

550-W diode-pumped Nd:YAG disk laser

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When a thin laser crystal disk is used with a nearly flat-top pump profile, the heat flux can be considered to be one-dimensional. This results in a homogeneous temperature and stress profile within the laser medium leading to reduction of thermal effects. A nearly flat-top pump profile is achieved with a two-pass cylindrical-lens coupling system. An average output power of 550 W is obtained by an average pumping power of 1650 W with a 40-mm diameter Nd:YAG disk. The optical-optical efficiency is 33%.

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High-average power diode-pumped solid-state lasers hold a promise of scalability to compact, lightweight, and high efficiency lasers that can meet a broad variety of industrial, scientific, and military applications^[1,2]. Optical pumping generates a large amount of heat within the solid-state laser medium. Removal of waste heat leads to thermal lensing, mechanical stresses, depolarization, and other effects. They present a major challenge to the scaling of the high-average power solid-state laser. Using a thin medium disk mounted with one face on a heat sink allows high pump power densities without high temperature gradients within the disk. If the diameter of the pumping beam is much larger than the thickness of the disk, the heat flux can be considered to be one-dimensional and directed towards the heat sink. This results in a homogeneous temperature and stress profile within the crystal leading to reduced thermal distortions compared with classical cooling schemes. The laser can be scalable to high output powers by increasing the pumping diameter at constant pumping power density.

Much experimental work has already been researched on disk lasers with Yb:YAG crystal as an active medium^[3-5]. We developed a diode-pumped disk laser with an average output power of more than 100 W using a small Nd:YAG disk^[6,7] and a diode-pumped Nd:YAG double-disk laser with an average output power of 216 W^[8]. In this work, we introduce a 550-W diode-pumped disk laser with a larger Nd:YAG disk with 40-mm diameter and 2.6-mm thickness. The optical-optical efficiency of the laser is about 33%.

Thermal fracture and amplified spontaneous emission (ASE) loss considerations are the main limitations for the scaling of the disk laser. In experiment, one side of the disk medium is for pumping and the other for cooling. For disk medium with one-side cooling, the maximum heat load allowed is determined by^[9]

$$Q_{\max} = 3RbS/l, \quad (1)$$

where R is the thermal stress resistance parameter being about 11 W/cm, b is the safe operation parameter, i.e., the ratio of the design tensile stress to the fracture stress on the cooled surface, S is the area of pumping region, and l is the thickness of the disk. The time-averaged heat

load of the disk by absorbing pump power is

$$Q = PD\eta_{co}\eta_a\eta, \quad (2)$$

where P is the peak output power of the diode array, D is the duty cycle, η_{co} is the efficiency of the coupling system being about 82% from measurement, η_a is the absorption efficiency, and η is the heat fraction (=heat induced/absorbed pump energy), for Nd:YAG, $\eta = 0.32$ ^[10].

The small-signal gain coefficient of the disk is

$$g_0 = \frac{P\eta_{co}\eta_a\eta_q\eta_s}{VI_s}, \quad (3)$$

where $\eta_q = 0.95$ is quantum efficiency of the Nd:YAG, $\eta_s = 0.76$ is Stokes efficiency, i.e., the ratio of pumping wavelength to laser wavelength, and I_s is the saturation intensity of the Nd:YAG being about 3 kW/cm².

The ASE criterion is

$$g_0d = \phi, \quad (4)$$

where d is the largest size of the pumping area. The ASE parameter ϕ depends on gain geometry and mode of operation. For example, $\phi = 2.5$ is often taken as a limit for Q -switched laser. ASE losses are far less severe for continuous wave (CW) and quasi-CW lasers, hence $\phi = 3.5$ is a conservative limit for the disk laser^[8].

By combining Eqs. (1)–(4) we obtain the disk thickness corresponding to the maximum design thermal and stress load

$$l = (3Rb\eta_q\eta_s d)^{1/2} (I_s D \phi \eta)^{-1/2}. \quad (5)$$

The pumping source is a self-developed laser module of diode array, whose output peak power is 11000 W, and the duty cycle is 15%. The diameter of the laser crystal disk is 40 mm which is the largest size produced in China. If a Nd:YAG disk with a thickness of 2.6 mm and 1.4 at.-% Nd³⁺ concentration doping is selected, an efficiency of about 90% could be figured out with 2-pass absorption. But it is measured to be about 79% because the spectral width of the diode array is wider than we expected. The safe operation parameter b is designed to be 0.35. The largest size of the pumping area d is about 3.96 cm on the basis of Eq. (5). The pumping dimensions are determined to be about 30 × 26 (mm) by the 30°

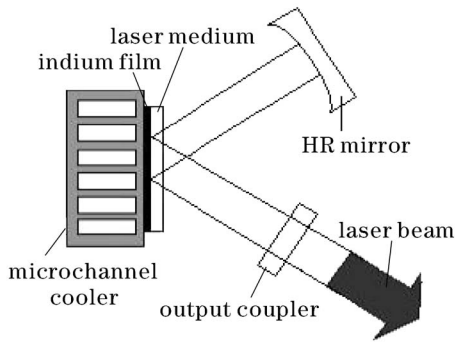


Fig. 1. Schematic diagram of disk laser.

incident angle of $1.064\text{-}\mu\text{m}$ laser to the disk medium, in order to make the laser aperture nearly the same size in two directions.

