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Compact diode-pumped Yb:YAl$_3$(BO$_3$)$_4$ laser generating 14.0 W of continuous-wave and 8.5 W of pulsed output powers

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Abstract An efficient compact diode-pumped Yb:YAl$_3$(BO$_3$)$_4$ laser operating at room temperature is demonstrated. Output powers of 14.0 and 8.5 W are generated in continuous-wave and passively Q-switched operation, respectively. Laser pulses of 262.8 µJ in energy and 8.1 ns in duration are obtained, the corresponding peak power amounting to 32.4 kW.

1 Introduction

The crystal of YAl$_3$(BO$_3$)$_4$ (YAB), belonging to the point group *32* (D_3), is a well-known nonlinear optical crystal. It can also serve as host medium for trivalent rare earth active ions such as Nd^{3+} and Yb^{3+}, which can occupy the lattice sites for the Y^{3+} ions in the structure of the YAB crystal. Such a nonlinear laser crystal enables the so-called self-frequency-doubling (SFD) action to occur in a laser resonator, converting the stimulated emission which is usually in the infrared region into the visible radiation.

It has been realized since late 1990s that the YAB crystal is more suitable to be utilized as host material for the Yb ion, instead of for the Nd ion [1], one reason for this situation is the closeness in ionic radii between the dopant Yb ion and the substituted host Y ion. As a very promising SFD laser crystal, the Yb:YAB has attracted a great deal of attention during the first decade of this century [2–6]. Output power of green light in excess of 1 W in continuous-wave (CW) and 2 W in actively Q-switched regimes has been achieved [3, 5]; coherent yellow light in mW level has also been obtained from an SFD Yb:YAB laser [6]. Although the thermal properties of Yb:YAB have not been measured directly, they seem to be fairly favorable for high-power laser operation; the thermal lensing measured under lasing conditions is shown to be even weaker than that of Nd:YAG [7]. While most of the early work on Yb:YAB was devoted to its SFD performance, the research into its fundamental laser properties has been ignored to a great extent, despite the promising results achieved in a preliminary experiment [8]. It was not until 2007 that the high-power laser performance as well as the spectroscopic properties was studied with Yb:YAB crystals cut along the crystallographic directions [9, 10], and thereafter, passively Q-switched laser oscillation was also demonstrated with either *a*- or *c*-cut Yb:YAB crystal [11].

In this paper, we report on the power-scaling capability of the Yb:YAB crystal. The output power, produced with a compact plano-concave resonator longitudinally pumped by a diode laser, reaches 14.0 and 8.5 W in CW and passively Q-switching modes, respectively. These power levels turn out to be, under similar resonator and pumping conditions, higher than those achieved with most of the Yb laser crystals developed so far.

2 Description of experiment

The compact Yb:YAB laser was built with a simple plano-concave resonator. The plane reflector was coated for high

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reflectance at 1,030–1,200 nm and high transmittance at 820–990 nm. As the output coupler, a group of concave mirrors, with radius-of-curvature (R_2) = 25 or 50 mm and output couplings in the range of $T = 0.5$–30 %, were employed. The Yb:YAB sample was cut along the crystallographic *c* axis, with a square aperture of 3.3 mm × 3.3 mm and a thickness of 3 mm. The Yb concentration in the crystal was 5.6 at.%. The uncoated crystal was held in a water-cooled copper block, and was placed close to the plane reflector inside the resonator. As saturable absorber for passive Q-switching, two Cr^{4+}:YAG crystal plates with anti-reflection coatings for 1.06 μm on both faces were used, their initial transmissions were $T_0 = 97.6$ and 93.8 % at 1.06 μm. The pump source used was a high-power fiber-coupled diode laser (fiber core diameter of 200 μm and NA of 0.22) producing unpolarized radiation at 970–975 nm depending on the output power level. The pump radiation was focused first by a focusing optics and then delivered through the plane reflector onto the laser crystal with a beam spot radius of ~100 μm.

