Appl Phys B (2008) 93: 753–757
DOI 10.1007/s00340-008-3276-z

Applied Physics B
Lasers and Optics

RAPID COMMUNICATION

Sub-90 fs pulses from a passively mode-locked Yb:$YAl_3(BO_3)_4$ laser

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Received: 11 July 2008 / Revised version: 1 October 2008 / Published online: 6 November 2008

Abstract Passive mode locking of the self-frequency doubling Yb:YAB crystal with a saturable absorber mirror is studied at the fundamental wavelength. This laser has a very low threshold, and pulses as short as 85 and 87 fs are obtained for Ti:sapphire and diode laser pumping, respectively.

PACS 42.55.Rz · 42.55.Xi · 42.60.Fc

1 Introduction

In the last years, mode-locked laser operation of Yb^{3+} based on several borate crystals was reported, demonstrating their high potential for femtosecond pulse generation. Pulse durations of 198 and 67 fs were obtained with Yb:$YAl_3(BO_3)_4$ (Yb:YAB) and Yb:$LaSc_3(BO_3)_4$ (Yb:LSB) crystals, respectively [1, 2]. The oxoborates Yb:$Ca_4YO(BO_3)_3$ (Yb:YCOB) and Yb:$Ca_4GdO(BO_3)_3$ (Yb:GdCOB) produced pulses as short as 210 and 90 fs, respectively [3–5], while pulse lengths of 69 fs were achieved with Yb:$Sr_3Y(BO_3)_3$ (Yb:BOYS) [6, 7]. The pulses obtained recently with Yb:$Li_6Y(BO_3)_3$ (Yb:LYB) were longer, 355 fs [8]. In all these cases the mode-locking was achieved employing a saturable absorber mirror (SAM) as an end reflector [9] and the reported pulse durations refer to diode-pumped operation (in fact, only Yb:LSB was also studied with Ti:sapphire laser pumping, and the pulses were slightly shorter—58 fs [2]).

This work is devoted to the femtosecond mode-locked operation of Yb:YAB, a borate crystal which is potentially interesting for several reasons. In fact, YAB is a well known laser host material, a negative uniaxial crystal with non-centrosymmetric 32 (D_3) huntite structure. Doped with Nd, it has been used for more than two decades 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 Yb attracted much more attention. In comparison with the Nd ion, the Yb ion is much closer in ionic radius to the Y ion, 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 [10]. The same holds if we compare with the isostructural Yb:$GdAl_3(BO_3)_4$ (Yb:GdAB) which is also non-centrosymmetric. These crystals belong to a more general class of borate compounds with the chemical formula $LnM_3(BO_3)_4$ where Ln is lanthanide or Y, and M = Al, Ga, Sc [11], however, not all of them (e.g., LSB) crystallize in the trigonal huntite structure with symmetry 32. At present Yb:YAB is recognized as the most promising SFD laser material—1.1 W of continuous-wave (CW) radiation and 2.27 W of average power in the Q-switched mode have been demonstrated by such lasers operating in the green [12, 13]. However, the paradox with YAB is that most of the previous studies were devoted to the SFD regime which concerns also the mode-locking, although the shortest pulses

