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Efficient, high power, Q-switched Nd:YLF slab laser end-pumped by diode stack

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Abstract

A high power diode stack end-pumped electro-optically Q-switched Nd:YLF slab laser with a stable and off-axis negative-branch confocal unstable hybrid resonator was demonstrated. By using a cylindrical lens in the stable direction the thermal lens effect was compensated. Pulse energy of 25 mJ was obtained with a pulse width of 22.4 ns at repetition rates of 500 Hz and a conversion efficiency of 22%. The stability was better than 0.8% and the beam propagation M^2 factor was about 1.2.

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Keywords: DPSSl; Slab laser; Hybrid resonator; Nd:YLF

Diode-pumped solid-state lasers have been shown to be efficient, lightweight, compact, and reliable sources [1]. In addition to these qualities, a large class of applications that ranges from laser machining to target tracking and illumination requires good transverse-beam quality that is diffraction limited in the ideal case, which allows the laser energy to be delivered within a small solid angle in the far field. When good beam quality is required from a laser that uses conventional stable resonator, pulse energy is limited owing to the small fundamental mode volume. Unstable resonators can produce near-diffraction-limited beams with larger transverse-mode volume than comparable sized stable resonators. As a result, unstable resonators enable higher-energy output pulses of good beam quality than those possible with stable resonators.

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Partially end-pumped slab lasers with hybrid resonators have proved to be favourite for power scaling at high beam quality and efficiency [2–4], as they have the properties of both the high overlapping efficiency of end-pumped rod lasers and the excellent cooling conductivity of slab lasers [2]. The hybrid resonator is stable in the plane of small dimension and is off-axis unstable in the plane of large dimension of the slab gain cross section.

In our previous experiments, a stable and positive off-axis unstable hybrid resonator was adopted, energy per pulse of 14.3 mJ with pulse width of 8.5 ns had been obtained with a diode-stack end-pumped Nd:YLF slab laser [5]. To achieve higher energy without increasing the peak power and damaging of optics, one way is to enlarge the pulse length by using a longer resonator, since the FWHM pulse width is directly proportional to the cavity round-trip time [1]. With the same magnification $M = 10/7$, using mirrors with larger radii can simply lengthen the resonator length, but we did not have mirrors with very large radii at hand (for example, the respective radii of the mirrors will be 2.67 and −1.87 m for a cavity length of 400 mm with the magnification remaining 10/7), so a negative branch off-axis confocal unstable resonator was used, since for a negative confocal resonator, the cavity length is $L = (R_1 + R_2)/2$, (R_1 and R_2 are positive for a negative confocal unstable resonator) [6].

The negative-branch resonator has been neglected in practical laser applications due to the presence of an intra-cavity focal point. Despite the potential problem of air breakdown this resonator merits consideration due to its unique feature of relatively large misalignment tolerances. Furthermore, there is rarely risk of air breakdown for small solid-state lasers, typical with peak power less than 5–10 MW [6].

The experimental arrangement of the slab laser is shown in Fig. 1. The pumping unit consists of an 8-bar diode stack, the radiation emitted by each diode laser bar was individually collimated by a microlens. The coupling system was the same as that used in Ref. [5]. After the coupling system, a homogeneous pumping line with dimensions of 0.4 mm × 12 mm was generated inside the Nd:YLF slab. With such pumping unit, 88% of the diode laser power was transmitted to the Nd:YLF slab. By controlling the temperature of the cooling water the central wavelength of the emission was fixed around 791 nm. The estimated pump absorption is about 95% in this configuration. In the experiments, the diode stack was used with rectangular-in-time 200-μs duration current pulses. The diode stack can operate at a maximum repetition frequency of 1000 Hz. To avoid any damage of the laser crystal due to thermal effects under high pump power, we operated the diode stack at a repetition frequency of 500 Hz. The spectral width of the diode laser stack was 3.5 nm.

