High-Power Laser Performance of Yb:$YAl_3(BO_3)_4$ Crystals Cut Along the Crystallographic Axes

Junhai Liu, Xavier Mateos, Huaijin Zhang, Jing Li, Jiyang Wang, and Valentin Petrov

Abstract—**High-power continuous-wave laser operation near 1 μm was demonstrated at room temperature with *c*-cut and *a*-cut Yb:$YAl_3(BO_3)_4$ crystals end-pumped by a fiber-coupled diode laser. Using a 2-mm-thick *c*-cut crystal, 10.6 W of output power was generated with an optical-to-optical efficiency of 65% and a slope efficiency of 72%. The complex polarization state of the generated laser radiation was also studied. With a 2-mm-thick *a*-cut crystal, σ-polarized laser oscillation was obtained, producing a maximum output power of 8.1 W; the optical-to-optical and slope efficiencies were 56% and 61%, respectively. Complete absorption and emission cross section spectra of the Yb:$YAl_3(BO_3)_4$ crystal were also derived, revealing very strong anisotropy of the spectroscopic properties.**

Index Terms—**Diode pumping, high-power operation, Yb laser, Yb:$YAl_3(BO_3)_4$ crystal.**

I. INTRODUCTION

YTTRIUM aluminum borate, $YAl_3(BO_3)_4$ (YAB), is a well known laser host material, a negative uniaxial crystal with 32 (D_3) point group symmetry, possessing nonlinear optical properties. It has been used for more than two decades, doped with the trivalent neodymium ion (Nd^{3+}), as a self-frequency doubling (SFD) laser crystal that is capable of converting the infrared radiation directly into visible through second harmonic generation. In recent years, the application of YAB as laser host material for another rare-earth ion, the ytterbium ion (Yb^{3+}), has attracted much attention [1]–[6]. In comparison with the Nd ion, the Yb ion is much closer in ionic radius to the Y ion [1], for which the active ion substitutes when doped into the host lattice. As a result, the optical quality of Yb:YAB is better since the lattice distortion caused by the ion substitution process will be greatly reduced [1]. As a SFD laser crystal, Yb:YAB also possesses several additional advantages over Nd:YAB originating from the unique electronic structure of the Yb ion, including a smaller quantum defect leading to less thermal load inside the crystal; the lack of concentration quenching, of up-conversion and excited-state absorption losses, and of 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 [2], [4]–[7]. The green output power generated has reached the 1-W level in continuous-wave (CW) operation, and exceeded 2 W in Q-switched operational regime [4], [6]. These represent the highest output powers ever achieved by utilizing the SFD technique. For other visible wavelengths, yellow light of mW level has also been obtained by SFD in Yb:YAB [7].

However, much less effort was devoted to the laser operation of Yb:YAB at the fundamental near 1 μm, despite the promising results reported in an early study (0.65 W of output power with a slope efficiency of 71%) [3]. The highest CW output power reported so far at the fundamental is 4.3 W, produced by diode end-pumping of a 3-mm-thick Yb:YAB crystal cut for type-I phase matching [4].

In this paper, we report high-power laser performance of Yb:YAB operating at the fundamental wavelength of ~ 1 μm, using different crystal samples cut along the main crystallographic directions. We also present complete absorption and emission cross section spectra measured and calculated for both σ- and π-polarizations. These spectra show very strong anisotropy, which is very different from that reported previously [1].

II. SPECTROSCOPIC PROPERTIES

The spectroscopic properties of Yb:YAB reported in the early literature are incomplete. The absorption spectra were presented only in the form of absorption coefficient; as for the emission data, only a part of σ-polarized cross section spectra and measured fluorescence spectra are available [1], [5], [8]. In Yb laser systems, due to their quasi-three-level nature, the absorption spectra usually overlap largely with the emission spectra. As a consequence, the fluorescence spectra measured experimentally are strongly affected by reabsorption and cannot be used to evaluate the emission cross sections. Very recently, the authors of [8] updated their results and published data on the polarized absorption and emission spectra based on measurements with a highly doped crystal (40.7 at. %) [9].

