

Direct-liquid-cooled Nd:YAG thin disk laser oscillator

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Abstract A Nd:YAG thin disk laser oscillator convection-cooled directly by the liquid is demonstrated. Lasing performance at different flow patterns and different flow rates is studied in detail. Micro-scale eddies that appear at the disk edge can induce decrease of the output power and the degradation of beam quality. 17.1 W of output power is realized at the maximum pump power of 54.8 W, corresponding to the optical–optical efficiency of 31.2 %, and the slope efficiency of 37.5 %.

1 Introduction

Thermal effect is one of the main limiting factors for raising the output power from the solid-state lasers [1, 2]. To dissipate the heat efficiently, most solid-state lasers nowadays employ the conduction cooling method, in which the heat deposited in the gain medium is conducted to the heat sink [3, 4]. Furthermore, various approaches to reduce the thermal gradient and ease the thermal effects have been proposed, such as the zig-zag optical path [5–7], ultrathin disk configuration [8, 9], and multi-level concentration doping of gain mediums [10, 11]. However, the output power and beam quality still suffer from extremely large thermal-induced stress at high pump power, with the risk of fracture of gain medium.

Direct-liquid-cooled configuration, in which the circulating liquid flows over the surfaces of the gain medium to carry the heat away, has been proven to be an alternative

cooling method, showing a great potential for producing high-power lasers. Textron Defense Inc. presented an impressive 27 kW output from a single laser oscillator module as well as 100 kW output from the single aperture with six laser modules placed within the cavity, by using Nd:YAG ceramic thin slabs and the direct-liquid-cooled configuration [12]. In addition, General Atomics Corp. has been proposing the “liquid laser” scheme that has the liquid flowing over the clear aperture, expecting to realize 150 kW output power with the weight no more than 750 kg [13], which would be a significant improvement on the compactness and output capability of current solid-state high-power laser systems.

Compared to conduction-cooled solid-state laser structure, convection-cooled solid-state laser configuration has several interesting features. First, convection cooling by the liquid is currently the most efficient and powerful cooling method, since it can realize much larger heat transfer coefficient than the conduction cooling. Second, for the case of convection cooling, the gain medium is totally immersed in the liquid that is moving and flexible, while in the conduction-cooled case, the gain medium contacts the heat sink that is static and rigid. Third, the laser beam passes through the flowing liquid, which may bring in variation of the refractive index and other effects that influence the laser output parameters. Fourth, the liquid may absorb a portion of the pump light and laser light, which would increase the cavity loss and reduce the pump absorption efficiency. Therefore, being different from the research on conduction-cooled laser, attention must be paid not only to the heat exchange process between the gain medium and cooling medium, but also to the interaction among the cooling liquid, gain medium and the optical beam.

In this letter, a direct-liquid-cooled Nd:YAG thin disk laser oscillator is presented. 17.1 W multimode laser

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output is achieved with the optical–optical efficiency of 31.2 %. Lasing performance is investigated at different flow pattern, flow rate, and pump current, in terms of output power, beam profile and beam quality, indicating that the turbulent flow results in the decreased mode-matching factor and degradation of beam quality.

2 Experimental setup

The experimental setup of the direct-liquid-cooled thin disk oscillator is shown in Fig. 1. Nd:YAG is chosen as the gain medium, while the de-ionized water is used as the cooling liquid. The Nd:YAG thin disk is supported in a water-filled chamber with two windows. Each window has one side antireflection (AR) coated (relative to air) for both 808 and 1,064 nm, and the other side AR coated (relative to water) for 808/1,064 nm. Circulating water at the temperature of 15 °C passes through the chamber from the inlet to the outlet, flowing all over the surfaces of the gain medium especially the two large apertures, and taking away the deposited heat in the way of convection cooling. The spacing between the disk end surface and the window is 2 mm.

The disk-shaped gain medium Nd:YAG is 20 mm in diameter and 6 mm in thickness with the Nd^{3+} doping concentration of 0.8 at. %. The end surface (S_1) closer to the pump source is coated with AR films (relative to water) at both 808 and 1,064 nm, while the other end surface (S_2) is AR coated (relative to water) at 1,064 nm and high-reflection (HR) coated (relative to water) at 808 nm. Therefore, the pump light undergoes double-pass absorption within the crystal, thus the absorption efficiency η_{abs} can be calculated as

$$\begin{aligned}\eta_{\text{abs}} &= 1 - \exp(-n_d \alpha_{\text{Nd}} l_{\text{ab}}) \\ &= 1 - \exp(-0.8 \times 3 \times 0.6 \times 2) = 94.4 \%\end{aligned}$$

where $n_d = 0.8$ is the relative doping concentration, $\alpha_{\text{Nd}} = 3 \text{ cm}^{-1}$ is the effective pump absorption coefficient

for 1 at. % doped Nd:YAG at 808 nm, and $l_{\text{ab}} = 1.2 \text{ cm}$ is the absorption length.