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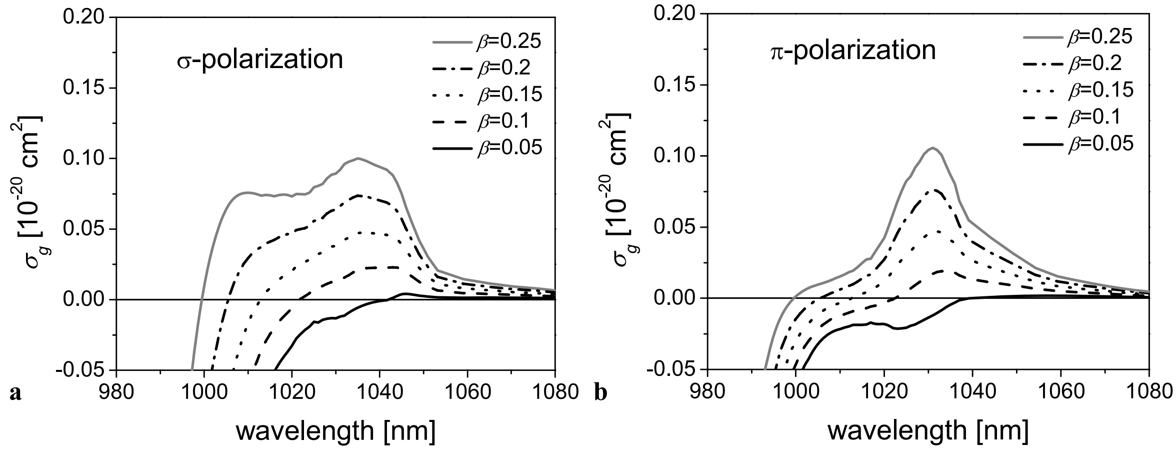

Fig. 1 Gain cross-sections σ_g of Yb:YAB for σ- (**a**) and π- (**b**) polarization depending on the inversion parameter β

of 198 fs reported in [1] refer to operation far from phase-matching. The host itself was studied as a nonlinear material only very recently [14] and showed very promising potential in the UV related to the good thermo-mechanical properties and the chemical stability of YAB. The thermal conductivity of Yb:YAG is also quite good (4.7 W m^{-1} K^{-1} for 5.6 at.% Yb doping [15]) which is promising for power scaling of such lasers. We demonstrated recently very high efficiency of diode-pumped Yb:YAB lasers operating at the fundamental in the CW [16] and Q-switched [17] regimes. Here we demonstrate that the passively mode-locked Yb:YAB laser can produce pulse durations below 90 fs both under Ti:sapphire and diode laser pumping. This is a good basis for the future design of sub-100 fs lasers operating in the green. Note that the green pulse duration was not measured in [1], but estimations lead to a lower limit of 250 fs with partial phase-matching when the fundamental pulse duration amounts to 245 fs.

2 Description of the experiment

Previous experiments indicated higher gain for σ-polarization in the uniaxial Yb:YAB [16, 17]. On the basis of the measured emission and absorption cross-sections we calculated the gain cross-sections defined by $\sigma_g = \beta\sigma_e - (1-\beta)\sigma_a$, where σ_e, σ_a denote the emission/absorption cross sections, and β is the inversion ratio in the CW regime which increases with the output coupling T_{OC}. As can be seen from Fig. 1, the σ-polarization exhibits much broader gain bandwidth, and consequently the present study was confined to this polarization. Using uncoated samples under Brewster angle, this simplifies the pumping scheme because the same polarization should be used for pumping due to an order of magnitude larger absorption cross section for σ-polarization [16].

The ***a***-cut Yb:YAB sample used in the present work was obtained from the boule with initial size of $21 \times 21 \times 30$ mm^3 which was doped with 8 at.% Yb. However, measurements by the X-ray fluorescence method indicated an actual doping level of 5.6 at.% equivalent to an Yb-ion density of 3.08×10^{20} cm^{-3}. The uncoated crystal was 2 mm thick with an aperture of 3.3×3.3 mm^2. It was mounted on a copper block without active cooling and placed in an astigmatically compensated Z-type cavity with the Brewster minimum loss condition fulfilled for both the laser and pump beam. Two pump sources, a Ti:sapphire and a diode laser, were used. The Ti:sapphire laser emitted up to 1.5 W near 975 nm (peak absorption). The diode laser consisted of a 50 μm broad-stripe single emitter. It generated as much as 4.5 W of output power at 974 nm with a spectral linewidth of about 6 nm (FWHM). The astigmatic beam of the broad-stripe diode laser was collimated by two crossed cylindrical micro-lenses. The diode laser itself emitted partially polarized light, but to avoid damage to the diode and to ensure polarized pumping a Faraday-isolator was placed into the pump beam. Both pump lasers were focused by an $f = 62.8$-mm spherical lens through one of the folding mirrors (radius of curvature, RC $= -10$ cm) of the resonator.