To obtain detailed information on both the absorption and emission spectra which is essential for the understanding of the laser operation in any crystal, we measured the polarized absorption spectra at room temperature by use of a 3-mm-thick Yb:YAB crystal cut along one of its ***a*** crystallographic axes. The Yb concentration in the Yb:YAB crystal was 5.6 at. %, corresponding to an ion density of 3.08×10^{20} cm^{-3} (the density of Yb:YAB crystal used is 3.7 g/cm^3). On the basis of the

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Manuscript received October 31, 2006; revised January 1, 2007. This work was supported in part by the EU Project DT-CRYS, NMP3-CT-2003-505580, in part by the National Natural Science Foundation of China under Grants 50672050, 50590401, and 50572054), in part by the Excellent Young Teachers Program of MOE, China, and in part by the Grand for State Key Program of China (2004CB619002).

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Digital Object Identifier 10.1109/JQE.2007.893900

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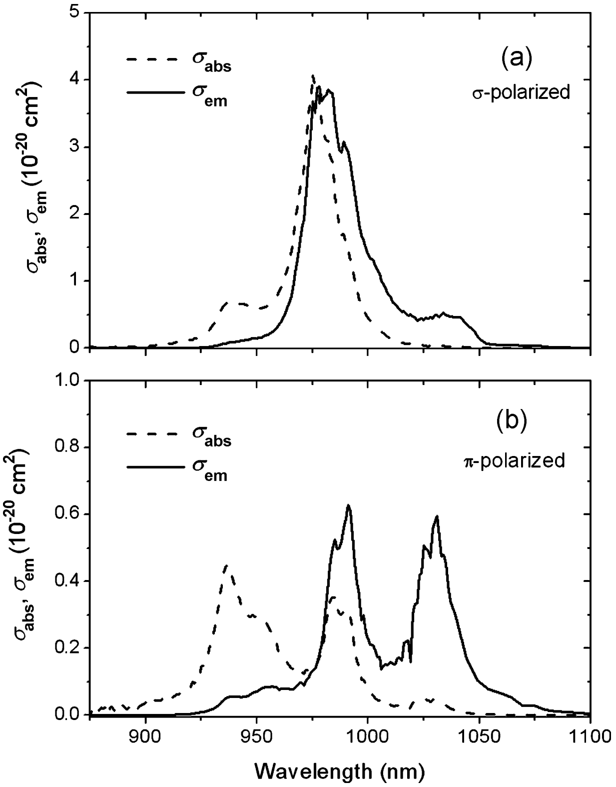

Fig. 1. Polarized absorption and emission spectra of Yb:YAB at room temperature. (a) σ-polarization. (b) π-polarization.

measured absorption spectra and the Stark levels given in [1], we calculated the emission spectra using the reciprocity method [10]. Fig. 1 shows the polarized absorption and emission spectra in terms of cross sections. The most pronounced feature different from the previous results is the very strong anisotropy characteristic for both the absorption and emission spectra. In fact, the σ-polarized spectra are totally distinct in shape from the π-polarized, this is in contrast to the results given in [1] where the profiles of the two polarized spectra were actually identical. More importantly, we note from Fig. 1 that the absorption of light of π polarization is approximately an order of magnitude lower than that of σ-polarization at their peak wavelengths, while according to the previous results given in [1], this difference is no more than two times. A great difference between the σ- and π-polarized absorption similar to the present results was also found in Yb:YAB of high Yb concentrations [8], [9]. It is also interesting to note from Fig. 1 that the π-polarized emission spectra consist of two separate bands of comparable peak magnitudes, with the first one centered at 991 nm and the second at 1031 nm. The second emission band, corresponding according to [1] to transitions from the second lowest Stark component of the upper $^2F_{5/2}$ level to the highest Stark component of the terminal laser level $^2F_{7/2}$, is of more importance; laser action is expected to take place at these wavelengths where the reabsorption losses are much lower. Most of the spectroscopic parameters important to laser operation are summarized in Table I, for comparison, the values published previously are also presented when available. One may note that the magnitude of $\sigma_{\mathrm{abs}}(\sigma)$ is larger than the previously reported values, this discrepancy probably arises from the calculated Yb ion density in the crystal, because the segregation coefficient we used in the calculation was 0.7, smaller than that given in [8], which is approximately unity.

