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56-fs diode-pumped SESAM mode-locked $Yb:YAl_3(BO_3)_4$ laser

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Abstract: We report on the first sub-60 fs pulse generated from a diode-pumped SESAM mode-locked Yb-laser based on a non-centrosymmetric $Yb:YAl_3(BO_3)_4$ crystal as a gain medium. In the continuous-wave regime, pumping with a spatially single-mode, fiber-coupled 976 nm InGaAs laser diode, the $Yb:YAl_3(BO_3)_4$ laser generated 391 mW at 1041.7 nm with a slope efficiency as high as 65.1%, and a wavelength tuning across 59 nm (1019 to 1078 nm) was achieved. By implementing a commercial SESAM to initiate and sustain the soliton type mode-locking, and using only a 1 mm-thick laser crystal, the $Yb:YAl_3(BO_3)_4$ laser delivered pulses as short as 56 fs at a central wavelength of 1044.6 nm with an average output power of 76 mW at a pulse repetition rate of ~67.55 MHz. To the best of our knowledge, this result represents the shortest pulses ever achieved from Yb:YAB crystal.

1. Introduction

Yb^{3+}-doped yttrium aluminum borate $YAl_3(BO_3)_4$ (abbreviated: Yb:YAB), represents one of the most promising structurally ordered crystals favoring high-power laser development [1–3]. It belongs to the trigonal class possessing a huntite structure with the space group of $R32$, the point group of $32(D_3)$, and the lattice parameters of undoped crystal: $a = b = 9.293$ Å, $c = 7.245$ Å, $\gamma = 120°$ [4]. YAB is an optically negative uniaxial crystal with its optical axis parallel to the ***c***-axis. It has an effective nonlinear coefficient exceeding 1 pm/V [5]. YAB has been widely used as a host in self-frequency doubling (SFD) Nd lasers. At present, Yb:YAB is recognized as one of the most promising SFD laser materials: about 1.1 W of continuous-wave (CW) radiation [6] and 2.27 W of average power in the Q-switched regime [7] have been extracted from such lasers emitting in the green.

The structure of YAB is characterized by providing isolated Y^{3+} ions and, consequently, high Yb^{3+} doping levels are possible with weak concentration quenching. Yb^{3+} ions in YAB exhibit high absorption and stimulated-emission cross-sections, broad and flat gain profiles, which, combined with the appealing thermal and thermo-optical properties of the host matrix [8–11], make this compound very suitable for high-power mode-locked (ML) laser operation [12].

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Employing a SEmiconductoir Saturable Absorber Mirror (SESAM), a thin-disk Yb:YAB laser delivered 462 fs pulses at 1040 nm with an average output power of 19.2 W at a pulse repetition rate of 50.4 MHz [13]. In a SFD ML Yb:YAB laser [14], soliton mode-locking with a pulse duration of 245 fs and an average green power of 60 mW could be achieved only for slight/partial phase mismatch. So far, the shortest pulses from any mode-locked Yb:YAB laser were reported by Rivier *et al.:* a SESAM mode-locked Yb:YAB laser without SFD pumped by a Ti:Saphhire laser at 975 nm emitted 85 fs pulses at 1050 nm corresponding to an output power of 47 mW [15]. Yb:YAB crystals with high doping levels (up to 29 at.%) are available [16]. This is an essential advantage allowing to use very thin crystals in ML lasers. The relatively good thermal conductivity of Yb:YAB (an average value of 4.7 $Wm^{-1}K^{-1}$ for 5.6 at.% Yb^{3+} doping) is a good prerequisite for this because the thermal load will be localized due to the short length.

In the present work, we investigate the passively mode-locked laser performance of a heavily doped Yb:YAB crystal with a thickness of only 1 mm pumped by a spatially single-mode, fiber-coupled InGaAs laser diode demonstrating its potential for sub-60 fs pulse generation.