The Nd:YLF slab was with an Nd concentration of approximately 1%. It had the size of 1 mm × 10 mm × 12 mm and was cut with its *c*-axis parallel to its 12-mm edge. The crystal was mounted between two water-cooled heat sinks with two large faces (12 mm × 10 mm), which

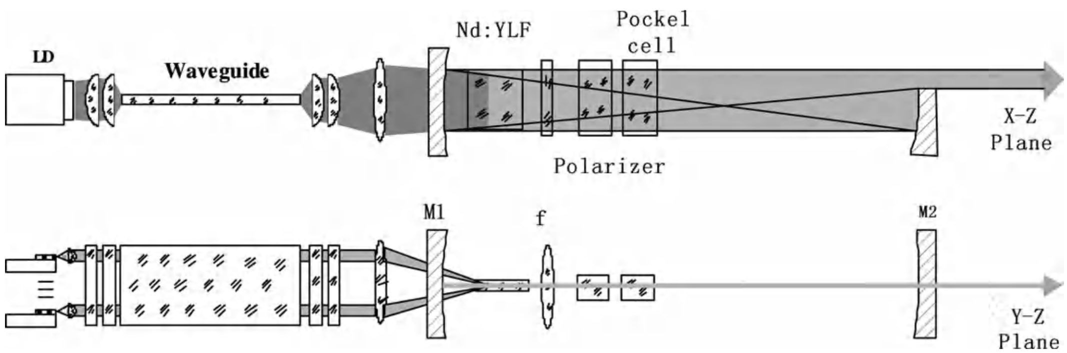

Fig. 1. Schematic diagram of the experimental setup.

served as thermally conducting surfaces. Indium foils were used for effective and uniform thermal contact and cooling. Only two 1-mm × 12-mm end faces of the slab crystal needed to be polished and coated for passing the pump radiation (791-nm) and laser beam (1047-nm).

Two spherical mirrors, with curvature radius of 500 and 350 mm were used as resonator mirrors, both the mirrors were coated high reflective (>99.5%) at 1047 nm and high transmission (>95%) at 791 nm. The distance between the two mirrors was 425 mm. In the x–z plane, a negative branch confocal off-axis unstable resonator with magnification $M = 1.4$ was formed [6]. The output coupling was $1 - 1/M = 30\%$. The mirror M_2 was cut and polished at one edge. The laser beam was coupled out by the edge.

It is known that in Nd:YLF the negative thermal dispersion can partly compensate the surface deformation and in π-polarization, the thermal dispersion even overcompensates the deformation and induces a strongly negative thermal lens [7,8]. To keep the resonator remaining stable in the plane perpendicular to the pump line and let the resonator mode size match that of the pump light, a cylindrical lens was inserted inside the resonator and placed near the Nd:YLF crystal.

Assuming that the pumped crystal can be modelled as a negative thermally induced cylindrical lens, we calculated the resonator TEM_{00} Gaussian modes size in the stable direction by applying the standard formalism of the q beam parameter and the ray matrix. Fig. 2 shows the calculated behaviour of the Gaussian TEM_{00} spot size in the crystal as a function of focal length of the negative thermal lens. This demonstrates that with a cylindrical lens of 100-mm focal length adjacent to the Nd:YLF crystal the mode size was about 0.4 mm at the crystal – nearly equal to the pump size – for focal length of thermal lens ranging from −1000 to −180 mm. As for $f = 200$, 300, or 400-mm cylindrical lens, the mode sizes become larger, the mode matching becomes worse. Cylindrical lens with focal length of 100 and 200-mm were tried in the experiments to compensate the thermally induced focus effect, in free-run condition (with the polarizer and Pockels box inside the resonator), the slope efficiencies were 34.7% and 30.5%, respectively, and the result is shown in Fig. 3. From Fig. 3 we can see that in the whole pump power range, the output energy with $f = 100$ mm cylindrical lens was higher than that with $f = 200$ mm cylindrical lens due to better modes matching, we can also see that in the whole pump power range, no saturation appears. So we chose the $f = 100$ mm cylindrical lens in the following experiments. In Fig. 3 and the figures followed, the x-coordinate pump

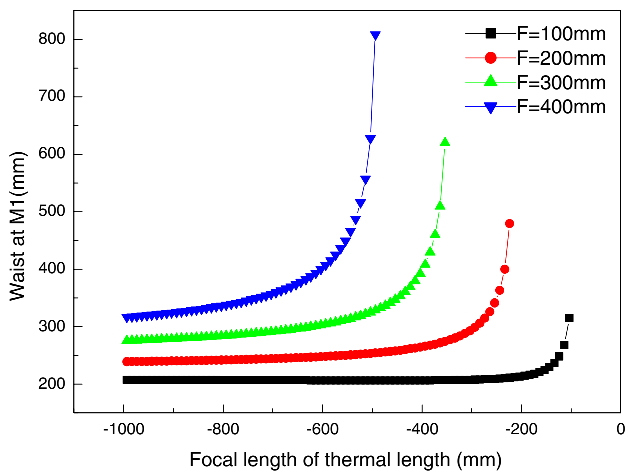

Fig. 2. Calculated mode sizes at laser crystal as a function of focal length of the thermal lens with $f = 100$, 200, 300 and 400-mm cylindrical lens inserted near the Nd:YLF crystal, respectively.