Employing the pin-hole technique to eliminate the effect of radiation trapping [11], we measured the fluorescence lifetime of Yb:YAB by use of a 2-mm-thick sample. Fig. 2 depicts the dependence of the measured fluorescence decay time on the pinhole diameter. The fluorescence lifetime was determined to be 450 μs by extrapolating the data to a pinhole diameter of zero. This up-dated value of the lifetime amounts to only ~2/3 of that reported previously [1], the latter probably was lengthened by the effect of radiation trapping. The radiative lifetime can be calculated from the obtained emission cross sections using the Fuchtbauer–Ladenburg equation and averaging over the polarization [10]. The result, 436 μs, is in excellent agreement with the measured fluorescence lifetime having in mind the errors in the two measurements. Since such intrinsic quantum efficiencies (≈ 1) are expected for the Yb^{3+} ion, this agreement gives us confidence in the accuracy of the measured and evaluated absorption and emission cross sections.

III. EXPERIMENTAL DESCRIPTION

The high-power CW laser performance of Yb:YAB near 1 μm was investigated in the present work by employing a simple plano-concave resonator, formed by a plane reflector highly reflecting in the wavelength range of 1015–1230 nm (>99.8%), and highly transmitting for 880–990 nm (>97%). As the output coupler, several 50-mm radius-of-curvature concave mirrors were used, with transmission at ~1030 nm in the range of 0.5%–10%. The physical cavity length was 49 mm. The pump source used was a high-power high-brightness fiber-coupled diode laser (S50-980-2, Apollo Instruments, Inc., fiber core diameter of 200 μm and NA of 0.22), it was capable of providing 50 W of unpolarized output power with emission wavelength varying from 974 to 983 nm depending on the driving current level. The pump light was imaged first by focusing optics and then delivered through the plane reflector onto the Yb:YAB crystal which was positioned very close to this reflector. The spot radius of the focused pump light at the crystal surface was about 100 μm. Two different types of Yb:YAB samples, ***a***-cut and ***c***-cut, were used in the laser experiment. All the samples were uncoated, 2- or 3-mm-thick, with same aperture of 3.3 mm × 3.3 mm. The crystals were cooled during laser operation by use of a water-cooling system (the cooling water was maintained at 12 °C).

IV. RESULTS AND DISCUSSION

A. Laser Performance of *c*-Cut Yb:YAB

As can be seen from Fig. 1, the absorption for π polarization is extremely low, in particular at wavelengths around 975 nm. This means a ***c***-cut Yb:YAB crystal should be used in order to get efficient pumping in the case of unpolarized pump sources. We measured the unpolarized small-signal absorption of different Yb:YAB samples under nonlasing conditions, the

TABLE I
SPECTROSCOPIC PARAMETERS OF YB:YAB IMPORTANT FOR LASER OPERATION

Spectroscopic parameters	Results of this work	Results from Refs [1], [5], [8], [9]
$\sigma_{abs}(\sigma)$ at 975 nm (10^{-20} cm^2)	4.1	3.4 [1], 2.6 [8], [9]
$\Delta\lambda_{abs}$ (σ) (nm)	20	20 [1], 22 [8]
$\sigma_{abs}(\pi)$ at 984 nm (10^{-20} cm^2)	0.38	0.29 [8], 0.23 [9]
$\Delta\lambda_{abs}$ (π) (nm)	11	
$\sigma_{em}(\sigma)$ at 982 nm (10^{-20} cm^2)	3.9	2.3 [9]
$\sigma_{em}(\pi)$ at 991, 1031 nm (10^{-20} cm^2)	0.63, 0.60	
Range of λ_{lasing} (nm)	1039–1050	1020–1080 [5][a]
$\sigma_{em}(\sigma)$ in this range (10^{-20} cm^2)	0.47–0.15	0.82–0.10 [5]
$\sigma_{em}(\pi)$ in this range (10^{-20} cm^2)	0.29–0.10	
Lifetime τ_f (μs)	450	680 [1], 480–541 [9]

[a] The tuning range obtained with output coupling $T = 0.5\%$ [5].

