High-power diode-pumped lasers based on Yb:$YAl_3(BO_3)_4$ crystals cut along the crystallographic axes

Junhai Liu, Xavier Mateos, and Valentin Petrov,
Max-Born-Institute for Nonlinear Optics and Ultrafast Spectroscopy, 2A Max-Born-Str., D-12489 Berlin, Germany,
jhliu@mbi-berlin.de

Huaijin Zhang, Jing Li, and Jiyang Wang
National Laboratory of Crystal Materials, Shandong University, Jinan 250100, China

Abstract: Continuous-wave laser operation near 1 µm is studied at room temperature with ***c***-cut and ***a***-cut Yb:$YAl_3(BO_3)_4$ crystals end-pumped by a fiber-coupled diode-laser achieving an output power of 10.6 W and a slope efficiency of 72%.
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Yttrium aluminum borate, $YAl_3(BO_3)_4$ (YAB), is a negative uniaxial crystal with 32 (D_3) point symmetry. As a non-centrosymmetric laser host its potential for self-frequency doubling (SFD) has been studied for more than two decades with Nd-doping and more recently also with Yb-doping. As a result of the closer ionic radius to the passive Y-ion, the lattice distortion is reduced and the optical quality of Yb:YAB is better than that of Nd:YAB [1]. As a SFD laser crystal, Yb:YAB possesses several additional advantages over Nd:YAB originating from the unique electronic structure of the Yb ion, including a smaller quantum defect which leads to less thermal load inside the crystal, the absence of concentration quenching, up-conversion and excited-state absorption losses, and absorption losses in the visible spectral range [1]. Most of the laser research performed so far on Yb:YAB has focused on its SFD performance: As a bi-functional material Yb:YAB provided the highest green output power (>1-W in the continuous-wave (CW) regime [2] and >2 W with Q-switching [3]). Less efforts were devoted, however, to the study of the Yb:YAB laser operation at the fundamental near 1 µm for which the highest CW output power demonstrated so far was 4.3 W [2]. Here, we report our results on the high-power laser performance of diode-pumped Yb:YAB operating at the fundamental, using crystal samples cut along the main crystallographic axes.

The laser studies were performed with a simple two-mirror cavity, formed by a plane mirror highly reflecting (>99.8%) between 1015 and 1230 nm and highly transmitting (>97%) in the 880-990 nm range, and a concave (RC=-50 mm) output coupler with transmission (T) near 1030 nm ranging from 0.5% to 10%. The physical cavity length was 49 mm. The pump source used was a high-brightness fiber-coupled diode laser (fiber core diameter of 200 µm and NA of 0.22) with a maximum power of 50 W. Its emission wavelength varied from 974 to 983 nm depending on the driving current. The Yb:YAB crystals were positioned very close to the plane mirror through which they were pumped. The pump spot radius at the crystal surface was ≈100 µm. Two different types of Yb:YAB samples, ***a***-cut and ***c***-cut, were used, all of them uncoated, 2 or 3 mm thick, with the same aperture of 3.3×3.3 mm^2. The crystals were cooled during laser operation by use of a water-cooling system (water temperature: 12°C).

In the case of unpolarized pump source, ***c***-cut Yb:YAB can be pumped more efficiently because the absorption cross section for π polarization is extremely low, in particular near 975 nm. Thus, e.g. for 2-mm thick Yb:YAB, we measured roughly 90% and 50% absorption with ***c***-cut and ***a***-cut samples, respectively. Figure 1 shows the CW output power versus the absorbed pump power (P_{abs}) obtained with a 2 mm thick ***c***-cut Yb:YAB. Output couplings of 2%-5% led to very close results in respect of output power as well as efficiency. The lasing threshold was reached at P_{abs}=0.59, 0.79, and 1.31 W, for T=0.5%, 3%, and 10%, respectively. In nearly the entire operational range, the most efficient operation was with T=3%. The highest output power generated before the roll-off set in was 10.6 W, reached at P_{abs}=16.2 W, resulting in an optical-to-optical efficiency of 65%, whereas the slope efficiency was η=72%. Further power scaling requires more efficient cooling of the Yb:YAB crystal. The highest output powers obtained in the cases of T=0.5% and 10% were 6.3 and 7.0 W, respectively, with η=49% and 56%. The emission wavelength λ, which for a quasi-three-level laser depends on the output coupling used, decreased from 1050 to 1040 nm when the output coupling was increased from 0.5% to 10% (Fig. 1a).

It is expected, as for any uniaxial crystal, that the polarization state of the laser radiation generated by a ***c***-cut Yb:YAB crystal would be undefined. Indeed, no unique direction in the plane perpendicular to the optic axis ***c*** was identified, however, the laser beam was not totally unpolarized; the powers in two arbitrary orthogonal polarized components were usually quite different, except for the two special directions when one of them was parallel to one of the three crystallographic ***a*** axes. Relating to the large variation in the polarized power ratio, significant power fluctuations were observed in any arbitrarily selected polarization direction except for those parallel or perpendicular to one of the three crystallographic ***a*** axes. The physical reasons behind such power fluctuations are likely related to the strong polarization competition, owing to the close gains seen by the two orthogonal polarization components.

