4.6-W compact and efficient $NdAl_3(BO_3)_4$ thin-disk laser

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The capabilities of a compact and highly efficient $NdAl_3(BO_3)_4$ (NAB) thin-disk laser are demonstrated. Under a pump power of 8.2 W, the NAB disk laser delivers an average output power of 4.6 W at 1 063 nm, with a slope efficiency of 64%. The difficulty and complexity of the thin-disk laser design are minimized by the high absorbance of the NAB crystal. To reduce the thermal effect, low repetition frequency pulsed 885 nm direct pumping is considered an efficient way to realize a compact and highly efficient NAB thin-disk laser.

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Since the first demonstration of the principle in 1993[1], the thin-disk laser has attracted considerable attention because of its outstanding features, which include high output power, high efficiency, and excellent beam quality. Greater than 5-kW continuous wave (CW) output power has been obtained with one single Yb:YAG disk, with a maximum optical efficiency of 65% and a beam propagation factor M^2 of approximately 20[2]. The core concept of the thin-disk laser is the use of a thin, disk-shaped active medium (thickness of 100–200 μm) cooled through one of the flat faces. The cooled face is used as one cavity mirror of the resonator. For a better thin-disk laser design, the laser crystal with relatively high absorption of pump radiation is preferred. Highly doped Yb:YAG is generally used as the active material. However, the complex system was designed for efficient absorption of pump power. For example, a 16 pump beam pass pumping system was designed for 9 at.-% doped Yb:YAG thin-disk laser to realize a maximum of 32 passes of the pump radiation through the disk. More than 90% of the pump power can be absorbed. Our team performed a similar work with 4 pump-beam passes where 60% pump power was absorbed[3]. Designing and obtaining such a complex mechanical and optical system require precision hence, a difficult task.

An efficient way to develop thin-disk lasers is to use self-activated crystals (SACs)[4] with a large absorption coefficient. In these crystals, active ions constitute the crystalline lattice with a low relevant luminescence quenching ratio[5]. Neodymium aluminum borate ($NdAl_3(BO_3)_4$(NAB)) is a well-known SAC because of its good mechanical and thermal characteristics. CW[6] and short pulse[7] generation from the NAB microchip laser has been reported. However, the output power was limited to 0.2 W because of the serious pump-induced thermal effect. In recent years, numerous investigations have focused on direct pumping to reduce thermal effects and improve laser performance[8,9].

In this letter, we demonstrate a compact and efficient thin-disk laser based on NAB crystal pulsed pumped by 885-nm laser diode (LD). A 4.6-W output power at 1.063 μm was obtained with a slope efficiency of 64%. Due to the high absorption of pump radiation ($\alpha = 95$ cm^{-1} at 883.5 nm), the complex pump design was simplified. The pump beam was imaged on the NAB disk with a small angle. The pump radiation passed through the active material twice. More than 90% pump power was absorbed.

Figure 1 shows the absorption spectrum of an a-cut NAB crystal with a 0.18-mm thickness at room temperature, measured by a Biorad FTS-60A Fourier transform spectrometer. For 100% Nd^{3+} concentration, the absorbance of NAB is significantly larger than the conventional laser medium. The absorption coefficient at 808 nm reached 350 cm^{-1}. However, the laser performance of NAB was of poor quality for the traditional $^4I_{9/2} \rightarrow {}^4F_{5/2}$ (808 nm) pumping due to serious heat generation[7]. As a consequence, an 885-nm LD was used as the pumping source in our experiment. For the favorable direct pump range of around 885 nm, the width of absorption spectrum should be approximately 20 nm and the efficient absorption coefficient should be greater than 30 cm^{-1}. This means that more than 90% pump radiation can be absorbed in a 0.4-mm-thick NAB for the one-pass pump design. Furthermore, its wide absorption spectrum of approximately 885 nm does not require precise wavelength stability of LD pump light. It is suitable for applications in execrable environments.

The NAB crystal has a serious thermal effect, owing to the high absorption coefficient and lower thermal conductivity of 7.2 W/m·K[10]. Figure 2 shows the spot radius of fundamental mode on the NAB surface as a

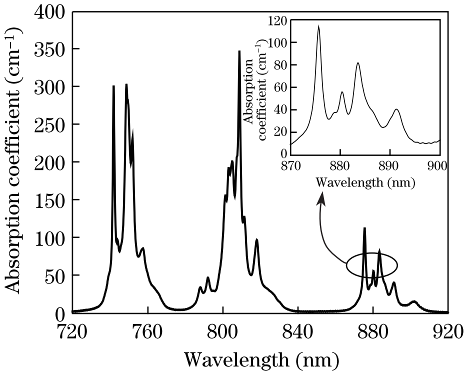

Fig. 1. Absorption spectrum of a-cut NAB crystal at room temperature.

function of thermal focal length f for cavity lengths of 2 and 45 mm. For the short cavity, $f_{\min}$ is 1.7 mm in the stable zone. For the long cavity, the fundamental mode is larger, but the cavity becomes unstable when f is less than 45 mm. This indicates that the short cavity is more suitable for high power output. As a result, the cavity length is fixed at 2 mm and at this value, the laser can work when f is greater than 1.7 mm. In previous work, NAB was pumped by continuous light, and the maximum output power was less than 0.2 W[7]. For better thermal management, pulse pumping is preferred. If pulse interval time Δt is longer than the thermal relaxation time τ, which is determined by the pump pulse energy and cooling condition, heat would not build up and the thermal focal length f would not be very small. Otherwise, the NAB crystal is mounted on a water-cooled heat sink, which dissipates the heat generated by the laser material.

