (1)$$

Thermal lens is an important factor which effects the output power and beam quality of laser. The thermal lens of laser in this experiment can be estimated as [23]

$$f = \left\{\frac{\eta I_0}{K_y}\left(\frac{dn}{dT}\right)_x [1 - \exp(-\alpha L)]\right\}^{-1}, \quad (2)$$

where η is the total heat generating efficiency, I_0 is the intensity of pumping laser, K_y is the heat conductivity coefficient, $\frac{dn}{dT}$ is thermal optical coefficient, α and L are the absorption coefficient and length of slab, respectively. Figure 2 shows thermal lens and g param-

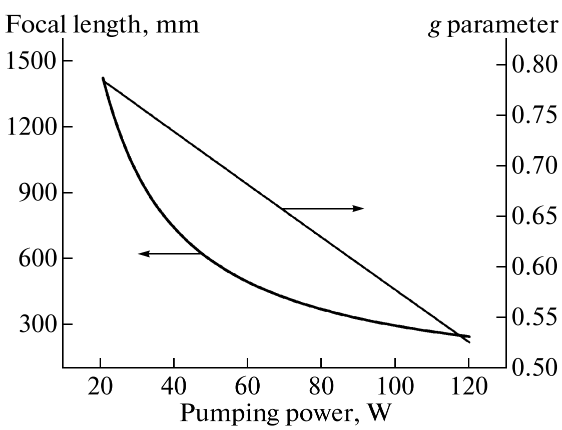

Fig. 2. Thermal lens and g parameter as a function of pumping power.

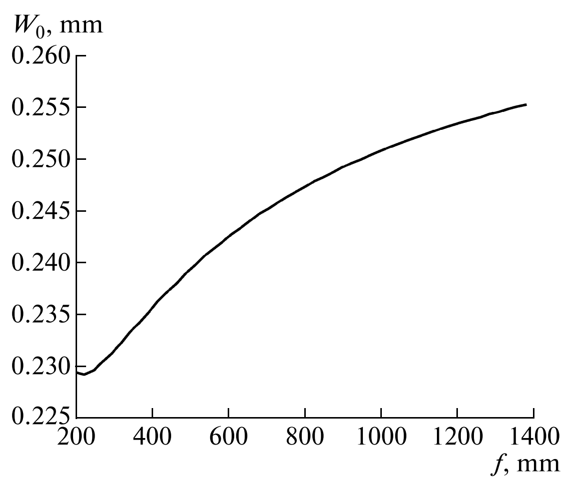

Fig. 3. Radius of spot at the end of slab in the Y–Z plane as a function of thermal lens.

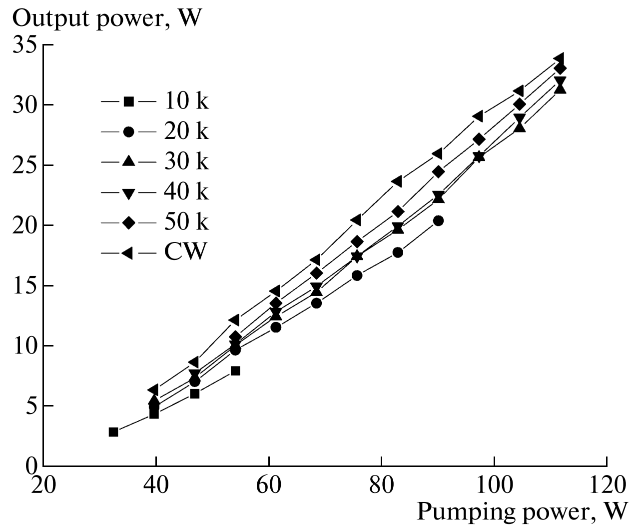

Fig. 4. Output power as a function of pumping power.

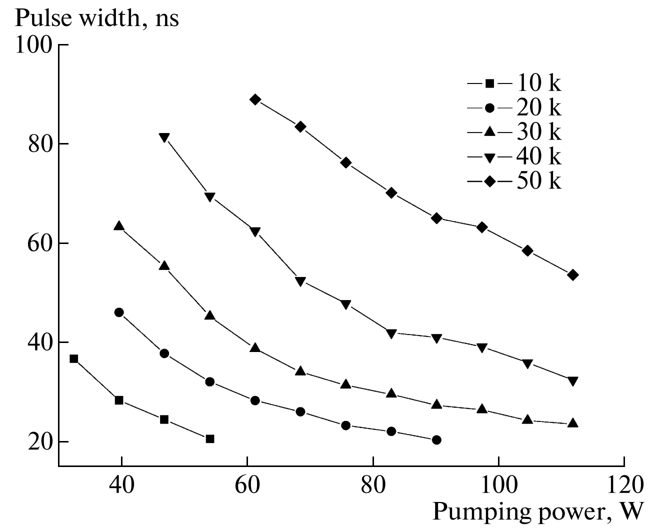

Fig. 5. Pulse width as a function of pumping power.