3 Results and discussion

The Yb:YAB crystal exhibits very strong anisotropy in absorption. For the pump wavelength ranging from 970 to 975 nm, the absorption coefficient increases from 8.0 to 12.5 cm^{-1} for σ polarization ($\mathbf{E}\perp c$); whereas for π polarization ($\mathbf{E} \parallel c$), it drops to roughly 0.45 cm^{-1} [9]. As a result, the calculated unsaturated absorption (the fraction of incident pump power absorbed, η_p) of a 3-mm thick *c*-cut crystal amounts to 0.90–0.97, in contrast to 0.50–0.55 for an *a*-cut crystal of the same length. In the present experiment, only a *c*-cut Yb:YAB crystal was used. The absorption for the unpolarized pump power was measured under nonlasing conditions over a wide range of incident pump power (P_{in}); with increasing P_{in}, the measured η_p was found to decrease from $\eta_p = 0.92$ at $P_{in} = 2.0$ W to $\eta_p = 0.61$ at $P_{in} = 30.8$ W, showing a significant bleaching behavior. Such absorption bleaching will be reduced or eliminated under lasing conditions, by the "population recycling" effect arising from the process of stimulated emission, provided that a sufficiently strong laser field is present in the resonator [12]. This situation usually occurs in the case where the output coupling of the resonator is sufficiently low, e.g., $T < 3$ %; on the contrary, however, the degree of absorption bleaching is difficult to estimate in the case where the output coupling is high, e.g., $T > 10$ %. Consequently, the performance of the Yb:YAB laser will be discussed in terms of incident pump power, instead of absorbed pump power.

For CW operation, the plano-concave resonator was formed with couplers of $R_2 = 25$ mm, and was adjusted to a near-hemispherical condition. Shown in Fig. 1 is the output power as a function of P_{in} for three output couplings of $T = 5$, 10, and 30 %. With couplers of lower transmissions ($T = 0.5$, 1, and 3 %), the laser oscillation was less efficient. It was also found that the laser operation achieved with couplers of $T = 10$, 15, and 20 % proved to be very similar in output characteristics, with the optimum output coupling falling in this range. In the case of $T = 10$ %, the laser action reached the threshold at $P_{in} = 1.1$ W, the output power scaled linearly with P_{in}, giving rise to a slope efficiency of $\eta_s = 55$ %. This holds until $P_{in} \approx 19.0$ W; in excess of this power level, the laser oscillation became less efficient; at $P_{in} = 30.8$ W, the maximum pump power available in the experiment, an output power of 14.0 W was measured, corresponding to an optical-to-optical efficiency of 45.5 %, the slope efficiency determined at this power level was still $\eta_s = 55$ %. With a coupler of $T = 30$ %, the Yb:YAB laser arrived at the threshold at $P_{in} = 3.0$ W, exhibiting similar power-scaling behavior; the maximum output power generated amounted to 9.8 W. From Fig. 1, in the low pump power range of $P_{in} < \sim 10$ W, the laser operation obtained with a coupler of $T = 5$ % actually obeys the same output-versus-input relation as in the case of $T = 10$ %; at higher power levels outside this region, however, the laser performance proves to be inferior to that demonstrated with the coupler of $T = 10$ %. In CW operation, the laser oscillation wavelengths were found changing only slightly, covering a narrow range of 1,039–1,043 nm in the cases of $T = 10$–30 %; the typical width of laser emission spectra was ~2 nm.

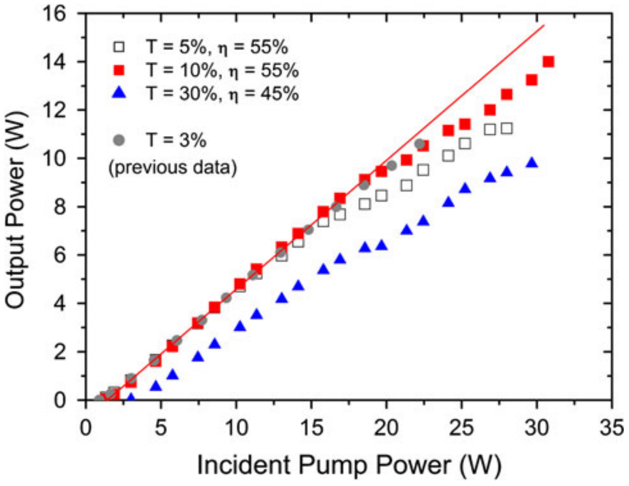

Fig. 1 Continuous-wave output power versus P_{in} measured for different output couplings