The absorption coefficient of the de-ionized water is measured as $\alpha_w = 0.1431 \text{ cm}^{-1}$ at 1,064 nm, which corresponds to that of the cooling medium of the total thickness of 4 mm adds a single-pass cavity loss σ as

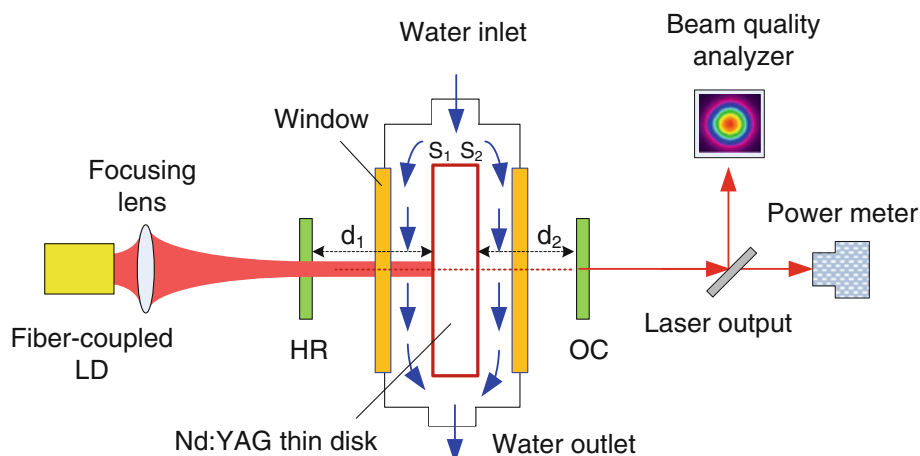
$$\sigma = 1 - \exp(-\alpha_w l_w) = 1 - \exp(-0.1431 \times 0.4) = 5.6 \%$$

The thin disk is pumped from one end by a fiber-coupled laser diode (Jenoptik JOLD-75-CPXF-1L) that provides continuous output power of up to around 55 W (at current of 6 A) at 808 nm through a 400- μm core, 0.22 NA fiber. The temperature of the pump source is controllable by the thermoelectric cooling module for the optimum pump absorption in the gain medium. The pump light from the coupling fiber is further imaged onto the pump surface of Nd:YAG thin disk by an aberration-free lens group, resulting in the waist size of 0.4 mm of the pump spot in the crystal, while the magnification of the lens coupling system is 1:2. A planar–planar cavity is used in the oscillator, with the arm length of $d_1 = 25 \text{ mm}$ and $d_2 = 40 \text{ mm}$. The output mirror has the transmission of 40 %. The dichroic mirror that placed between the pump source and the crystal is AR coated (relative to air) at 808 nm for pump light passage, and HR coated (relative to air) at 1,064 nm, serving as the high reflector of the resonator. The output power of the oscillator is measured by the Ophir power meter, and a Spiricon M2-200s laser beam analyzer is used to measure the beam quality, while the wavefront of laser output is measured by a Shack–Hartmann wavefront sensor.

3 Experimental results and discussion

In order to figure out the change of water flow pattern at different flow rates, a few bubbles are deliberately mixed into the flow, which clearly indicates the track of water

