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Thin Nd:YAG slab laser pumped by lens duct coupled diode laser stacks

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ABSTRACT High power continuous wave operation of a diode face-pumped thin Nd:YAG slab laser is reported. A novel pumping geometry for a thin Nd:YAG slab using cylindrical lens duct coupled diode laser stacks is demonstrated. In a close-coupled resonator, a maximum laser output power of 260 W in multimode operation is obtained. This corresponds to a slope efficiency of 34% and an optical-to-optical efficiency of 27%, respectively. In high-brightness operation, a polarized laser output of 70 W has been obtained with a beam quality factor close to 4 in both directions. The polarization contrast ratio is > 100.

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Thermal management is a challenging issue in the design of high average power solid-state laser systems with good beam quality [1, 2]. Several pumping schemes have been developed for high power and high beam quality oscillation including the rod [3, 4], the slab [5], and the thin disk [6]. Face-pumped slab [7, 8] geometry eliminates thermal effects present in the rod system including thermal lensing and thermal birefringence. It is necessary to compensate for the thermally induced birefringence to obtain polarized output radiation. When diode stacks are directly employed as a pump source, the slab width and thickness need to be carefully chosen for higher pump absorption efficiency. However, thermal fracture of the slab scales inversely with thickness, conflicting with absorption efficiency, which increases with increasing thickness.

In the conventional lamp or diode stack pumped Nd:YAG slab laser, a large width is employed to match the emitting aperture of the pump source [5]. We have developed a novel pumping geometry for thin Nd:YAG slabs using cylindrical lens duct coupled continuous wave (cw) diode laser stacks. In this letter, we present the results of the diode stack pumped thin slab Nd:YAG laser in multimode and high-brightness operation. We have used a Brewster-cut Nd:YAG slab of 1.1% doped crystal measuring 77.5 mm in length. The cross section of the slab is $1.8 \times 5\ \text{mm}^2$. The pump faces of the slab are coated with a SiO_2 film of thickness $\leq 3\ \mu\text{m}$ to easily place the O-ring for water sealing without burning [9]. Also, this coating helps in any coolant-induced contamination to frustrate total internal reflection. The pump enclosure is a circular quartz flow tube of 6-mm inner diameter. The outer circumference of the flow tube is gold coated except for two narrow windows for pump light coupling. The size of the window is $1.5 \times 18\ \text{mm}^2$ to match the exit aperture of the cylindrical lens duct. The purpose of the gold reflective coating over the tube is to increase the coupling efficiency of the pump light by multiple reflections.

We have used two 500-W cw diode stacks at the 808-nm wavelength. Each diode stack consists of 10 1-cm bars. The emitting aperture of the diode stack is $10 \times 16\ \text{mm}^2$. The polarization direction of the diode radiation is along the slow axis of the diode bar. Two antireflection-coated cylindrical lens ducts have been used to compress the pump radiation in the slow axis from 10 mm to 1.5 mm. The pump radiation is incident upon the lens duct in p-polarization, which increases transport efficiency [10]. The transfer efficiency of the lens duct is measured to be greater than 95% for all the pump powers. This method allows the use of direct uncollimated diode stacks instead of microlensed stacks. The pump modules are placed opposite each other and interleaved laterally. A schematic of the top down and end on views of the slab laser head is shown in Fig. 1. Lateral interleaving is necessary for two reasons; first, it traps the pump light without it being transmitted through the opposite side and secondly the pump power density has to be maintained less than the fracture limit. In our case, assuming that 30% of the pump light is dissipated as heat and for the maximum pump power, the laser is operated close to 40% of the fracture limit. Figure 2 shows the pump distribution across the slab aperture by imaging its fluorescence on a pyroelectric camera. Laser performance studies are carried out in both multimode and TEM_{00} operation by different resonator setups. In a close-coupled resonator formed by a high-reflective mirror of 200-mm radius of curvature and a plane

