# Large-aperture end-pumped Nd:YAG thin-disk laser directly cooled by liquid

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A large-aperture Nd:YAG thin-disk laser directly cooled by liquid is end-pumped by two spatial self-organized laser diode arrays. The pump coupling efficiency reaches as high as 93%. Without any complex pump coupling components, the structure becomes simplified and compact. By optimizing the incident angle of the pump beam, a pump power density of 578 W/cm$^2$ is achieved with a pump uniformity of 5.52%. Up to 1 346-W peak output power with a slope efficiency of 54.9% is obtained when pumping with a long pulse. The near-field pattern of the laser output is uniform.

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Recently, diode-pumped solid-state lasers (DPLs) have attracted considerable attention because of their compact structure, high efficiency, good beam quality, power scalability, and good operation stability[1−4]. At present, the thermal effects of laser gain medium restrict further development of DPLs[5−7]. Solid laser gain medium generates heat when pumped by high-power diode lasers. Thermal effects, such as thermally induced stress and beam aberration, limit the output power and beam quality of solid-state lasers, whereas extremely high thermal intensity can cause the fracture of solid laser gain materials. To reduce thermal effects, various configurations of high-power solid-state lasers were proposed and developed, such as heat capacity lasers[8], slab lasers[9], and disk lasers[10]. In 2009, Avizonis *et al.*[11] demonstrated a 27-kW output by combining 10 modules of a Yb:YAG laser, in which disk-shaped gain medium was cooled by a microchannel heat sink through one of the flat surfaces. A thin-disk laser is an effective architecture used to reduce thermal effects because of its large cooling surface and the short distance between the cooling surface and the heat source. However, thermally induced stress and beam aberration still limit the output power and beam quality of disk lasers. Controlling thermal effects remains to be a very important task in disk lasers. In 2008, a patent was granted to General Atomics Corp. with the title "Laser containing a distributed gain medium". The patent comprised a scheme in which coolant liquid that directly flows over the surfaces of laser gain medium is proposed to achieve high cooling efficiency[12]. In 2007, Textron Defense Inc. presented a 27-kW output produced by a single laser module and a 100-kW output from six laser modules by employing Nd:YAG ceramic thin slab as gain medium and using the scheme in which coolant liquid directly flows over the slab surfaces[13]. Based on the schemes used by General Atomics Corp. and Textron Defense Inc., the scheme in which coolant liquid directly flows over the surfaces of laser gain medium has become an important trend because it results in weakened thermal effects. In this letter, a large-aperture end-pumped Nd:YAG thin-disk laser directly cooled by liquid is demonstrated to reduce the thermal effects of laser gain medium. A direct pumping scheme that contains spatial self-organized laser diode arrays (LDAs) is adopted without any optical coupling components, and good pump uniformity is achieved together with high coupling efficiency. Without any optical coupling components, the thermal effects of high-power pump coupling components are avoided, endowing the system with compact structure, high reliability, and high stability.

The experimental setup of the large-aperture end-pumped Nd:YAG thin-disk laser directly cooled by liquid is depicted in Fig. 1. The laser gain medium is a 1.0-at.-%-doped Nd:YAG disk. The dimension of the disk is 50×30×5 (mm), with a large aperture (50×30 (mm)) for light passage. The disk is end-pumped from a single side by two LDAs. The pump beam reaches the pump surface of the disk after passing through a 2-mm-thick quartz window and a 2-mm-thick coolant water layer. A coating (HR@1 064 nm, AR@808 nm) is deposited on the pump surface of the disk, which serves as the reflector of the resonator, whereas a plane output mirror (OC) of 40% transmission is positioned at a distance of 10 mm from the disk surface.

The disk is directly pumped by two LDAs with an emission area of 38×10 (mm). Each LDA, consisting of 20 laser diode bars, emits a peak output power of 2 500 W at a wavelength of approximately 808 nm at a coolant

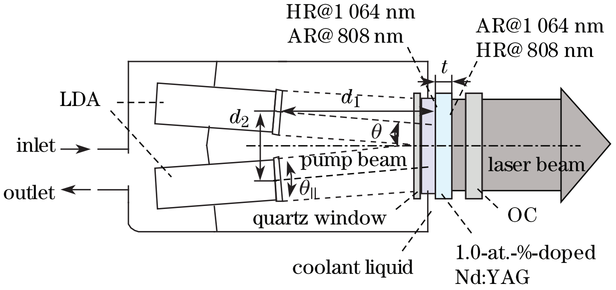

Fig. 1. Experimental setup of large-aperture end-pumped Nd:YAG thin-disk laser directly cooled by liquid.

temperature of 25°C. Each laser diode bar is collimated in fast axis by a microlens but not in slow axis, corresponding to a fast-axis divergence angle ($\theta_\perp$) of 2° and a slow-axis divergence angle ($\theta_\parallel$) of 8°. Without optical coupling element, the pump beam goes through the quartz window and the coolant water layer, and then projects on the pump surface of the disk. The dimension of the pump surface is 50×30 (mm), and the thickness of the disk is $t$ = 5 mm. Both LDAs are positioned at a distance of $d_1$=70 mm from the pump surface of the disk. The center distance of the two emitting areas of LDAs is $d_2$=15 mm. A coating (AR@1 064 nm, HR@808 nm) is deposited on the other surface of the disk, through which the unabsorbed pump power is reflected back. Thus, the pump light undergoes a two-pass absorption in the disk.