Passive mode-locking was achieved by a SAM employed as an end reflector on which the beam was focused using a third curved mirror of RC $= -15$ cm. Two SF10 prisms with a tip-to-tip separation of 39 cm were used for dispersion compensation in the other arm containing the output coupler. In this case, the cavity length corresponded to a repetition rate of 92 MHz.

3 Results and discussion

As a first step, the CW laser characteristics were measured with Ti:sapphire laser pumping. With the prisms removed,

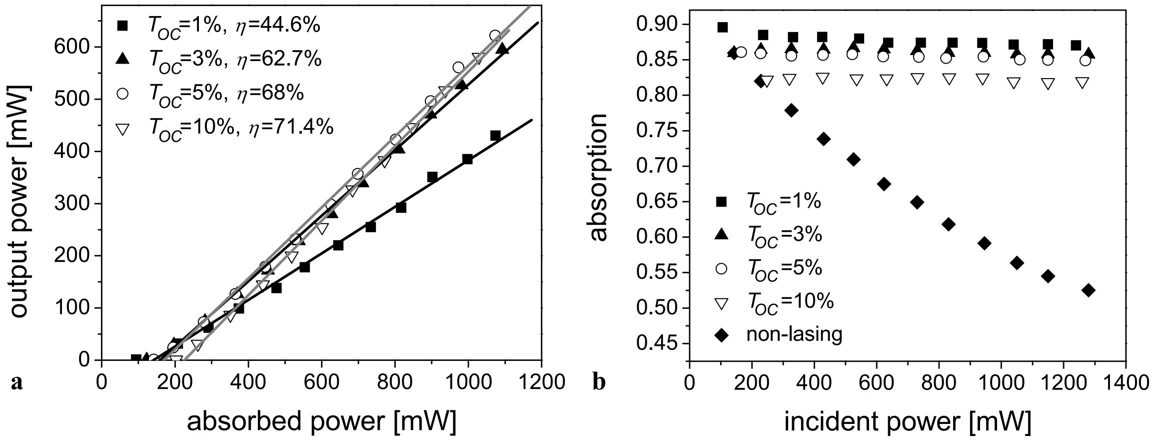

Fig. 2 Output power versus absorbed pump power (**a**) and absorption versus incident pump power (**b**) for the CW Ti:sapphire laser pumped Yb:YAB laser using different output couplers with transmission T_{OC}. The slope efficiency (linear fits) is denoted by η

the cavity length amounted to 140 cm in this case. The high slope efficiencies together with the substantial recycling of the population (compensation of the absorption bleaching by the increasing pump saturation intensity in the 3-level Yb-laser system as shown in Fig. 2(b)) lead to a maximum output power exceeding 620 mW (Fig. 2(a)). The threshold with $T_{OC} = 1\%$ was as low as 90 mW of absorbed pump power.

Three different SAMs from BATOP GmbH were tested first with Ti:sapphire laser pumping in the cavity used for mode-locking. All of them were designed for a central wavelength of 1040 nm and their saturable loss and relaxation time were specified as 0.7%/500 fs, 1%/500 fs, and 1%/10 ps, respectively. The modulation depth of the first one turned out to be too low to obtain stable mode-locking. The second SAM enabled stable mode-locked operation with pulse durations of roughly 120 fs but the last one, although having rather long relaxation constant, provided shorter pulse durations. With $T_{OC} = 1\%$ the minimum pulse duration was 101 fs (FWHM from the $sech^2$-fit for the pulse intensity), Fig. 3(a). The corresponding average output power was 122 mW. The pulse spectrum was centered at 1045 nm. With a 0.4% output coupler, it was possible to shift the wavelength to 1050 nm and profit from the broader gain bandwidth. The output power decreased to 47 mW but the pulse duration was as short as 85 fs (Fig. 3(b)). However, the time-bandwidth product (0.39) remained almost unchanged. In both cases, the incident pump power was 1.05 W.