In our previous work on Yb:YAB, efficient laser operation was also achieved with a similar plano-concave resonator ($R_2 = 50$ mm) [9]. To give a comparison, the previous results, which were obtained with a 2-mm thick *c*-cut crystal under optimum coupling conditions ($T = 3$ %), are re-plotted also in Fig. 1 against incident pump power. It is interesting to note that the output characteristics of the two Yb:YAB lasers operating under optimal conditions turn out to be identical, obeying exactly the same linear power-scaling law. The undefined polarization state (with no unique polarization direction), which was observed for the laser radiation generated by the two lasers, proved also the same. Nevertheless, the highest output power produced in the previous experiment was limited to 10.6 W [9].

It is worth noting that the maximum output power generated with the Yb:YAB laser proves to be higher than most of compact diode-end-pumped Yb crystal lasers that have been demonstrated so far. In fact, among the wide variety of Yb laser crystals available at present, only the monoclinic potassium double tungstates, Yb:KT(WO$_4$)$_2$, with *T* denoting *Y*, Gd, or Lu, which are of extraordinarily high absorption and emission cross-sections originating due to the presence of unique local environment for the Yb ions, are comparable to the Yb:YAB in the capacity of laser power scaling. Under similar pumping and resonator conditions, the maximum output power produced with the Yb:KLu(WO$_4$)$_2$ and Yb:KGd(WO$_4$)$_2$ lasers amounts to 11.5 and 12.4 W, respectively [13, 14]. Furthermore, as in Fig. 1, the output power generated in the case of $T = 10$ % was limited only by the highest available pump power, implying the potential of further power scaling.

The laser beam quality was examined for the case of $T = 10$ %, by measuring the beam-quality factors for the horizontal and vertical directions, M_x^2 and M_y^2, over a wide operational range from the threshold to $P_{\mathrm{in}} = 12.5$ W at which the output power reached 6.0 W. Just above threshold, the beam-quality factors were measured to be $M_x^2 = 2.2$, and $M_y^2 = 2.0$; with rising pump power, these factors were found to increase roughly linearly, reaching $M_x^2 = 4.3$, and $M_y^2 = 4.0$ at $P_{\mathrm{in}} = 12.5$ W. Clearly, the enlargement of M^2 factor implies the presence of more high-order transverse modes oscillating in the laser beam. Due to the small TEM$_{00}$ mode size within the laser crystal which was calculated to be about 30 µm in radius, more and more high-order modes would get oscillating with the pump power being increased continuously. Through a linear extrapolation of the measured data, the beam-quality factors for the highest output power, 14.0 W, were estimated to be $M_x^2 = 6.4$, and $M_y^2 = 6.1$. Shown in Fig. 2 is a typical beam profile measured at $P_{\mathrm{in}} = 12.5$ W. As can be noted, the spatial intensity distribution can be well fitted to a Gaussian in both the horizontal and vertical directions, despite the multimode nature of the laser beam.