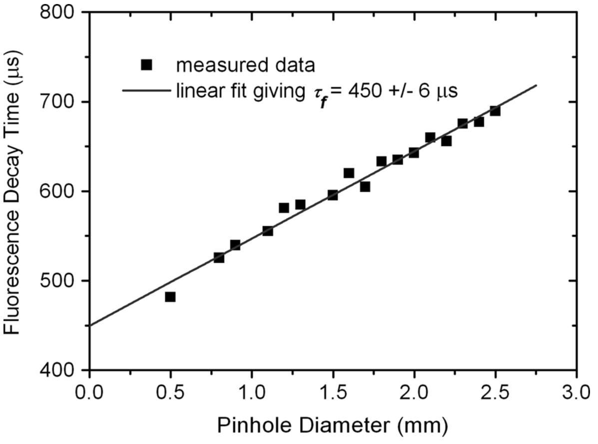

Fig. 2. Fluorescence decay time versus pinhole diameter measured with a 2-mm-thick Yb:YAB crystal, giving an extrapolated fluorescence lifetime of ≈ 450 μs.

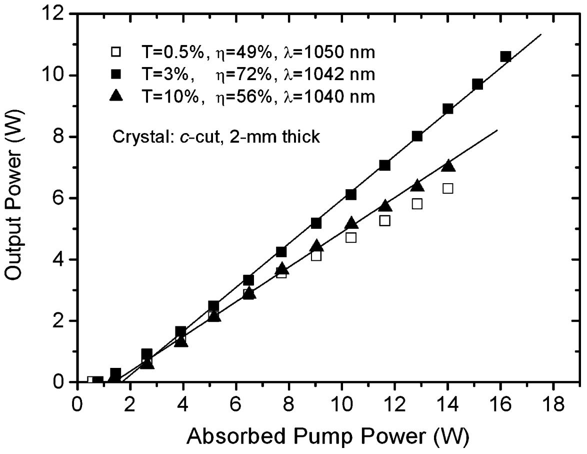

Fig. 3. Output power as a function of absorbed pump power obtained with a 2-mm-thick ***c***-cut Yb:YAB crystal.

pumping levels were limited to less than 1 W during this measurement, to avoid absorption bleaching. The pump wavelength at these power levels was ~975 nm. The measured fractions of pump power absorbed by the crystals are in very close agreement with the corresponding values calculated on the basis of the absorption spectra given in Fig. 1. The results indicate that the absorption for the mixed $(\sigma + \pi)$-polarization amounts to ~60% of that for pure σ-polarization, for the same thickness.

Laser oscillation was achieved at room temperature with output coupler transmissions (T) varying from 0.5% up to 10%, which was the largest coupling available in our experiment. Fig. 3 shows the CW output power versus the absorbed pump power for $T = 0.5\%$, 3%, and 10%, obtained with the 2-mm-thick ***c***-cut Yb:YAB crystal. 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 absorbed pump power (P_{abs}) of 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 realized with $T = 3\%$. The highest output power generated before the roll-off set in was 10.6 W, reached at $P_{\text{abs}} = 16.2$ W, resulting in an optical-to-optical efficiency of 65%, whereas the slope efficiency was determined to be 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 slope efficiencies of 49% and 56%. The emission wavelength, which for a quasi-three-level laser depends on the output coupling used, decreased from 1050 to 1040 nm at $P_{\text{abs}} = 14$ W when the output coupling was increased from 0.5% to 10%.