2. Laser set-up

A high-quality Yb:YAB single-crystal was grown by the top-seeded solution growth (TSSG) method. The actual Yb^{3+} doping level was measured by the inductively coupled plasma mass spectrometry (ICP-MS) to be 10 at.% (Yb^{3+} ion density: $N_{Yb} = 5.54 \times 10^{20}$ cm^{-3}). For optically uniaxial crystals, there are two principal light polarizations, denoted as π (***E*** || O.A.) and σ (***E*** ⊥ O.A., O.A. is the optical axis). They correspond to the extraordinary (*e*) and ordinary (*o*) waves and refractive indices (n_o and n_e). Considering uniaxial crystals as gain media, those being optically negative ($n_e < n_o$) with type-I phase-matching are preferable for SFD lasers because the transition cross sections of active ions will not depend on the cut angle and there will be no spatial walk-off at the fundamental wavelength. Yb:YAB not only satisfies these requirements but the stimulated-emission cross sections for the corresponding light polarization (σ) are much higher and this polarization will be naturally selected in a laser [1]. The spectroscopic data for Yb:YAB can be found in [1,2], corresponding to 5.6 at.% Yb^{3+}-doping.

The experimental configuration of the diode-pumped Yb:YAB laser is shown in Fig. 1. The uncoated laser crystal, a 10 at.% Yb:YAB, with a thickness of only 1 mm (previously, Yb:YAB mode-locked laser employed 2–3 mm-thick crystals doped with ~5 at.% Yb^{3+}) and an aperture of 3 mm × 3 mm was mounted on a passively cooled copper holder and placed at Brewster's angle between two dichroic folding mirrors M_1 and M_2 (radius of curvature, RoC = -100 mm) in an X-folded astigmatically compensated linear cavity. The crystal was cut at an angle $\theta = 31$ (from ***c*** to ***a***-axis) but tilted in such a way with both ***c*** and ***a***-axes in the horizontal plane, so that under Brewster's angle, the light propagation inside the crystal was approximately along the ***c***-axis and the polarization ***E*** was almost parallel to the ***a***-axis (σ-polarization). The calculated internal Brewster's angle was 29.6°, i.e., the deviation was very small. Having in mind the weak reflection loss dependence near the zero reflection point for the σ-polarization, also propagation exactly along the ***c***-axis is feasible. The deviation from phase-matching direction was roughly 30° and this effect, a priori, was impossible to attain. The pump source was a spatially single-mode, fiber-coupled InGaAs laser diode delivering a maximum incident power of 1.29 W at 976 nm (unpolarized radiation). Its emission wavelength was locked by a fiber Bragg grating (FBG) resulting in a spectral linewidth (FWHM) of 0.2 nm. The beam propagation factor (M^2) of the pump radiation at the maximum output power was measured to be 1.02. The pump beam was collimated by an aspherical lens L_1 (focal length: $f = 26$ mm) and focused into the laser crystal through the M_1 mirror by an achromatic doublet lens L_2 ($f = 100$ mm), which yielded a beam waist (radius) of 18.9 μm × 37.8 μm in the sagittal and tangential planes, respectively.

A four-mirror cavity was used to evaluate the laser performance in the CW regime. One of the cavity arms was terminated by a flat rear mirror M_3, and the other cavity arm was ended

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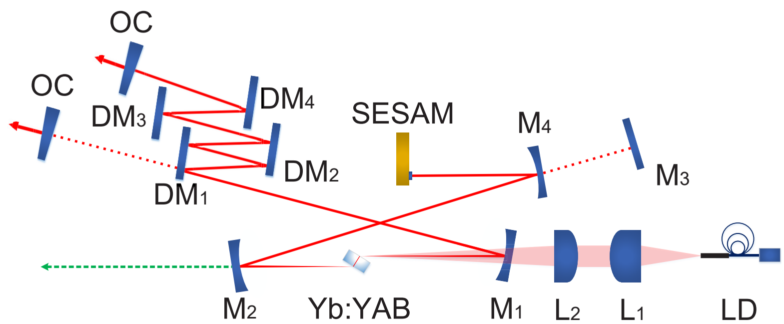

Fig. 1. Schematic of the diode-pumped Yb:YAB laser. LD: fiber-coupled InGaAs laser diode; L_1: aspherical lens; L_2: achromatic doublet lens; M_1, M_2 and M_4: curved mirrors (RoC = -100 mm); M_3: flat rear mirror for CW laser operation; DM_1 – DM_4: flat dispersive mirrors; OC: output coupler; SESAM: SEmiconductor Saturable Absorber Mirror. *Dashed green arrow* indicates the leakage of the green SFD output.

with a plane-wedged output coupler (OC) having a transmission T_{OC} at the laser wavelength in the range 0.4% to 7.5%. The fundamental mode size inside the laser crystal was estimated using the ray transfer matrix formalism giving a beam radius of 24.4 µm × 41.2 µm in the sagittal and tangential planes, respectively. The measured single-pass pump absorption under lasing conditions slightly decreased with the output coupling from 52% to 47% due to the decreasing recycling effect at lower intracavity intensity.