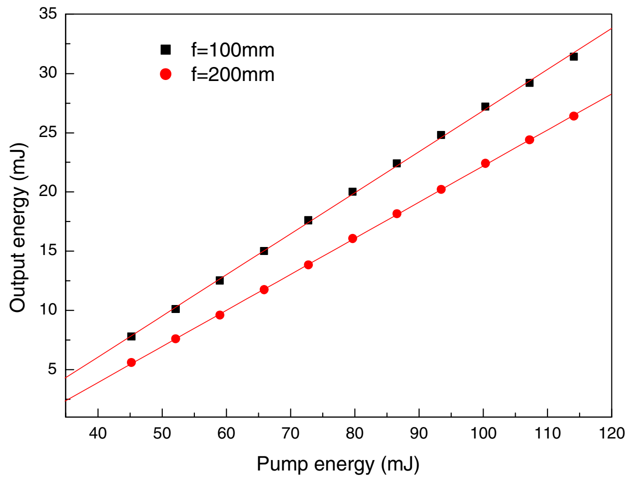

Fig. 3. Experimental results with f = 100 and 200-mm cylindrical lens to compensate the thermally induced focal lens effect.

energy referred to the energy that incident upon the input mirror.

A birefringent polarizer and a high power β-BBO electro-optical Pockels cell were used for Q-switching. To maximize the Q-switched energy and to optimize the pulse shape, we synchronized the high-voltage pulse with falling edge of the pump pulse, and the rise time was about 20 ns.

Fig. 4 shows the measured output laser energy per pulse as a function of the pump energy in free-run and Q-switching regimes, at 500 Hz repetition frequency. In the Q-switching regime, 25 mJ was obtained at a pump energy of 114 mJ, the optical slope efficiency was ~24.4% and the overall optical efficiency was ~22%. The efficiencies from pump to output energy in both free-running mode and in Q-switched mode were higher than those we obtained in Ref. [5], where a stable and positive branch unstable hybrid resonator was used, the reason we think was mainly due to better mode size matching in this experiments. The pulse width was measured by a fast photo diode (~0.3 ns rise time) and a 600-MHz bandwidth Tektronix digital

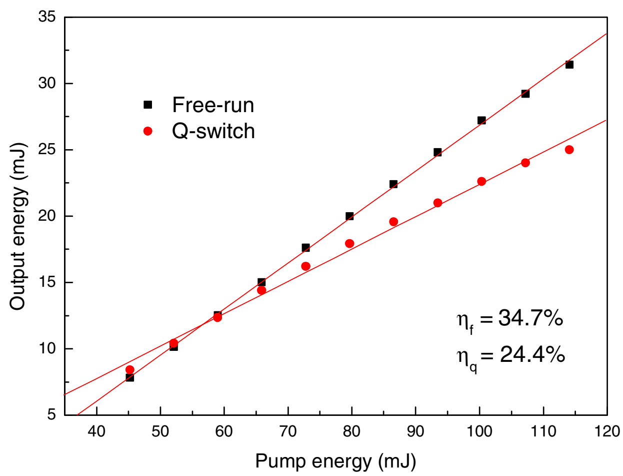

Fig. 4. Output energy per pulse as a function of pump energy in free-run mode and Q-switched mode.

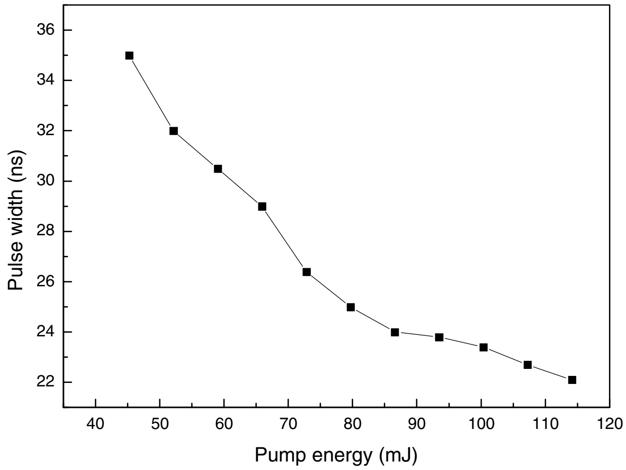

Fig. 5. Pulse width as a function of pump energy.