According to Eq. (3), the small-signal gain coefficient is about 0.84 cm^{-1} . The round-trip loss is measured to be about 1.4%. Using a solid-state oscillator model we calculate that with a 10% output coupler, an output power of 587 W can be extracted from the laser system, and the optical-optical efficiency is about 35.6%.

The principle schematic of the disk laser is shown in Fig. 1. A Nd:YAG crystal with a diameter of 40 mm and thickness of 2.6 mm is adopted as the laser medium. The crystal, which is antireflection (AR) coating for the pumping wavelength and laser radiation at the front side and high-reflection (HR) coating for both wavelengths at the back side, is fixed with a layer of indium on a micro-channel heat sink. Pumping light and laser radiation enter into the disk in two perpendicular directions with the same incident angle of 30° . The diode laser array consists of 110-diode bar with total peak power of 11000 W and duty cycle of 15%. The material of the micro-channel cooler for diode cooling is W-Cu alloy, because its hardness is high enough to obtain a high quality polished surface so as to raise the uniformity of output laser profile. Adjusting beam divergent angle of the diode laser collimated by the micro-cylindrical-lens, a nearly flat-top profile of pumping beam is formed on the disk.

Using a flat-concave stable resonator with 450 mm in length, a reflector with a radius of curvature of 5 m and 10% output coupler, an average output power of 193 W is obtained when the diode array peak power is 11000 W and the duty cycle is 5%, and an optical-optical efficiency is about 35%. An average output power of 380 W is obtained with an optical-optical efficiency of about 34.5% when duty cycle is 10%. And an average output power of 550 W is obtained with an optical-optical efficiency of about 33% when duty cycle is 15%. This means that there still exists a weak thermal lens effect. The curves of average output power of the disk laser versus peak pumping power are shown in Fig. 2, and those of optical-optical efficiency versus pumping power in Fig. 3.

The beam quality factor M^2 is measured to be about 190 with an average output power of 550 W at the duty cycle of 15%. The beam profiles in the near field and far field are shown in Figs. 4 and 5, respectively. The beam quality factor M^2 is nearly the same with an average

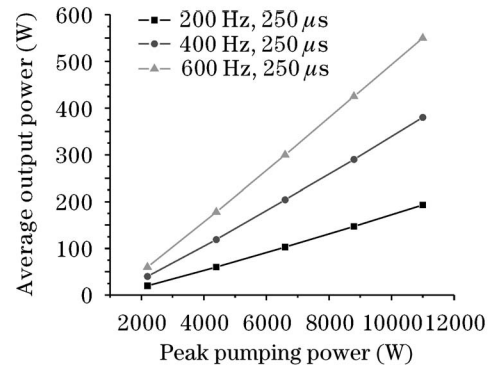


Fig. 2. Average output power versus peak pumping power.

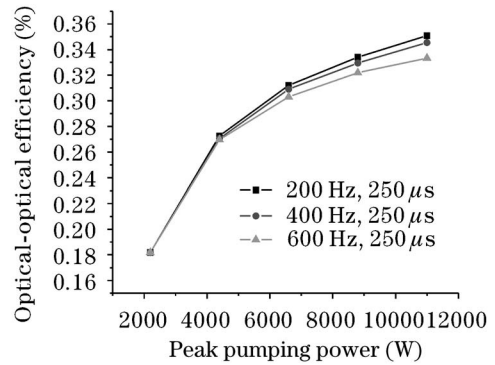


Fig. 3. Optical-optical efficiency versus peak pumping power.

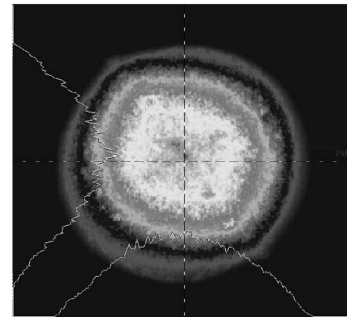


Fig. 4. Beam profile in the near field.

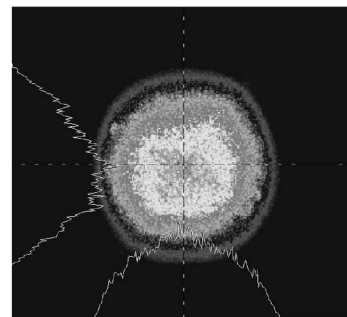


Fig. 5. Beam profile in the far field.

output power of 193 W at the duty cycle of 5%. This means that the bad beam quality is mainly caused by multi-mode oscillation.

In summary, the two-fold pass coupling optical system is designed. The cooling efficiency for the laser disk

greatly increases by means of micro-channel cooling and indium-welding technology. An average output power of 550 W is obtained with an optical-optical efficiency of about 33%.

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