Fig. 1 Experimental setup of the direct-liquid-cooled thin disk oscillator



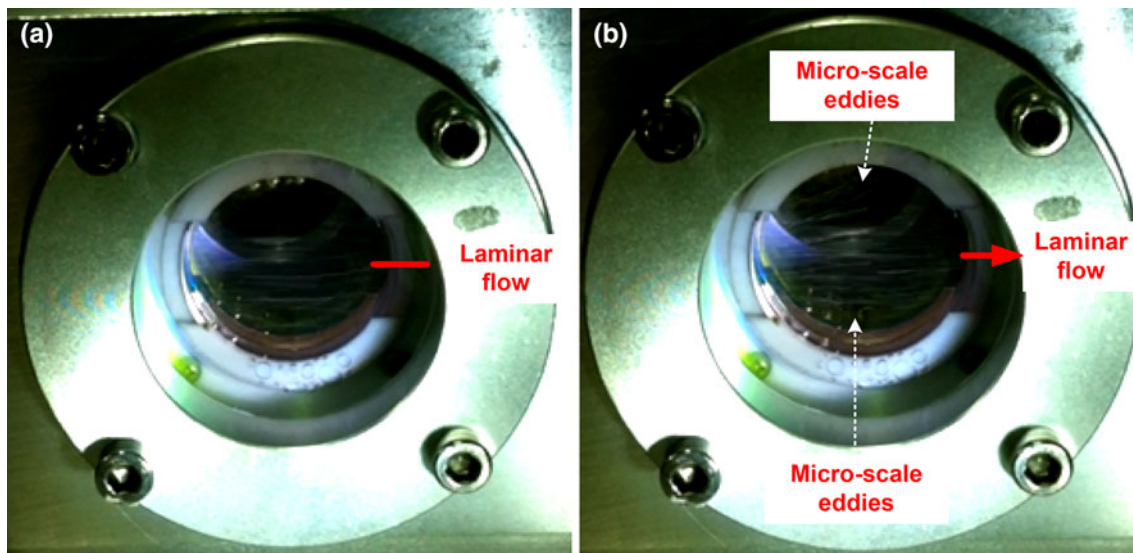


Fig. 2 Photograph of the water flow pattern at the flow rate of **a** 1 m/s, **b** 2 m/s

fluid within the chamber. Cases at the flow velocity of 1 and 2 m/s are observed and studied, with the photograph shown in Fig. 2a, b, respectively. It can be seen that in both cases, the water fluid intensity is much stronger at the disk center region than at the upper/lower edge region, due to smaller width of water inlet than the disk diameter. With the flow rate as low as 1 m/s, the water stream is basically smooth and straight, flowing from the inlet (left) to the outlet (right) in the pattern of laminar flow. However, with the flow velocity increased to 2 m/s, micro-scale eddies appear at the upper and lower edge of the disk, indicating the turbulence performance, while at the region along the line connecting the inlet and the outlet, water is still mainly in the pattern of laminar flow. Studying the influence of water flow pattern and flow rate on the laser performance of the direct-liquid-cooled thin disk oscillator is of great interest and significance. As Fig. 3 illustrates, experiments

with pump spot focused on the disk center (laminar region) and on the upper edge (turbulent region) of the disk are carried out individually.

Laser outputs are successfully obtained in both cases, and the output power curves versus pump power are described in Fig. 4. With the pump spot at the disk center and the cooling flow rate of 2 m/s, 17.1 W of output power is achieved at the maximum pump power of 54.8 W, corresponding to the optical–optical efficiency of 31.2 %, and the slope efficiency of 37.5 %. When the flow velocity decreases to 1 m/s, the maximum output power drops to 14.5 W. It indicates that reduction of flow velocity weakens the cooling capacity, therefore the laser suffers from more serious thermal effect and thus the power drops, especially at higher pump power. In addition, by comparing the square-marked curve and triangle-marked curve, we can see the maximum output power drops even further to

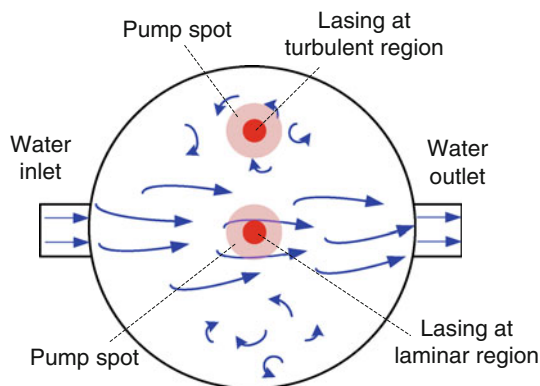


Fig. 3 Diagram of the water flow pattern in laminar and turbulent region

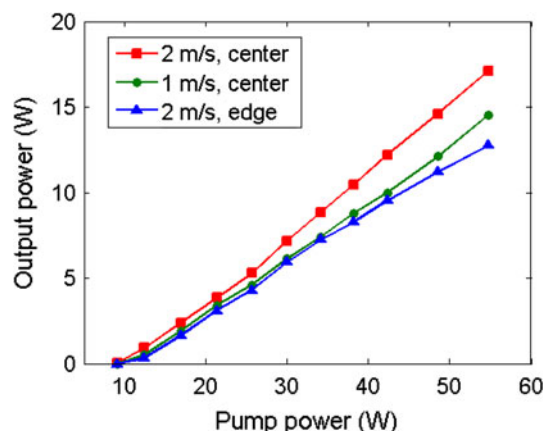


Fig. 4 Output power vs. pump power, for different lasing region and flow rate

Table 1 Beam profile vs. different pump power and flow rate, with the pump spot at edge