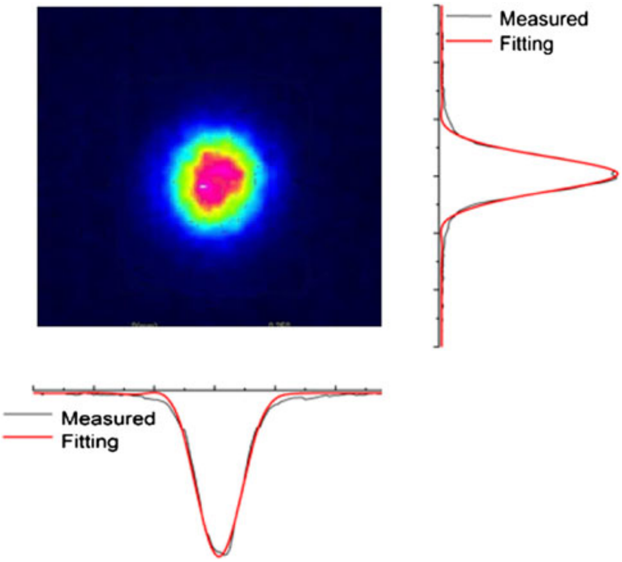

Fig. 2 Beam profile measured at $P_{\mathrm{in}} = 12.5$ W for the CW Yb:YAB laser in the case of $T = 10$ %, including spatial intensity distributions and their Gaussian fittings for both horizontal and vertical directions

It is also instructive to compare the present Yb:YAB laser with a Nd:YAB one (Nd concentration of 6 at.%) which was studied in our early work [15]. With a 4-mm thick crystal (cut along the type I phase-matching direction, θ = 32.9°) in a flat–flat cavity longitudinally pumped by a high-power diode, a maximum output power of 3.2 W was obtained with an optical-to-optical efficiency of 29.1 %. Such a comparison confirms the suitability of the YAB crystal as host medium for the Yb ion, rather than for the Nd ion.

For efficient stable passively Q-switched operation, the plano-concave resonator was formed with couplers of $R_2 = 50$ mm, with the physical cavity length adjusted to 26 mm. To prevent possible damage to the intracavity elements, only the couplers of higher transmissions, $T = 20$ and 30 %, were employed for Q-switching operation.

Figure 3 shows the average output power (P_{avr}) as a function of P_{in} for Q-switched operation, achieved with a saturable absorber of $T_0 = 97.6$ % or $T_0 = 93.8$ %, the output coupling was $T = 20$ %. For comparison, the results of CW operation are also presented. With the saturable absorber of $T_0 = 97.6$ %, the Q-switching action occurred starting at $P_{\mathrm{in}} = 2.7$ W; above this threshold point the average output power increased linearly with P_{in}, leading to a slope efficiency of $\eta_s = 54$ %. Such a linear scaling of P_{avr} continued until $P_{\mathrm{in}} \approx 15$ W, above which the Q-switching action became gradually less efficient; a maximum output power of $P_{\mathrm{avr}} = 8.5$ W was measured at $P_{\mathrm{in}} = 20.4$ W, resulting in an optical-to-optical efficiency of 41.7 %. From Fig. 3, over the entire operational range in

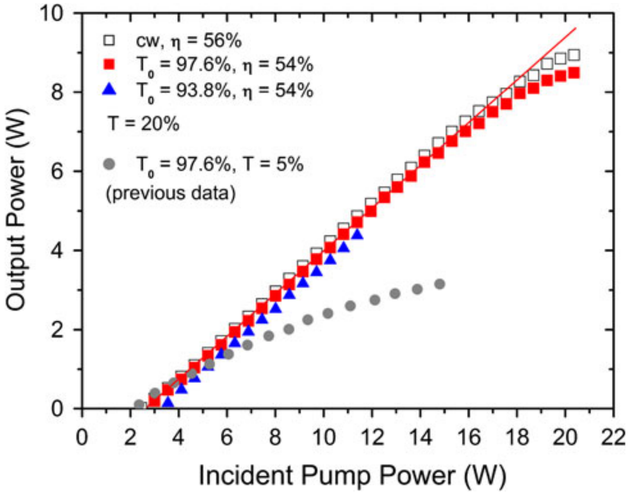

Fig. 3 Average output power versus P_{in}, generated in two cases of $T_0 = 97.6\ \%$ and $T_0 = 93.8\ \%$, the output coupling was $T = 20\ \%$