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, by examination of the polarization state, no unique direction in the plane perpendicular to the optic axis ***c*** was identified. It was also found, however, that 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. Table II gives the power ratios (ξ_1, ξ_2) between the two orthogonal polarized components measured at three low power levels. In this Table, $\xi_1 = P_1/P_2$, with the two polarizations along directions which are at ±45° with respect to ***a*** axis; $\xi_2 = P_3/P_4$, with the two polarizations parallel and perpendicular to ***a*** axis. One can see

TABLE II
RATIOS OF THE POLARIZED POWER COMPONENTS MEASURED AT THREE LOW POWER LEVELS

P_{abs} (W)	ξ_1			ξ_2		
	$T = 0.5\%$	$T = 3\%$	$T = 10\%$	$T = 0.5\%$	$T = 3\%$	$T = 10\%$
1.3	0.49	1.75	0.59	0.93	0.96	0.90
2.5	1.67	1.57	0.75	1.06	1.12	1.02
3.7	3.08	2.05	0.31	1.06	1.05	1.03

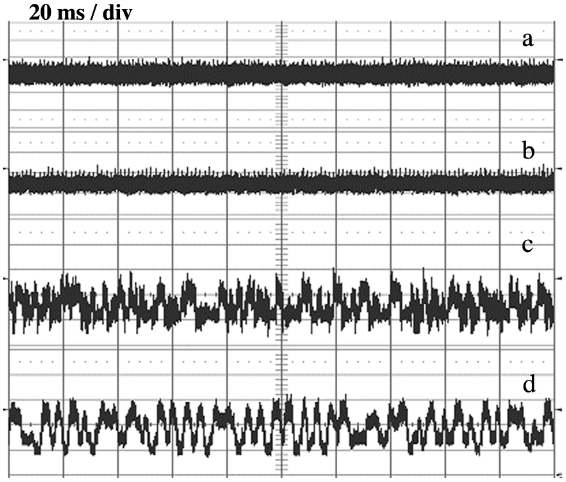

Fig. 4. Oscilloscope traces of the laser output generated with the 2-mm-thick ***c***-cut Yb:YAB crystal at $P_{\mathrm{abs}} = 2.5$ W in the case of $T = 3\%$. (a) Without any polarization selection. (b) Component polarized along the ***a*** axis. (c) Component polarized along the direction with an angle of 45° from the ***a*** axis. (d) Component polarized along an arbitrary direction, neither parallel nor perpendicular to any of the three ***a***-axes. The horizontal time scale is 20 ms/div.

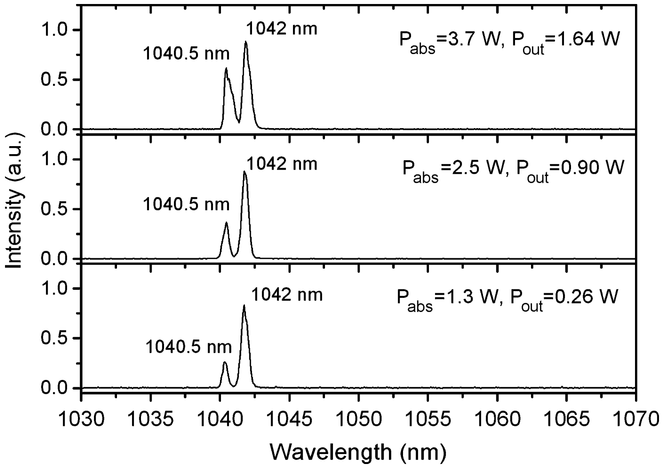

Fig. 5. Emission spectra of the Yb:YAB laser with the 2-mm-thick ***c***-cut crystal recorded at three low absorbed pump power levels in the case of $T = 3\%$.

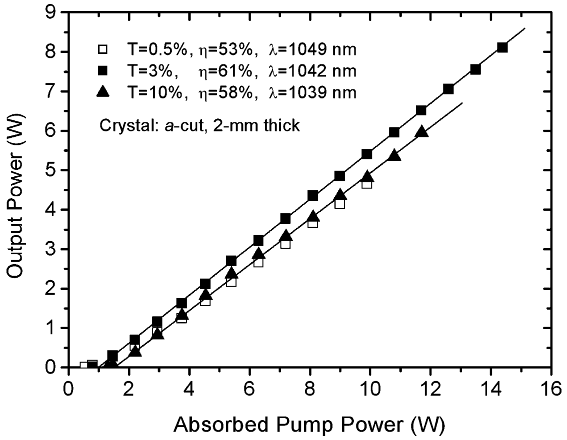

Fig. 6. Output power as a function of absorbed pump power obtained with a 2-mm-thick ***a***-cut Yb:YAB crystal.

that ξ_1 varied largely with the power level; whereas ξ_2 changed only slightly, with its magnitude close to unity.