	2A (10.5 W)	3A (21.4 W)	4A (32.1 W)	5A (42.3 W)	6A (54.8 W)
2 m/s @Crystal Edge					
1 m/s @Crystal Edge				No laser output	No laser output

12.8 W with the pump spot location moved to the disk upper edge. This is partly due to weaker heat exchange in turbulence region than the laminar flow region, and partly because the turbulence itself makes small-scale variation of refractive index distribution and thus degrade the mode matching between the pump mode and the laser mode. The pump thresholds for the three cases are, respectively, 9.13 W (2 m/s, center), 9.28 W (1 m/s, center) and 9.42 W (2 m/s, edge), indicating that the threshold is slightly raised with stronger thermal effects. The pump threshold would be further reduced if a specific liquid with little absorption at 808 and 1,064 nm is used as the cooling medium instead of the de-ionized water.

Beam quality of the direct-liquid-cooled thin disk oscillator is studied in the following. Table 1 illustrates the evolution of laser output profile as the pump current increases, for the case of pump spot at disk edge, with the flow rate of 1 and 2 m/s, respectively. The output profile is measured at the location of beam waist using the beam quality analyzer. It can be found that for the case with the flow rate of 2 m/s, the beam profile keeps good roundness as the pump power rises, in spite of the turbulent flow. However, for the case with the flow rate of 1 m/s, the flow intensity at disk edge is so weak that the cooling capacity can not afford the serious thermal effects, thus the beam profile quickly deteriorates from circular shape and it even collapses with no laser output at the current over 5 A.

Figure 5 compares the beam quality of laser output in horizontal (M_x^2) and vertical (M_y^2) direction, respectively, for different flow pattern and flow rate. At the maximum pump power of 54.8 W, the beam quality for the case with pumping at center and the flow rate of 2 m/s, is measured as $M_x^2 = 5.80$ and $M_y^2 = 6.33$. For the case of same flow rate but with the pumping location at disk edge, the beam quality degrades to $M_x^2 = 6.61$, $M_y^2 = 7.44$. It indicates that the swirling flow in turbulent region did influence the propagation of oscillating laser and the formation process of self-reproductive mode in the cavity, leading to smaller mode-matching factor and thus the degradation of beam quality, which is consistent with the phenomenon of power

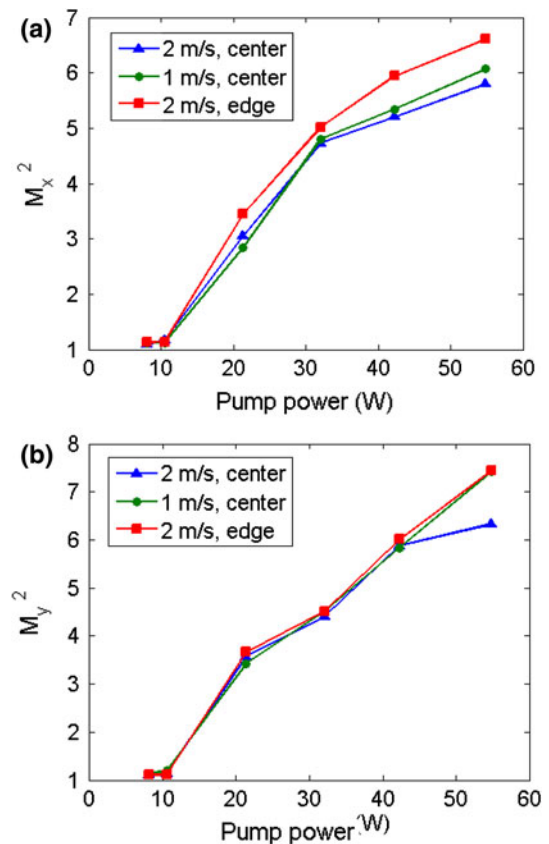


Fig. 5 Beam quality for different lasing region and flow rate: **a** M_x^2 , **b** M_y^2

drop in turbulent region as mentioned above. For the case with pump spot at center, as the flow rate get down to 1 m/s, the beam quality degrades to $M_x^2 = 6.07$ and $M_y^2 = 7.42$, apparently due to reduced convection heat transfer coefficient. It should be noted that in x direction the beam quality for three cases barely change until the pump power goes over 45 W. Beam quality in y direction is worse than that in x direction, because of lower uniformity of flow intensity in y direction than in x direction since the water flowing direction is along x axis.