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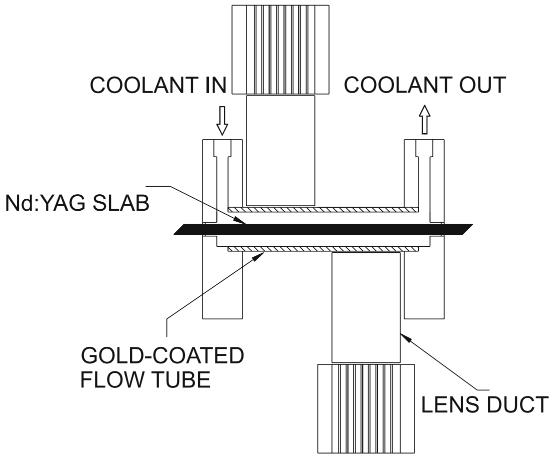
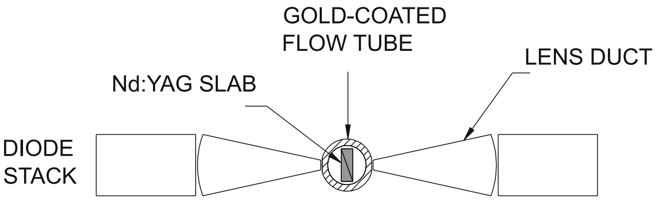


a TOP DOWN VIEW



b END ON VIEW

FIGURE 1 Schematic of the top down (**a**) and end on (**b**) views of the slab laser head

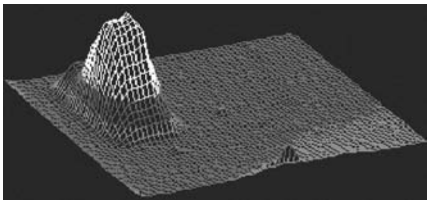


FIGURE 2 Pump distribution across the slab aperture by imaging its fluorescence on a pyroelectric camera

30% output coupler separated by a distance of 225 mm, the threshold pump power was 110 W. A maximum output power of 260 W was obtained for the pump power of 960 W. Figure 3 shows the multimode output power as a function of the diode pumping power. This corresponds to a slope efficiency of 34% and an optical-to-optical efficiency of 27%, respectively. The thermal lensing was measured by passing the collimated He-Ne laser beam as a probe beam for various pump input powers. Although there was no significant focusing in the zigzag plane, a focal length of 2.5 m was observed for the maximum pump power. This may be due to the heating of the slab ends, which are slightly protruding outside the slab housing. However, in the non-zigzag plane strong focusing was noticed. Although the slab edges are very close to the inner periphery of the flow tube, still significant heat removal takes place due to coolant passage. The thermal focal length of 75 mm was measured for the maximum pump power.