For ML operation, a commercial SESAM (BATOP, GmbH) with a modulation depth of 1.2%, and a relaxation time of ~1 ps (at ~1 µm) was employed instead of the flat rear mirror M_3. It served basically to initiate and sustain the ML operation. A second cavity beam waist (a spot radius of ~70 µm) was created on the SESAM by a concave mirror M_4 (RoC = -100 mm) to ensure its efficient bleaching. Four flat dispersive mirrors (DMs) were implemented in the other cavity arm for providing a total round-trip negative group delay dispersion (GDD) of -1620 fs^2. They mainly served to balance the self-phase modulation (SPM) for soliton pulse shaping because the material dispersion of the Yb:YAB crystal (estimated from the dispersion curves to be ~26.7 fs^2/mm at 1040 nm for σ-polarization [17]) was rather low for 1 mm thickness. The geometrical cavity length of the ML laser was roughly 2.2 m.

3. Experimental results

3.1. Continuous-wave laser operation

The power transfer characteristics and the typical laser spectra of the diode-pumped Yb:YAB laser in the CW regime are presented in Fig. 2(a). The maximum output power amounted to 391 mW at 1041.7 nm for 1% OC at an absorbed pump power of 675 mW. This corresponds to a slope efficiency η of 65.1% (with respect to the absorbed pump power) and an optical efficiency of 57.9%. A slightly higher η of 66.3% and lower output power of 337 mW was obtained with 4.5% OC. The laser threshold gradually increased with the output coupling, from 46 mW (T_{OC} = 0.4%) to 165 mW (T_{OC} = 7.5%). The measured laser spectra experienced a monotonic blue-shift in the range of 1033 - 1050 nm with increasing T_{OC}, which agrees well with the quasi-three-level Yb^{3+} laser scheme, see Fig. 2(b).

The total round-trip cavity loss δ (reabsorption losses excluded) and the intrinsic slope efficiency η_0 (accounting for the mode-matching and the quantum efficiencies) were evaluated by carrying out the Caird analysis through fitting the measured laser slope efficiency as a function of the output coupler reflectivity, R_{OC} = 1 - T_{OC} [18]. The estimated intrinsic slope efficiency η_0

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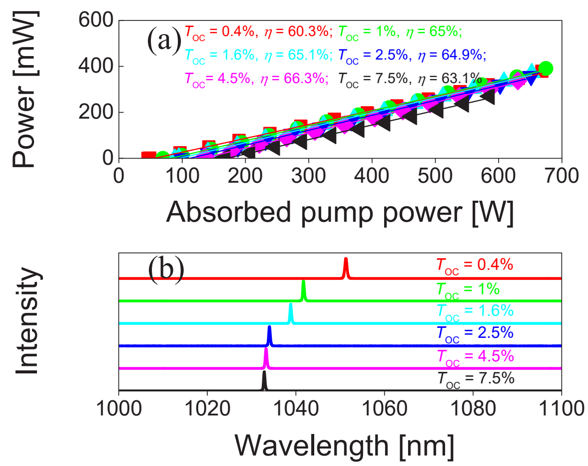

Fig. 2. Continuous-wave diode-pumped Yb:YAB laser: (a) Input - output dependences for different OCs, η – slope efficiency; (b) spectra of laser emission (σ-polarization).

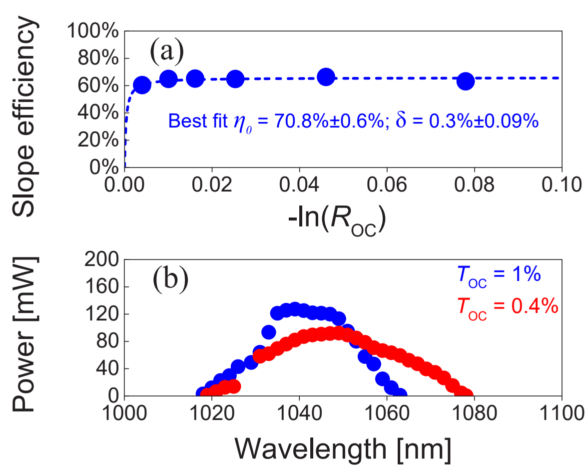

Fig. 3. Diode-pumped Yb:YAB laser in the CW regime: (a) Caird analysis: slope efficiency vs $R_{OC} = 1 - T_{OC}$; (b) tuning curve obtained using a SF-10 prism with and $T_{OC} = 0.4\%$ and 1%.

was 70.8 ± 0.6% and the total round-trip cavity loss was δ = 0.3 ± 0.09%, as shown in Fig. 3(a). The extremely low value of δ indicates the good optical quality of the implemented laser crystal.