4 Conclusion

We demonstrate a Nd:YAG thin disk laser oscillator convection-cooled directly by the liquid. 17.1 W of output power is realized at the maximum pump power of 54.8 W, corresponding to the optical–optical efficiency of 31.2 %, and the slope efficiency of 37.5 %, with the multimode beam quality measured as $M_x^2 = 5.80/M_y^2 = 6.33$. Micro-scale eddies are observed at the upper and lower edge of the disk, while the main stream within the chamber passes the disk center. Comparing to the case with laminar flow, turbulent flow brings degradation to the power and beam quality. Based on this work, fundamental mode output are expected to be realized in the near future by using the stable resonator with optimized cavity length and curvature of mirrors, or using the unstable resonator, while higher output power would be available by injecting more pump power. In addition, the detailed theoretical modeling will be developed on the interaction among the gain medium, optical beam and the flowing liquid.

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References

1. A.E. Blume, K.F. Tittel, Thermal effects in laser amplifiers and oscillators. *Appl. Opt.* **3**, 527–530 (1964)
2. V. Sazegari, M.R.J. Milani, A.K. Jafari, Structural and optical behavior due to thermal effects in end-pumped Yb:YAG disk lasers. *Appl. Opt.* **49**, 6910–6916 (2010)
3. A. Minassian, B. Thompson, M.J. Damzen, Ultrahigh-efficiency TEM₀₀ diode-side-pumped Nd:YVO₄ laser. *Appl. Phys. B* **76**(4), 341–343 (2003)
4. S. Tokita, J. Kawanaka, M. Fujita, T. Kawashima, Y. Izawa, Sapphire-conductive end-cooling of high power cryogenic Yb:YAG lasers. *Appl. Phys. B* **80**(64), 634–638 (2005)
5. G.D. Goodno, H. Komine, S.J. McNaught, S.B. Weiss, S. Redmond, W. Long, R. Simpson, E.C. Cheung, D. Howland, P. Epp, M. Webber, M. McClellan, J. Sollee, H. Injeyan, Coherent combination of high-power, zigzag slab lasers. *Opt. Lett.* **31**(9), 1247–1249 (2006)
6. A.K. Sridharan, S. Saraf, S. Sinha, R.L. Byer, Zigzag slabs for solid-state laser amplifiers: Batch fabrication and parasitic oscillation suppression. *Appl. Opt.* **45**(14), 3340–3351 (2006)
7. R. Yasuhara, T. Kawashima, T. Sekine et al., 213 W average power of 2.4 GW pulsed thermally controlled Nd:glass zigzag slab laser with a stimulated Brillouin scattering mirror. *Opt. Lett.* **33**, 1711–1713 (2008)
8. J. Speiser, A. Giesen, *Scaling of Thin Disk Pulse Amplifiers* in Proc. SPIE, 2008, vol. 6871, p. 68710J
9. A. Giesen, J. Speiser, Fifteen years of work on thin-disk lasers: results and scaling laws. *IEEE J Sel Topics Quantum Electron* **13**(3), 598–609 (2007)
10. C. Orth, R. Beach, C. Bibeau, et al., *Design Modeling of the 100-J Diode-Pumped Solid-State Laser for Project Mercury*. in Proc. of SPIE, 1998, vol. 3265, pp. 114–129
11. R. Wilhelm, D. Freiburg, M. Frede, D. Kracht, End-pumped Nd:YAG laser with a longitudinal hyperbolic dopant concentration profile. *Opt. Express* **16**(24), 20106–20116 (2008)
12. A. Mandl, D.E. Klimek, *Textron's J-HPSSL 100 kW ThinZag® Laser Program*, in Conference on Lasers and Electro-Optics, OSA Technical Digest (CD) (Optical Society of America, 2010), paper JThH2
13. http://en.wikipedia.org/wiki/High_Energy_Liquid_Laser_Area_Defense_System. Accessed 13 Feb 2013