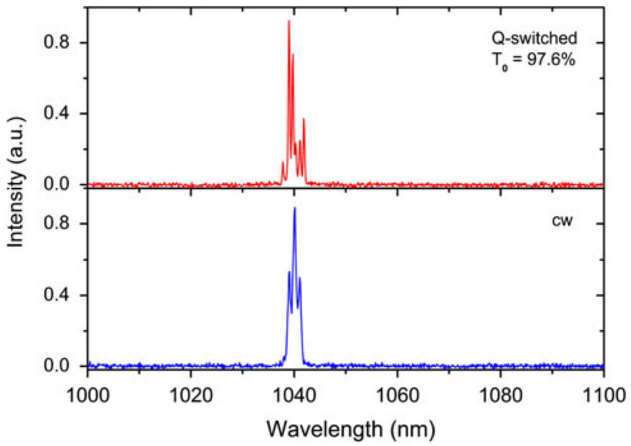

Fig. 4 Laser-emission spectra measured for the Q-switched and CW operation at $P_{\text{in}} = 14.1$ W, the output coupling was $T = 20\ \%$

which the linear scaling law holds, the difference in output characteristics between the Q-switched and CW operation is negligibly small, this is a clear indication of very efficient Q-switching action. The ratio of Q-switched to CW output power, produced at a given P_{in}, is a direct measure of the Q-switching efficiency (η_Q). This efficiency determined at $P_{\text{in}} = 20.4$ W, where the highest P_{avr} was produced, amounts to $\eta_Q = 95\ \%$. With the saturable absorber replaced by another one of $T_0 = 93.8\ \%$, the threshold pump power increased to $P_{\text{in}} = 3.3$ W. Exceeding the threshold pump level the average output power increased linearly, with a slope efficiency determined to be 54 %. The output power reached $P_{\text{avr}} = 4.38$ W at $P_{\text{in}} = 11.4$ W, with an optical-to-optical efficiency of 38.4 %. In excess of this power level, damage was easy to occur to the coatings on the surface of the Cr^{4+}:YAG crystal.

Figure 4 depicts the emission spectra of the CW and Q-switched laser operation measured at $P_{\text{in}} = 14.1$ W in the case of $T = 20\ \%$. The Q-switched oscillation, achieved with the saturable absorber of $T_0 = 97.6\ \%$, occurred in a wavelength range of 1,039–1,042 nm, compared to 1,039–1,041 nm for the CW operation.

As usual, the pulse-repetition frequency (PRF) in the passively Q-switched operation was found rising with pump power. In the case of $T_0 = 97.6\ \%$, the PRF increased rapidly, from 2.8 kHz at $P_{\text{in}} = 3.0$ W to 55.6 kHz at $P_{\text{in}} = 20.4$ W. Combining with the average output power presented in Fig. 3, one can estimate the energy contained in a single laser pulse to be in a range of $E = 69.5$–152.8 μJ, depending upon the pump power. In contrast, the PRF measured in the case of $T_0 = 93.8\ \%$ varied more slowly with increasing pump power, from 0.63 kHz at $P_{\text{in}} = 3.6$ W to 16.7 kHz at $P_{\text{in}} = 11.4$ W, at which the highest output power of 4.38 W was obtained, the corresponding pulse energy being in a range of $E = 224$–262.8 μJ.

Passively Q-switched laser operation was also realized with a coupler of higher transmission $T = 30\ \%$. In this case, the maximum average output power, produced with the saturable absorber of $T_0 = 93.8\ \%$, was measured to be 2.41 W at a PRF of 8.3 kHz at $P_{\text{in}} = 12.0$ W, yielding a pulse energy of 290.4 μJ, the optical-to-optical efficiency being 20 %. For the passively Q-switched laser oscillation generated in the current experiment, the amplitude fluctuations of laser pulses were approximately 20 % at most; while the time jittering was estimated to be <20 %.