The pump uniformity and pump power density on the pump surface are extremely important for a laser with large-aperture disk configuration. Therefore, when adopting the spatial self-organized LDA direct pumping scheme, the parameters (e.g., spatial position and angle) of LDAs must be carefully designed. The incident angle $\theta$ of two pump beams, that is, the angle between the principal direction of the pump beam and the normal direction of the pump surface, should be optimized. Raytracing with the software TracePro is implemented to optimize the pump system. In the simulation, we adjusted the direction of the two LDAs and simulated the pump distribution at the pump surface when the incident angle $\theta$ is set at 1.2°, 2.2°, and 3.2°, respectively. Figure 2 depicts the pump distribution at the pump surface in the slow axis direction as a function of the incident angle of pumping, from which we can deduce that an incident angle of 2.2° leads to the most uniform distribution among the three cases.

According to the simulation, the optimized pump distribution at the pump surface of the disk is demonstrated in Fig. 3, showing good pump uniformity along the length and width of the disk. The raytracing result shows that the size of the pump spot at the pump surface is approximately 40×20 (mm) and that the average pump power density is 578 W/cm$^2$. The simulated distribution of pump power density is sampled in a spatial resolution of 800×400 pixels. The root mean square (RMS) of the pump power density at sampling points is used to evaluate the pump uniformity, which can be described as

$$\mathrm{RMS} = \frac{\sqrt{\frac{\sum_{i=1}^{n}\left(I_i-\overline{I}\right)^2}{n-1}}}{\overline{I}}, \qquad (1)$$

where $I_i$ is the pump power density at the sampling point, $\overline{I}$ is the average pump power density, and $n$ is the number of sampling points. The calculation result shows that the RMS index of pump uniformity on the pump surface is 5.52%, indicating that the pump profile has good uniformity. Thus, the temperature distribution is uniform, and the temperature gradient is small in disk gain medium, effectively restraining the thermally induced stress and beam aberration.

Pump beams are shaped and coupled by optical components in traditional pump systems, such as lens beam shaping system, hollow lens duct shaping system, and wedge lens beam shaping system[14−17]. In traditional pump systems, the diode laser loses a portion of its power when it passes through optical coupling components, resulting in a decrease in pump efficiency. In this letter, a spatial self-organized LDA direct pumping scheme without an optical coupling component is used. A pump coupling efficiency as high as 93% is reached from the emitting surface of LDA to the pump area of the disk, as demonstrated in the simulation. The pump absorption efficiency of the two-pass absorption by the disk can be calculated as

$$\eta_{\mathrm{abs}} = 1 - \exp\left\{-\alpha \times \frac{2t}{\cos\left[\arcsin\left(\frac{\sin\theta}{n_{\mathrm{YAG}}}\right)\right]}\right\}, \qquad (2)$$

where $n_{\mathrm{YAG}}$=1.82 is the refraction index of Nd:YAG at 808 nm, $\alpha$ = 3.0 cm$^{-1}$ is the efficient absorption coefficient for 1.0-at.%-doped Nd:YAG at 808 nm, $t$ = 5 mm is the thickness of the disk, and $\theta$ = 2.2° is the incident angle of the pump beam. The simulation result of the software TracePro indicates that the absorption efficiency is 95.1%, which is in good agreement with the calculation result (95.0%) obtained using Eq. (2).

The optical coupling components possess a certain absorption of pump power, and the coupling components have a certain thickness. Thus, in a traditional pump beam shaping system, some of the pump power transforms to heat. When the pump power is extremely high, the thermal effects of the optical coupling components become serious and can even damage the components. If the optical coupling components are cooled by a heat-dissipating device, the system becomes complex, unreliable, and unstable. Using a direct pumping scheme without optical coupling components, the thermal effects

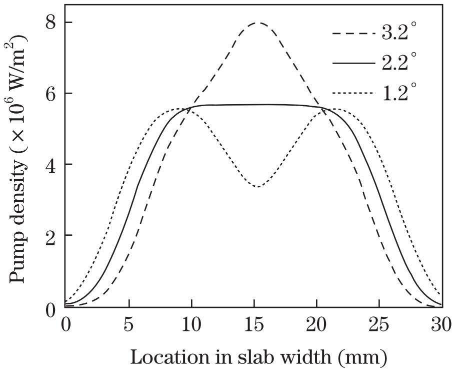

Fig. 2. Pump uniformity for different angles between the principal direction of the pump beam and the normal direction of the pump surface.