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. Fig. 4 shows oscilloscope traces of the output power recorded by use of a photodiode, corresponding to several different polarization directions. We note that the total output power (trace a) as well as the polarized component along the ***a*** axis (trace b) remained quite stable; by contrast, large power fluctuations occurred on ms time scale for polarization components along any other direction. The physical reasons behind such power fluctuations are probably related to the strong polarization competition accompanying the laser operation, owing to the very close gains seen by each of the two orthogonal polarization components.

Despite the variation in the polarized power ratio and the large power fluctuations, the laser emission spectra evolved only slowly with increasing pump power. This is an indication of weak thermal influence on the population of the terminal laser level. Fig. 5 presents the emission spectra recorded at the same three power levels at which the polarized power ratios were measured. The laser oscillated simultaneously at two discrete lines centered at 1040.5 and 1042 nm, with the shorter wavelength getting stronger when the pump power was increased.

It is interesting to compare the laser polarization behavior of ***c***-cut Yb:YAB and Yb:$\mathrm{LuVO_4}$ crystals in the same setup. The laser oscillation achieved in ***c***-cut Yb:$\mathrm{LuVO_4}$ crystal was found to be linearly polarized along the [110] and $[\bar{1}10]$ crystallographic directions and the presence of eigen-polarizations results from the induced weak birefringence by the residual strain in the crystal [12]. In the ***c***-cut Yb:YAB, however, this effect was not encountered. The only remaining explanation is slight variation of the gain cross section with polarization, which cannot be detected by spectroscopic means.

*B. Laser Performance of **a**-Cut Yb:YAB*

With a 2-mm-thick ***a***-cut Yb:YAB crystal, σ-polarized laser oscillation was obtained at room temperature. The dependence of output power upon absorbed pump power is depicted in Fig. 6 for three output couplings of 0.5%, 3%, and 10%. As in the case of the ***c***-cut crystal, the results were very close for $T = 2\%-5\%$. The absorbed pump power at threshold was measured to be 0.55, 0.80, and 1.31 W for $T = 0.5\%$, 3%, and 10%, respectively, very close to the corresponding values measured in the case of the 2-mm ***c***-cut crystal, this is 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 a slope efficiency of 61%. The maximum achievable output power was 8.1 W, reached at $P_{\rm abs} = 14.4$ 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 slope efficiencies of 53% ($T = 0.5\%$) and 58% ($T = 10\%$). The laser emission wavelength varied from 1049 nm ($T = 0.5\%$) to 1039 nm ($T = 10\%$).

The σ-polarized laser oscillation achieved with the 2-mm-thick ***a***-cut crystal is governed by the gain cross section $\sigma_{\rm g}(\lambda) = \beta\sigma_{\rm em}(\lambda) - (1-\beta)\sigma_{\rm abs}(\lambda)$, which is larger for σ-polarization in the wavelength range of 1039–1049 nm for $\beta > 0.06$ (β is the fraction of inversion). However, the difference is not very large, one notes from Table I that the emission cross section is only slightly greater for σ polarization than for π polarization. As a result, polarization competition might be expected. Indeed, experimentally we did observe π-polarized lasing with a thicker crystal oscillating at 1052 nm where the gain cross section favours the π-polarization.

Making a comparison of Fig. 3 with Fig. 6, one sees that the slope efficiency obtained with ***c***-cut crystal (72%) is higher than with ***a***-cut crystal (61%) in the case of $T = 3\%$; conversely, for $T = 0.5\%$ and 10%, slightly higher slope efficiencies were achieved with ***a***-cut crystal. This inconsistency might be attributed to the unoptimized operation while the measurement was taken. Nevertheless, the highest achievable output power with ***c***-cut crystal was also higher than that with ***a***-cut crystal, and it is likely to get larger slope efficiencies through more careful alignment of the laser.