The wavelength tuning of the diode-pumped CW Yb:YAB laser was studied by inserting a SF10 dispersive Brewster prism close to the OC at an incident pump power of 900 mW. For higher T_{OC} = 1%, the laser wavelength was continuously tunable from 1018 nm to 1063 nm, i.e., across 45 nm at the zero-power-level. For the lower T_{OC} = 0.4% at the same pump level, the tuning range was much broader, 59 nm (1019 - 1078 nm), see Fig. 3(b). The smooth and relatively broad tuning curves indicated high potential for sub-100 fs pulse generation.

3.2. SESAM mode-locked laser operation

Stable and self-starting mode-locked operation of the diode-pumped Yb:YAB laser could be readily achieved by a careful cavity alignment after implementing DMs and SESAM. Using a 1.6% OC, the Yb:YAB laser delivered soliton pulses with a maximum average output power of 220 mW at an absorbed pump power of 654 mW, which corresponded to an optical efficiency of 33.7%. The measured spectrum of the ML laser pulses was centered at 1038.3 nm and had a sech^2-shaped spectral profile with a bandwidth of 8.5 nm (FWHM), see Fig. 4(a). The recorded SHG-based intensity autocorrelation trace could be well fitted with a sech^2-shaped temporal profile yielding an estimated pulse duration of 137 fs, see Fig. 4(b). The corresponding time-bandwidth product (TBP) of 0.324 was only slightly above the Fourier-transform limit for sech^2-shaped pulses (0.315). The long-scale autocorrelation scan over 50 ps shown in the inset of Fig. 4(b) confirmed single-pulse CW-ML operation without any pedestals or multi-pulsing instabilities.

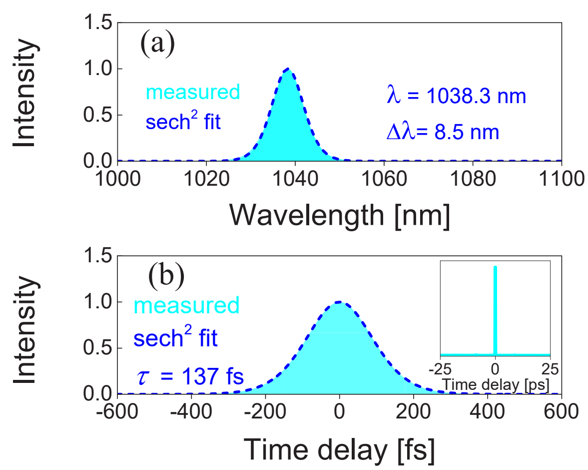

Fig. 4. Diode-pumped SESAM ML Yb:YAB laser with 1.6% OC. (a) Optical spectrum and (b) measured SHG-based intensity autocorrelation trace. *Inset* in (b) – a long-scale (50 ps) trace.

The shortest pulse duration was obtained by using 1% OC while sustaining the same amount of negative GDD introduced by the DMs. Soliton-like pulses were generated at 1044.6 nm with a spectral bandwidth of 20.7 nm (FWHM) by assuming a sech^2-shaped spectral profile, as shown in Fig. 5(a). Figure 5(b) shows the measured SHG-based background-free intensity autocorrelation trace for the shortest pulses. The curve was almost perfectly fitted by a sech^2-shaped temporal profile, yielding an estimate pulse duration (FWHM) of 56 fs. For this output coupler, the average output power dropped to 76 mW at an absorbed pump power of 704 mW, which corresponds to an optical efficiency of only 10.8%. The corresponding TBP was 0.318 being very close

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to the Fourier-transform-limited value. The inset of Fig. 5(b) shows a 50-ps scale SHG-based background-free intensity autocorrelation trace evindencing single-pulse CW-ML operation.