The schematic of the experimental setup is shown in Fig. 3. A 4 × 4 × 0.39 (mm) NAB disk was fixated through its backside on a water-cooled Cu heat sink using silver loaded epoxy system with thermal conductivity of 50 W/m·K. The top face was anti-reflective coated at 1.06 and 0.88 μm. The backside of NAB was high-reflective coated for both the laser and the pump light, and used as a cavity-mirror. M1 (R = 50 mm) is the other cavity-mirror with a transmission of 3% at 1.06 μm. A total of 885-nm pump light input the crystal though a homemade chopper with pulse width of 400 μs. The maximum peak power of 180 W and a repetition frequency (RF) could be set up at 57, 114, 171, and 228 Hz. The diameter of the pump spot on the surface of the NAB surface was 1.6 mm.

The 1 063-nm power, as a function of incidence pump power at different RFs, is shown in Fig. 4. Under an RF of 57 Hz, the output power increased almost linearly with the pump power. Good laser performance was also observed at a RF of 114 Hz, twice as that of the former, with a maximum output power of 4.64 W (at an average pump power of 8.16 W) and a slope efficiency of 64%. When the RF was increased three and four times from 57 Hz, the output power turned over at the pump power of 4.4 and 3.6 W, respectively. This indicates that the thermal effect became critical for higher pump RF. In our experiment, the optimum RF was approximately 114 Hz and the pulse interval time was approximately 8.8 ms. Under these conditions, the NAB crystal returned to ambient temperature before the onset of the next pump pulse.

The $^4F_{3/2}$ life time of NAB is 20 μs[11], which is much shorter than that of Nd:YAG. However, its efficiency did not reduce considerably. Under a different RF, the slope efficiency before the output power turned over was approximately 64%, and the maximum optical-optical (o-o) efficiency of the 885 nm pump power to the 1.06-μm laser power was 56.9%. Considering that the absorbance of the NAB crystal for pump light was approximately 79%, the efficiency of the absorbed pump power to laser output was modified to 72%. This indicates that NAB is a good candidate for thin-disk lasers.

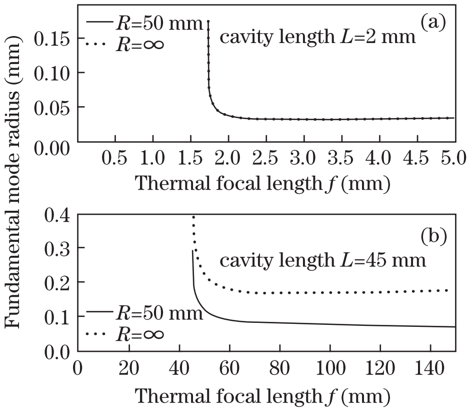

Fig. 2. Spot radius of fundamental mode on crystal surface as a function of thermal focal length f with cavity lengths of (a) 2 and (b) 45 mm.

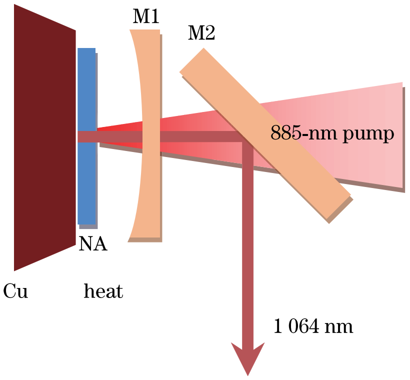

Fig. 3. Experimental configuration of compact NAB thin-disk laser for one pump beam pass.

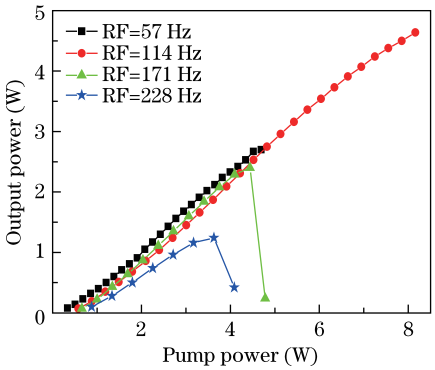

Fig. 4. Output power at different pump RF values.

In conclusion, we demonstrate the characteristics of a 4.6-W efficient thin-disk laser with a simple design based on a self-active crystal NAB with good mechanical properties. A high slope efficiency of 64% and an o-o efficiency of 57% are obtained. Compared with the conventional many-pump-beam pass design, the difficulty and complexity of the thin-disk laser design is significantly reduced in our experiment due to the huge absorption coefficient and low quenching ratio of the NAB crystal. The resonant and low RF pulse pumping is an efficient way to realize compact and high efficiency NAB thin-disk lasers.

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