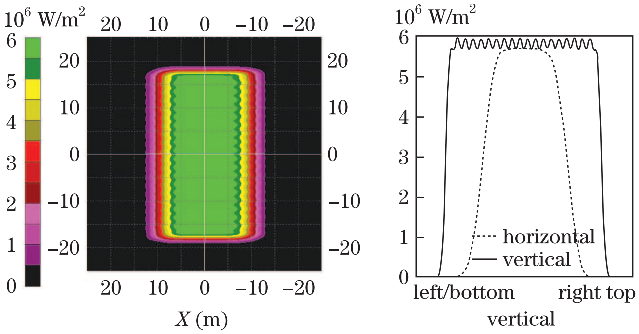

Fig. 3. (Color online) Optimized pump distribution on the pump surface of the disk.

of high-power pump coupling components are avoided. Thus, the system has compact structure, high reliability, and high stability.

The spatial self-organized direct pumping scheme with two LDAs described in this letter can be extended to multiple LDAs (the spatial structure of LDAs can have an orderly shape such as an arc or a sphere, or a disorderly shape). Thus, high pump power density and high total pump power can be obtained while maintaining good pump uniformity.

With the coolant water directly flowing over the pump surface of the disk, a forced convection heat transfer between the coolant water and the disk occurs. The heat transfer coefficient of the water-forced convection heat transfer is at a level of $10^4$ W/(m$^2$K). By comparison, the heat transfer coefficient of a copper heat sink is 398 W/(m$^2$K). Assuming that the convective heat transfer coefficient is $2\times10^4$ W/(m$^2$K) and the pump repetition frequency is 1 kHz with a pulse width of 276 $\mu$s, the simulated first principal stress distribution at the disk cross-section (length×thickness plane) is shown in Fig. 4, indicating that the maximum stress is 23 MPa, which is much smaller than the rupture stress of Nd:YAG (130 to 260 MPa). Therefore, using the scheme in which the coolant liquid directly flows over the surfaces of laser gain medium, the heat generated in the disk can be rapidly conducted out to reduce thermal effects.

In the experiment using long-pulse pumping with a pulse width of 276 $\mu$s, the laser pulse width is measured as 208 $\mu$s. The oscilloscope trace of the single pulse is shown in Fig. 5. The peak output power extracted from the large-aperture end-pumped Nd:YAG thin-disk resonator as a function of peak pump power is shown in Fig. 6. The peak pump power for the laser threshold is 1 200 W. By pumping with a peak pump power of 4 627 W, a maximum peak output power of 1 346 W at 1 064 nm is achieved, with a slope efficiency of 54.9%. The spot size of the near-field pattern is approximately 42×22 (mm). Figure 7 demonstrates a uniform profile of the near-field pattern of the output because of good pump uniformity.

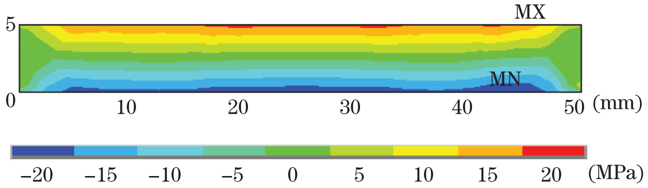

Fig. 4. (Color online) First principal stress distribution at the disk cross-section (length×thickness plane).

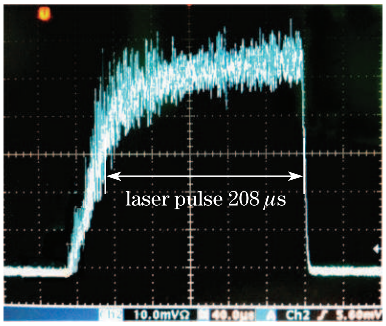

Fig. 5. Oscilloscope trace of the single pulse (40 $\mu$s/div).

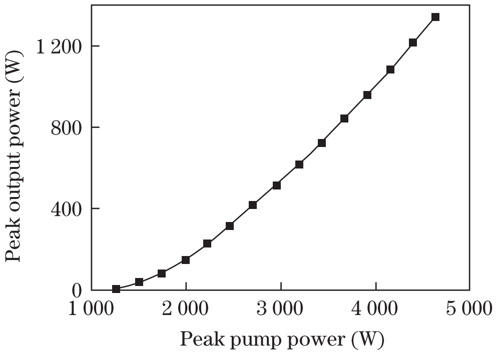

Fig. 6. Peak output power versus peak pump power of the oscillator.

Fig. 7. Near-field pattern of the laser output.

In conclusion, we present a large-aperture end-pumped Nd:YAG thin-disk laser directly cooled by liquid. Using a spatial self-organized LDA direct pumping scheme with careful optimization of the pump incidence angle, we demonstrate that a pump power density of 578 W/cm$^2$ is achieved with a pump uniformity of 5.52% (RMS) and a pump coupling efficiency of 93%. Without any optical coupling components, the thermal effects of high-power pump coupling components are avoided, and the system becomes simplified and compact. With a long-duration pump pulse, a peak output power of 1 346 W is produced at a peak pump power of 4 627 W, corresponding to a slope efficiency of 54.9%. The near-field pattern of the output is uniform. This thin-disk configuration has excellent performance in power scaling. High output can be achieved by increasing the pump power and the area of disk surfaces. This letter presents a feasible method of achieving solid-state lasers with high power output.

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