Diode pumping of the same cavity was rather uncritical and efficient as the absorption band for σ-polarization is very broad ($\Delta\lambda = 20$ nm). In particular, the slight modulation of the output power due to the temperature variation of the diode usually seen with other crystals was not observed in the case of Yb:YAB. As with Ti:sapphire laser pumping, the operation in the mode-locked regime was self-starting. The shortest pulse durations were achieved with the same

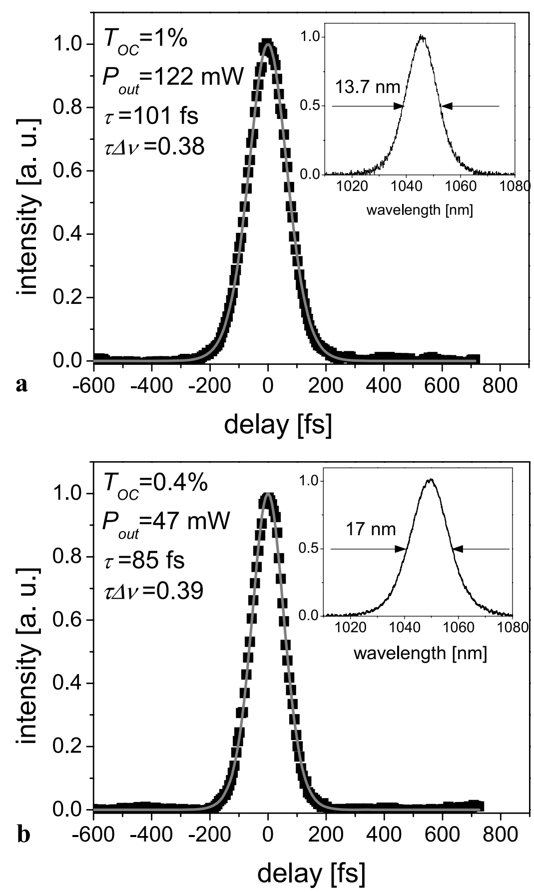

Fig. 3 Autocorrelation traces (*symbols*) with fits (*gray curves*) and spectra (*insets*) obtained for the Ti:sapphire laser pumped mode-locked Yb:YAB laser using $T_{OC} = 1\%$ (**a**) and $T_{OC} = 0.4\%$ (**b**). P_{out} denotes the average output power and $\tau\Delta\nu$ is the time-bandwidth product with τ-pulse FWHM

SAM that was optimum for Ti:sapphire laser pumping. For an incident pump power of 2.46 W, careful adjustment of the cavity resulted in stable mode-locked operation with pulse