For comparison, the average output power, produced in the passively Q-switched laser operation of a 2-mm thick *c*-cut Yb:YAB crystal, which was achieved in a similar resonator under conditions of $T = 5\ \%$, $T_0 = 97.6\ \%$ [11], is re-plotted in Fig. 3 against the incident pump power. One sees that except for the low pump power region of $P_{\text{in}} < \sim 5$ W, the passively Q-switching performance of

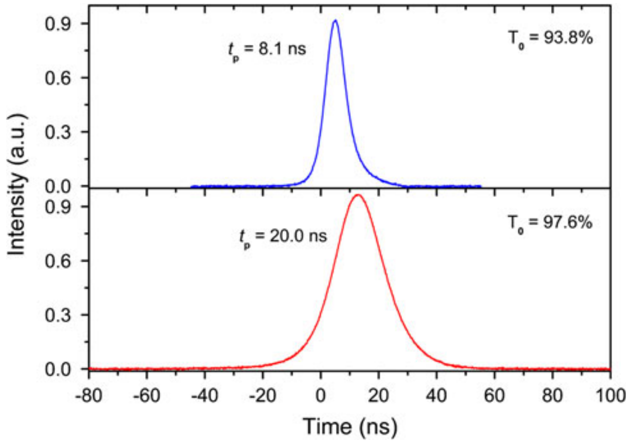

Fig. 5 Typical pulse profiles measured at $P_{\text{in}} = 8.6$ W in the case of $T = 20\ \%$

Table 1 Parameters characterizing the passively Q-switched Yb:YAB laser

Conditions (%)	P_{th} (W)	P_{avr} (W)	PRF (kHz)	E (μJ)	t_p (ns)	P_p (kW)	η_{opt} (%)	η_s (%)	η_Q (%)
$T = 20$ $T_0 = 97.6$	2.7	8.5	55.6	152.8	20.0	7.6	41.7	54	95
$T = 20$ $T_0 = 93.8$	3.3	4.38	16.7	262.8	8.1	32.4	38.4	54	90
$T = 30$ $T_0 = 93.8$	4.5	2.41	8.3	290.4	8.1	35.9	20	38	86

the previously reported Yb:YAB laser proves inferior to that demonstrated in the present experiment, especially for high power levels.

It is also interesting to make a comparison with a Yb:GdAl$_3$(BO$_3$)$_4$ (Yb:GdAB) laser formed with a similar plano-concave resonator, which was passively Q-switched by a Cr^{4+}:YAG saturable absorber of $T_0 = 96$ % [16]. With a coupler of $T = 4$ %, an average output power of ~0.65 W was generated with a slope efficiency of 39.5 % (with respect to absorbed pump power), the corresponding pulse energy was 165 μJ [16], comparable to that produced with the Yb:YAB laser under conditions of $T = 20$ %, $T_0 = 97.6$ %.

Despite the variation of laser pulse energy, the pulse duration (t_p) was found remaining unchanged, independent of the pump power. Figure 5 illustrates typical pulse profiles recorded at $P_{in} = 8.6$ W for the two cases of $T_0 = 97.6$ and 93.8 %, the output coupling was $T = 20$ %. Pulse durations of 20.0 and 8.1 ns were measured for $T_0 = 97.6$ and 93.8 %, respectively. Given the pulse energy and duration, the peak power can be estimated according to $P_p = E/t_p$. The highest peak power, calculated for the cases of $T_0 = 97.6$ and 93.8 %, amounts to 7.6 and 32.4 kW, respectively. A summary of the primary parameters characterizing the passively Q-switched Yb:YAB laser is given in Table 1, where P_{th} denotes the threshold pump power, η_{opt} is optical-to-optical efficiency, other symbols are defined in preceding sections.

4 Conclusions

In summary, high-power laser operation was demonstrated with Yb:YAB crystal in a compact resonator. 14.0 W of CW output power was generated with an optical-to-optical efficiency of 45.5 % with respect to incident pump power. In passively Q-switched operation, an average output power of 8.5 W at a pulse-repetition rate of 55.6 kHz was obtained, with an optical-to-optical and a slope efficiency of 41.7 and 54 %, respectively. Laser pulses of 262.8 μJ in energy and 8.1 ns in duration were obtained, the corresponding peak power amounting to 32.4 kW. These results reveal the great potential of Yb:YAB for the applications in high-power systems, e.g., thin-disk lasers operating in CW, Q-switched, or mode-locked regimes.

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