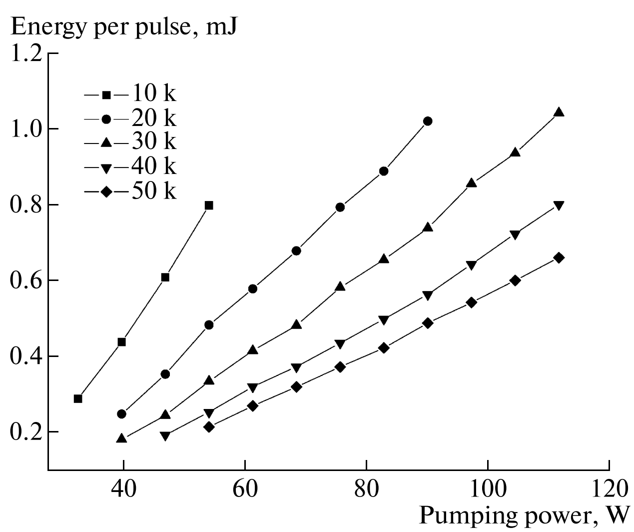

Fig. 6. Energy per pulse as a function of pumping power.

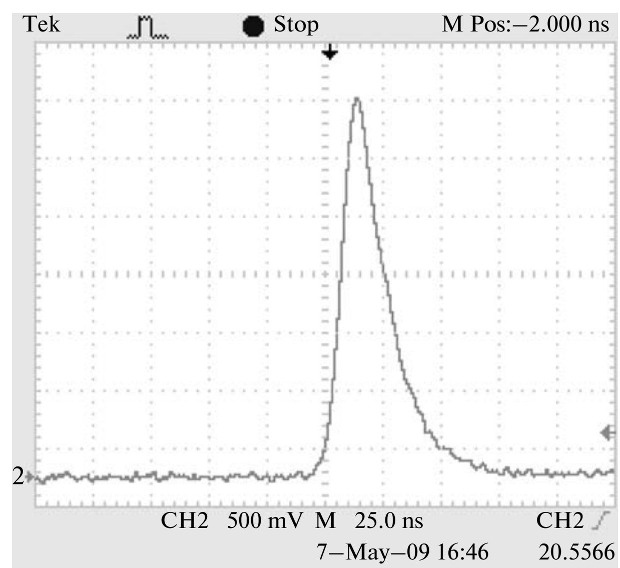

Fig. 7. Typical pulse profile with the pulse width of 20.9 ns.

eter as a function of pumping power. It can be seen that, with the pumping power from 20 to 120 W, the thermal lens ranged from ~1400 to ~200 mm and the g parameter of resonator in Y–Z plane changed from 0.77–0.52, which keeping in stable scope. Figure 4 gave the radius of TEM00 mode at the end of slab as a function of focal length. In order to get a high beam quality laser in the stable direction, the match of pumping laser and oscillator laser is necessary. In our experiment, a one dimension top-hat pumping line with the size of 12 × 0.5 mm was adjusted to obtain TEM00 operation.

Figure 4 gave the output power as a function of pumping power at continuous wave and Q-switched situation with different repetition rate. With the same pumping power, the higher repetition rate the laser operated, the more average power was got. Figures 5 and 6 showed the pulse width and energy per pulse at different repetition rate respectively. Under the pumping power of 112 W, the highest power of 32.1 W was obtained with the pulse width of 32.47 ns and energy per pulse of 0.8 mJ. At this moment, the peak power reached 24.6 kW, the slope efficiency and optical-to-optical efficiency were 37 and 28.7%, respectively. At

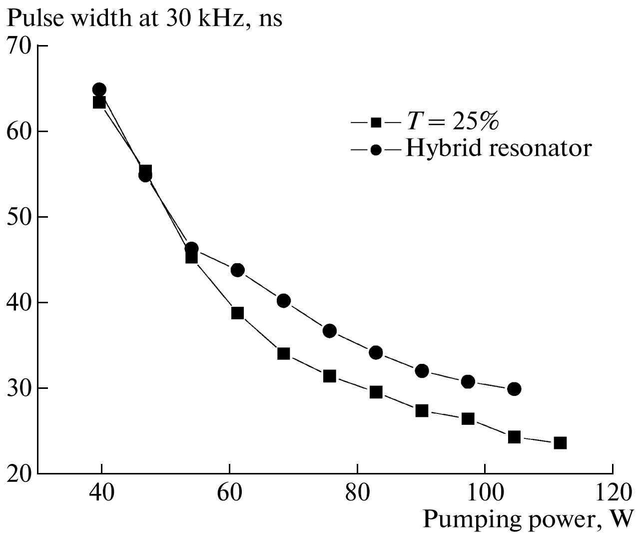

Fig. 8. Pulse width of LD end-pumped Nd:YVO_4 slab laser with stable and hybrid resonator at the repetition of 30 kHz.