analyzer (DSA 602). Fig. 5 shows the pulse width as a function of pump energy. At a pump energy of 114 mJ, the pulse width was 22.4 ns, corresponding to a peak power of 1.14 MW. Output pulses were always observed to be at 1047 nm and polarized parallel to the YLF *c*-axis. A typical pulse profile was shown in Fig. 6. The stability of 1047 nm pulse energies was also measured by the Tektronix digital signal analyzer, the standard deviation of pulse-to-pulse energy was less than 0.8% as the incident pump energy was 114 mJ, this is much better than that of in Ref. [5] (1.3%), which is mainly due to the large misalignment tolerances of the negative-branch resonator.

A lens (*f* = 300-mm) and a CCD camera (Spiricon) were used to measure the laser beam quality. When we measured the beam factor, the beam radius was defined to enclose about 86% of the total power. Since the central maximum enclosed more than 90% of the power, in this case the side lobes do not influence the beam quality. M^2 in both the stable and the unstable direction were about 1.2. Fig. 7 shows the intensity distribution in the far-field for a pump energy of 114 mJ. In the stable

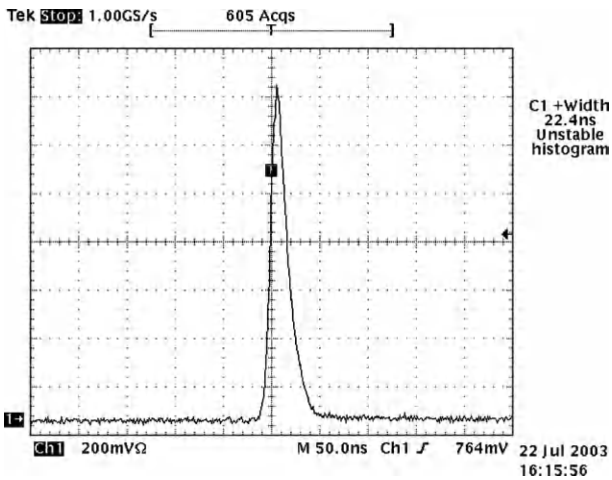

Fig. 6. A typical Q-switched pulse profile.

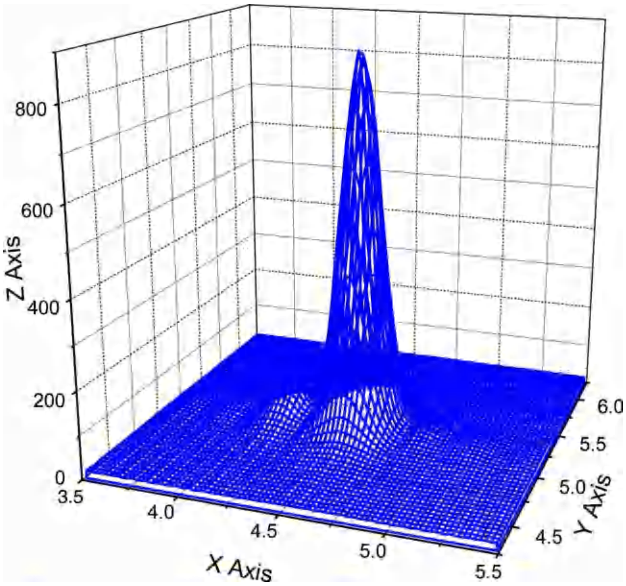

Fig. 7. Far-field intensity distribution.

direction it is Gaussian. As expected, in the unstable plane it shows a maximum with side lobs of low intensity due to the diffraction on the edge of the output coupling mirror.

In conclusion, we demonstrated an efficient diode stack end-pumped electro-optically Q-switched Nd:YLF slab laser with a stable and off-axis negative unstable hybrid resonator. Energy per pulse of 25 mJ with pulse width of 22 ns at 500 Hz was achieved, the overall efficiency from pump (incident upon the input mirror) to output was 22%, the stability is better than 0.8% and the M^2 factors in both directions are about 1.2.

Acknowledgements

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