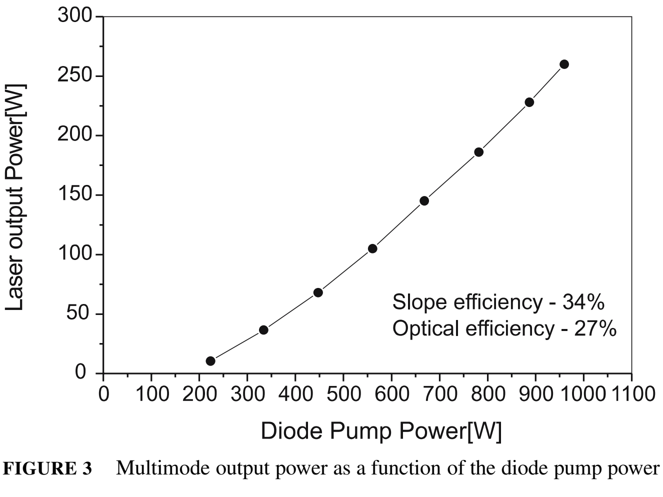


FIGURE 3 Multimode output power as a function of the diode pump power

To achieve lower order mode operation we have used a cylindrical convex rear mirror of radius of curvature 150 mm to compensate the thermal lensing in the width plane and a plane 30% output coupler. The high reflector is separated from the slab end by 70 mm; the output coupler, from the other end of the slab by 20 mm. Figure 4 shows the calculated spot sizes in the slab and mirrors versus dioptric power of the thermal lensing in the non-zigzag plane. Since the output mirror is very close to the slab end, the spot sizes on both are nearly the same. However, in the zigzag plane the spot size remains around 350 μm on both slab and mirrors over the pump power range. The pump power range for this dynamically stable resonator is up to 550 W and at this pump power a maximum polarized output power of 70 W was achieved. The beam quality was characterized by using Coherent's ModeMaster. Figure 5 shows the low order mode output power and M^2 factor as a function of pump input power. The polarization contrast ratio was analyzed with a thin-film polarizer and found to vary from 1 : 60 for the full pump power to 1 : 100 in lower pumping. The improvement in the contrast ratio (> 1 : 100) over the full pump range was observed when a thin-film polarizer was inserted in the resonator without any significant reduction in output power.

In conclusion, we have developed a thin-slab Nd:YAG laser. A novel pumping geometry for a thin Nd:YAG slab using cylindrical lens duct coupled diode laser stacks was demonstrated. A multimode laser power of 260 W was obtained with a slope efficiency of 34%

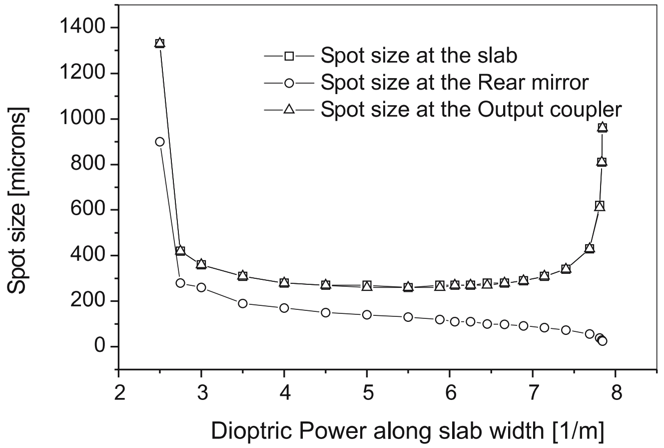


FIGURE 4 Calculated spot sizes at the slab and mirrors versus dioptric power

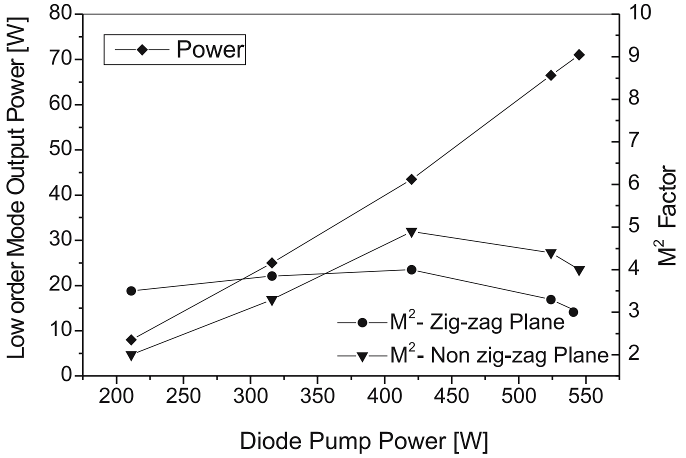


FIGURE 5 Low order mode output power and M^2 factor as a function of pump power

and an optical conversion efficiency of 27%. A low order mode polarized output power of 70 W with a beam quality factor M^2 close to 4 in both axes were achieved. The lower optimum output reflectivity may be attributed to the high gain present in the system. Since the output beam is polarized along the non-zigzag plane of the slab, by employing electro-optic Q-switching one can obtain very high peak power pulses even at high repetition rates. Furthermore, thermal insulation over the edges of the slab with the modified pump housing is underway to ensure one-dimensional heat transport for the improvement in the efficiency of the system.

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