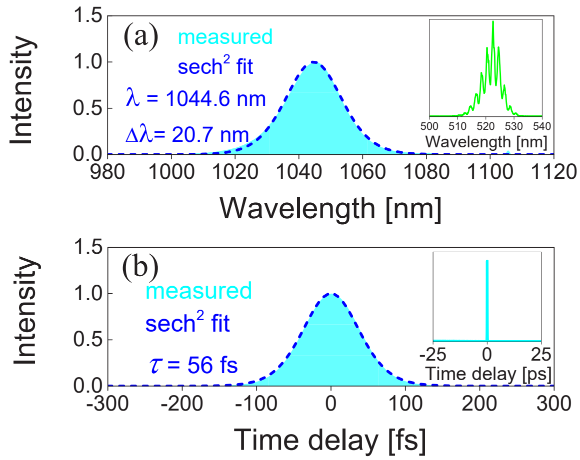

Fig. 5. Diode-pumped SESAM ML Yb:YAB laser with 1% OC. (a) Optical spectrum of the fundamental laser emission, *Inse*t – spectrum of the green SFD output; (b) measured SHG-based intensity autocorrelation trace, *inset* - long-scale (50-ps) autocorrelation trace.

Due to the non-centrosymmetric structure of the Yb:YAB crystal, non-phase matched SFD of femtosecond pulses was observed during the ML operation. The inset of Fig. 5(a) represents the optical spectrum of the green SFD output with strong interference fringes corresponding to the shortest pulse duration for the fundamental radiation. The well-defined spectral fringes in the SHG spectrum with ~2 nm fringe spacing originate from interference of two green pulses in the laser crystal under non-phase matching conditions and a strong group velocity mismatch (GVM) with the fundamental radiation [19–21]. The measured average green power behind the M_2 mirror was of the order of 100 μW. In fact, YAB possesses under Kleinman symmetry only a single non-zero component of the nonlinear tensor. This same component d_{11} is also responsible for non-phase-matched SFD when the polarizations of both fundamental and second harmonic are along the *a*-axis (σ).

The measured radio frequency (RF) spectra of the shortest pulses are shown in Fig. 6. A very sharp peak at the fundamental beat-note near 67.55 MHz with a high extinction ratio of more than 80 dBc above the noise level is observed in Fig. 6(a). The 1-GHz wide frequency span measurement indicates uniform harmonics of the fundamental beat of the RF signal, see Fig. 6(b). These results confirm the stable single-pulse CW-ML operation of the diode-pumped Yb:YAB laser without any sign of Q-switching instabilities or multiple pulses.

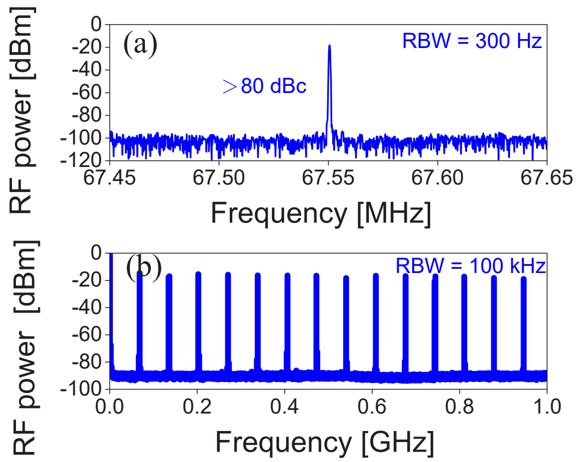

Fig. 6. RF spectra of the diode-pumped SESAM ML Yb:YAB laser: (a) fundamental beat note at 67.55 MHz measured with a resolution bandwidth (RBW) of 300 Hz; (b) harmonics on a 1-GHz frequency span (RBW = 100 kHz). T_{OC} = 1% OC.

4. Conclusion

In conclusion, we demonstrate sub-60 fs pulse generation from a diode-pumped SESAM mode-locked Yb:YAB laser with a 1-mm thick active element. Near Fourier-transform-limited soliton pulses as short as 56 fs were generated at 1044.6 nm with an average output power of 76 mW at a pulse repetition rate of 67.55 MHz. Higher output coupling allowed: to achieve a maximum output power of 220 mW at the expense of longer pulse duration of 137 fs. The corresponding laser efficiency with respect to the absorbed pump power was reasonably high, 33.7%. Besides the first sub-60 fs pulse generation in Yb:YAB crystals, non-phase-matched SFD of the sub-100-fs pulses was also observed in the ML regime, with pronounced spectral fringes. Our results represent the shortest pulses ever achieved from any Yb:YAB lasers.