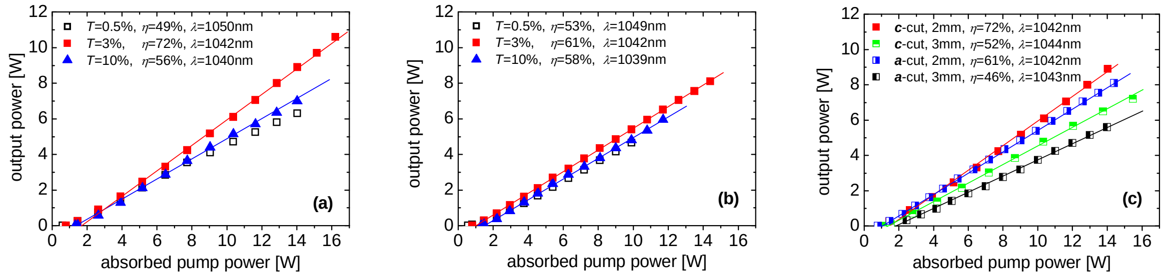

Fig. 1. Output power as a function of absorbed pump power obtained with 2-mm thick ***c***-cut (a) and ***a***-cut (b) Yb:YAB crystals. In (c) crystals of different thickness and orientation are compared at the optimum output coupling of T=3%.

With a 2 mm thick ***a***-cut Yb:YAB, the laser emission was σ-polarized. The dependence of output power on P_{abs} is depicted in Fig. 1b. Again, the results were very close for T=2%-5%. At threshold, P_{abs}=0.55, 0.80, and 1.31 W for T=0.5%, 3%, and 10%, respectively. These values are very close to the corresponding values measured with the 2 mm ***c***-cut crystal: This was expected since the gain cross section is the same. Similar to the situation with the ***c***-cut crystal, the optimum output coupling of the ***a***-cut Yb:YAB laser was also T=3%, leading to η=61%. The maximum achievable output power was 8.1 W, reached at P_{abs}=14.4 W, corresponding to an optical-to-optical efficiency of 56%. The highest output power generated for T=0.5% and 10% was 4.7 and 6.0 W, respectively, with η=53% (T=0.5%) and 58% (T=10%). The laser emission wavelength varied from 1049 nm (T=0.5%) to 1039 nm (T=10%).

In a quasi-three-level system like Yb:YAB, reabsorption losses at the lasing wavelength are inevitable at room temperature, owing to the thermal population of the terminal laser level. Consequently, the crystal thickness has critical effect on the laser performance. Figure 1c gives a comparison of the laser output characteristics obtained with Yb:YAB crystals of different thickness and orientation. For both ***c***-cut and ***a***-cut crystals, increasing the crystal thickness from 2 to 3 mm led to deterioration of the laser performance; the slope efficiency dropped to 72% (***c***-cut) and 75% (***a***-cut) of that achieved with 2 mm thick crystals. The highest output powers obtained with 3 mm thick crystals were also considerably lower than those achieved with 2 mm thick samples.

From a point of view of power scaling, ***c***-cut Yb:YAB crystals are much more advantageous in comparison to ***a***-cut ones, not only due to the higher attainable output power, but because of the much more efficient pumping. For example, the maximum output power of 10.6 W in the case of 2 mm ***c***-cut Yb:YAB was reached at an incident pump power of 24 W, corresponding to a diode-to-laser efficiency of 44%; by contrast, 8.1 W of maximum output obtained with the 2 mm ***a***-cut crystal required an incident pump power of 32 W, the diode-to-laser efficiency being only 25%. More importantly, as demonstrated in Fig. 1c, increasing the crystal thickness to improve the pumping efficiency does not contribute to power scaling. On the other hand, however, it should also be clear that the generation of linearly polarized laser radiation with Yb:YAB requires the use of ***a***-cut crystals.

In summary, we studied the high-power laser performance of Yb:YAB by using different samples cut along the crystallographic axes. Employing a ***c***-cut crystal to take advantage of the large absorption, we obtained 10.6 W of CW output power at room temperature through simple diode end-pumping and water-cooling, the optical-to-optical and slope efficiencies were 65% and 72%, respectively. The polarization state of the generated laser radiation exhibited some complex behaviour the output being not totally unpolarized; large power fluctuations were usually present in individual polarization directions except for those parallel or perpendicular to one of the three ***a***-axes. With an ***a***-cut crystal, the σ-polarization oscillated: The maximum output power of 8.1 W gives an optical-to-optical efficiency of 56%, the slope efficiency was 61%. The high-power laser performance achieved demonstrates the great potential of Yb:YAB as a laser medium for generating infrared coherent radiation in the 1 µm spectral range.

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