We measured the M^2 factor of the laser beam by using the knife-edge scanning method. For the 2 mm ***c***-cut crystal, $\mathrm{M}^2 = 2.0$ (horizontal) and 2.3 (vertical) at an output power of 8.0 W; while for the 2 mm ***a***-cut crystal, $\mathrm{M}^2 = 2.2$ (horizontal) and 2.4 (vertical) at an output power of 6.0 W. These results indicate the presence of higher order transverse modes in the generated laser oscillation. For the resonator configuration utilized in our experiment, the fundamental mode radius was calculated to be ~ 50 μm at the position where the crystal was placed, whereas the focused pump spot was ~ 100 μm in radius. Therefore, higher order transverse modes are expected to be oscillating under high pump power conditions.

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 thickness of the active medium has critical influence on the laser performance. Fig. 7 gives a comparison of laser output characteristics obtained with Yb:YAB crystals of different thickness (2 mm and 3 mm) and different orientations (***c***-cut and ***a***-cut), the output transmission was $T = 3\%$ as it was optimum in all the cases. 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 crystals.

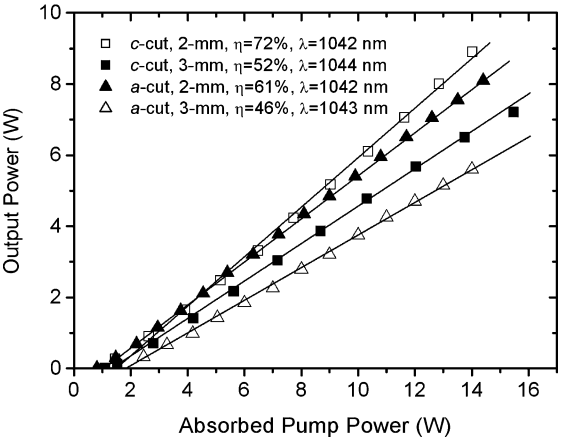

Fig. 7. Comparison of output power versus absorbed pump power for Yb:YAB crystals of different orientations and thickness. In all cases $T = 3\%$.

It should be noted, however, that the optimum crystal thickness (2 mm) is related to the specific laser configuration and pumping conditions involved in the present experiment. Under different pumping conditions (e.g., higher pump power with a larger pump beam spot), the 3-mm-thick crystal might result in more efficient laser operation.

It is worthwhile to point out that from a point of view of power scaling of a Yb:YAB laser, ***c***-cut 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. 7, increasing the crystal thickness to improve the pumping efficiency does not contribute to power scaling. On the other hand, however, it should also be noted that the laser radiation generated with ***a***-cut Yb:YAB crystals is linearly polarized, which is advantageous for many practical applications.

V. CONCLUSION

In summary, we have studied the spectroscopic properties and high-power laser performance of Yb:YAB crystal by using different samples cut along the crystallographic axes. Polarized absorption and emission cross sections were derived in the whole wavelength range of interest for laser operation, revealing very strong anisotropy in the spectroscopy of Yb:YAB, in contrast to the results given previously. The peak absorption cross section for π polarization, 0.45×10^{-20} cm^2 at 937 nm and 0.38×10^{-20} cm^2 at 984 nm, amounts to merely ~1/10 of the σ-polarized one at 975 nm (4.1×10^{-20} cm^2). Employing a ***c***-cut crystal (2-mm-thick) 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 behavior: the output was 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 a 2-mm-thick ***a***-cut crystal, σ-polarized laser oscillation was obtained. The maximum output power of 8.1 W at an absorbed pump power of 14.4 W, gives an optical-to-optical efficiency of 56%, the slope efficiency was 61%. The high-power laser performance achieved in this work demonstrates the great potential of Yb:YAB as a promising laser medium for generating infrared coherent radiation at $\sim 1\ \mu$m.

ACKNOWLEDGMENT

The authors would like to thank C. Kränkel and K. Petermann (University of Hamburg, Hamburg, Germany) for the fluorescence lifetime measurement.

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