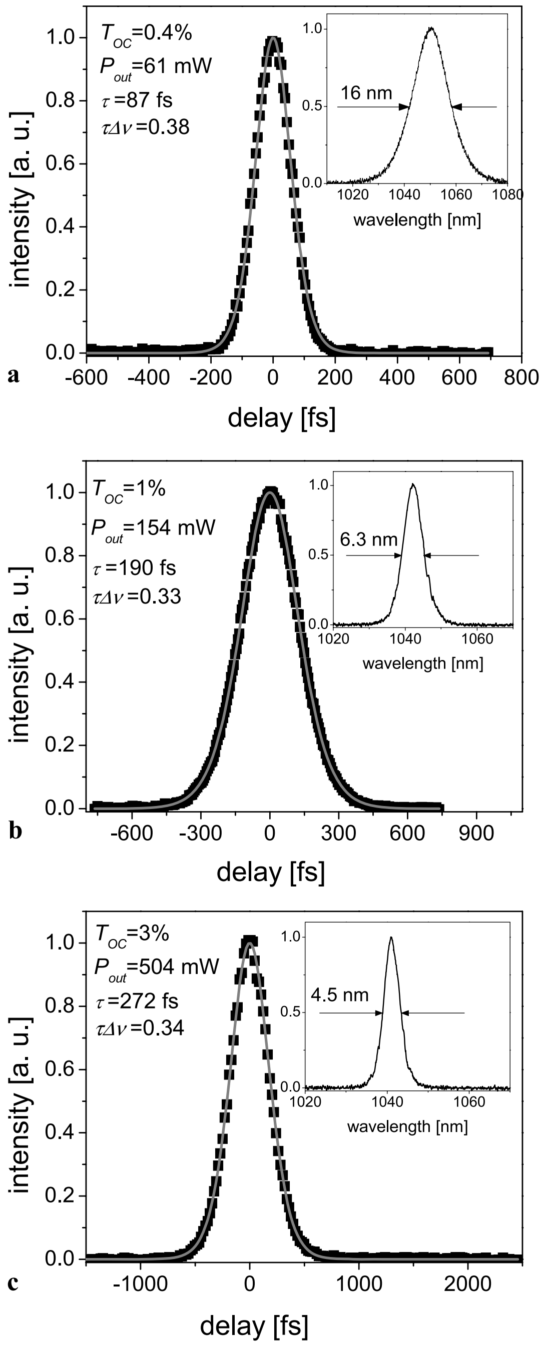

Fig. 4 Autocorrelation traces (*symbols*) with fits (*gray curves*) and spectra (*insets*) obtained for the diode pumped mode-locked Yb:YAB laser using $T_{OC} = 0.4\%$ (**a**), $T_{OC} = 1\%$ (**b**), and $T_{OC} = 3\%$ (**c**). P_{out} denotes the average output power, and $\tau\Delta\nu$ is the time-bandwidth product with τ-pulse FWHM

durations as short as 87 fs for $T_{OC} = 0.4\%$ (Fig. 4(a)). The spectrum was centered at 1050 nm with a FWHM of 16 nm corresponding to a time-bandwidth product of 0.38. The average output power amounted to 61 mW. The laser exhibited some tunability to shorter wavelengths (down to 1040 nm) by adjusting the prisms, and remained stable, however, the pulse durations at shorter wavelengths were substantially longer. Increasing the pump power to 2.6 W lead to instabilities (occurrence of a CW peak at 1040 nm, Q-switching mode-locking, or even the presence of higher transversal modes) that are related to the deterioration of the mode profile of the pump beam.

Using output couplers with higher transmission permitted to increase the average output power. This was associated with a blue shift of the central wavelength and lengthening of the pulse duration. With $T_{OC} = 1\%$, an average output power of 154 mW was obtained for a pulse duration of 190 fs and a central wavelength of 1042 nm (Fig. 4(b)) while $T_{OC} = 3\%$ lead to an average output power of 504 mW with a pulse duration of 272 fs (Fig. 4(c)) and the central wavelength was further shifted to 1041 nm. The wavelength shifting is in accordance with the spectral dependence of the gain cross-section in Fig. 1(a) when increasing the output coupling which is equivalent to higher inversion in the steady state. With higher output coupling, the time-bandwidth product got slightly closer to the value for Fourier-limited pulses with the assumed sech^2 pulse shape (0.315).

In all cases, both for Ti:sapphire and diode laser pumping, the optical-to-optical efficiency of the mode-locked laser was much lower in comparison to CW operation. This is related not only to the insertion losses of the elements added but also to the additional realignment of the whole cavity which is necessary in the presence of a third focusing mirror to find the stable mode-locking regime.

4 Conclusions

We conclude that Yb:YAB laser exhibits low threshold and high efficiency in comparison with other Yb-doped materials in cavity configurations suitable for mode-locking. Applying a SAM with dispersion compensation enabled us to produce sub-90 fs pulses, both under Ti:sapphire and diode laser pumping. The improvement in terms of pulse length in comparison to the original work presented in [1] is about 2.3 times. Our further work will be devoted to the generation of sub-100 fs pulses in the green by SFD. According to the estimations given in [1] for the spectral acceptance, this will require a crystal thickness of about 1 mm which means that the doping level should be increased at least twice. Such crystals of Yb:YAB have already been grown and exhibit good optical quality.

Acknowledgements This work was supported by the National Natural Science Foundation of China (No. 50590401 and No. 50721002), the Grant for State Key Program of China (2004CB619002) and the EU project DT-CRYS, NMP3-CT-2003-505580.

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