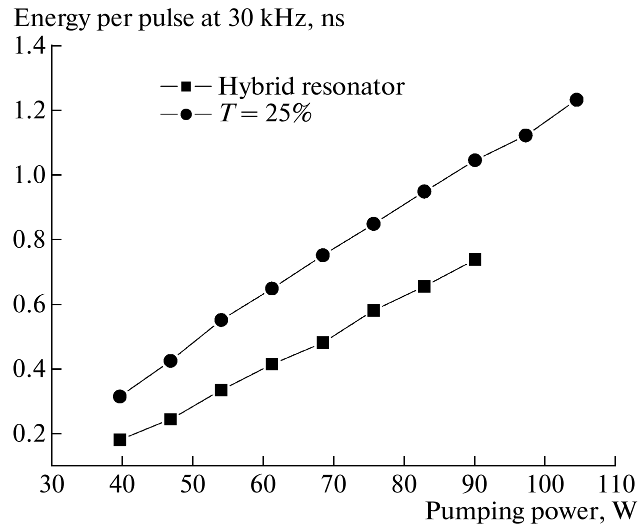

Fig. 9. Energy per pulse of LD end-pumped Nd:YVO_4 slab laser with stable and hybrid resonator at the repetition of 30 kHz.

the repetition rate of 20 kHz and pumping power of 90 W, the shortest pulse width of 20.43 ns and average output power of 20.4 W were got. Figure 7 was the typical pulse profile with the pulse width of 20.9 ns.

The pulse width and energy per pulse of output laser between stable resonator and hybrid resonator at 30 kHz were shown in Figs. 8 and 9. The transmission of output mirror was chosen as 25%, as the equal transmission of hybrid resonator in our experiment was 30%. The cavity length was the same as hybrid resonator (110 mm). It can be seen that, the pulse width and energy per power with hybrid resonator were both lower due to larger transmission and geometrical diffraction looses.

In the *Y–Z* plane, the beam quality of hybrid resonator can be considered as the same as that of stable resonator, while in *X–Z* plane it was much better. As mentioned in [21], the number of transverse mode in *X–Z* plane was estimated as $N \approx \pi a\theta/\lambda$, where a was half width of slab and θ was far-field divergence half-angle, which was ~140 in our experiment. However, a near-diffraction-limited beam quality could be achieved with hybrid resonator. To measured beam quality of output laser, a lens ($f = 350$ mm) and a thin knife was used. Under the pumping power of 112 W, the beam quality M^2 factors in CW operation were measured as shown in Fig. 10. In the stable direction, the M^2 factor was 1.3 and in the other direction was 1.6. The M^2 factor in unstable direction was larger than that investigated in [24] (1.4) and [25] (1.3). The reason was that diffraction of both output mirror and Q-switch was formed in this experiment.

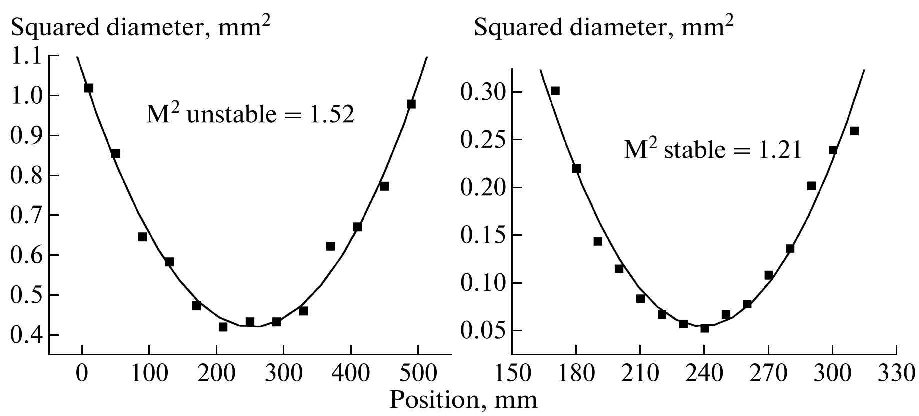

Fig. 10. Beam quality of CW laser under the pumping power of 112 W.

In conclusion, using AO Q-switch, a 32.1 W laser-diode-stack pumped $Nd:YVO_4$ slab laser with hybrid resonator was achieved under the pumping power of 112 W and the repetition rate of 40 kHz. The slope efficiency and optical-to-optical efficiency were 37 and 28.7%, respectively. It was experimentally proved that with the same pumping power, shorter pulse width, lower energy per pulse and better beam quality was generated by using hybrid resonator.

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