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Disclosures. The authors declare no conflicts of interest.

Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

References

1. J. Liu, X. Mateos, H. Zhang, J. Li, J. Wang, and V. Petrov, "High-power laser performance of Yb:$YAl_3(BO_3)_4$ crystals cut along the crystallographic axes," IEEE J. Quantum. Electron. **43**(5), 385–390 (2007).
2. J. Liu, Y. Wan, X. Tian, Z. Zhou, W. Han, J. Li, H. Zhang, and J. Wang, "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," Appl. Phys. B **111**(2), 233–237 (2013).
3. B. Weichelt, M. Rumpel, A. Voss, A. Gross, V. Wesemann, D. Rytz, M. A. Ahmed, and T. Graf, "Yb:$YAl_3(BO_3)_4$ as gain material in thin-disk oscillators: demonstration of 109 W of IR output power," Opt. Express **21**(22), 25708–25714 (2013).
4. J. M. Dawes, P. Dekker, P. Burns, and J. A. Piper, "Self-frequency-doubling ytterbium lasers," Opt. Rev. **12**(2), 101–104 (2005).
5. P. Wang, P. Dekker, J. M. Dawes, J. A. Piper, Y. Liu, and J. Wang, "Efficient continuous-wave self-frequency-doubling green diode-pumped Yb:YAl3(BO3)4 lasers," Opt. Lett. **25**(10), 731–733 (2000).
6. P. Dekker, J. M. Dawes, J. A. Piper, Y. G. Liu, and J. Y. Wang, "1.1 WCW self-frequency-doubled diode-pumped Yb:YAl3(BO3)4 laser," Opt. Commun. **195**(5-6), 431–436 (2001).

Optics EXPRESS

7. P. Dekker, J. M. Dawes, and J. A. Piper, "2.27-W Q-switched self-doubling Yb:YAB laser with controllable pulse length," J. Opt. Soc. Am. B **22**(2), 378–384 (2005).
8. P. A. Loiko, V. V. Filippov, N. V. Kuleshov, N. I. Leonyuk, V. V. Maltsev, and K. V. Yumashev, "Thermo-optic characterization of Yb:$YAl_3(BO_3)_4$ laser crystal," Appl. Phys. B **117**(2), 577–583 (2014).
9. J. L. Blows, P. Dekker, P. Wang, J. M. Dawes, and T. Omatsu, "Thermal lensing measurements and thermal conductivity of Yb:YAB," Appl. Phys. B **76**(3), 289–292 (2003).
10. J. Li, J. Wang, X. Cheng, X. Hu, P. Burns, and J. M. Dawes, "Thermal and laser properties of Yb:$YAl_3(BO_3)_4$ crystal," J. Cryst. Growth **250**(3-4), 458–462 (2003).
11. J. M. Serres, P. A. Loiko, X. Mateos, J. Liu, H. Zhang, K. Yumashev, U. Griebner, V. Petrov, M. Aguiló, and F. Díaz, "Multi-watt passively Q-switched Yb:YAB/Cr:YAG microchip lasers," Proc. SPIE **10082**, 100820 T (2017).
12. A. Rudenkov, V. Kisel, K. Gorbachenya, A. Yasukevich, V. Maltsev, N. Leonyuk, N. Rubtsova, B. Semyagin, A. Kovalyov, and V. Preobrazhenskii, "Growth, spectroscopy and high power laser operation of Yb:$YAl_3(BO_3)_4$ crystal: Continuous-wave, mode-locking and chirped pulse regenerative amplification," Opt. Mater. **89**, 261–267 (2019).
13. B. Dannecker, F. Beirow, B. Weichelt, D. Rytz, T. Graf, and M. A. Ahmed, "SESAM mode-locked Yb:YAB thin-disk oscillator delivering an average power of 19 W," Opt. Lett. **46**(4), 912–915 (2021).
14. M. J. Lederer, M. Hildebrandt, V. Z. Kolev, B. Luther-Davies, B. Taylor, J. Dawes, P. Dekker, J. Piper, H. Tan, and C. Jagadish, "Passive mode locking of a self-frequency-doubling Yb:YAl3(BO3)4 laser," Opt. Lett. **27**(6), 436–438 (2002).
15. S. Rivier, U. Griebner, V. Petrov, H. Zhang, J. Li, J. Wang, and J. Liu, "Sub-90 fs pulses from a passively mode-locked Yb:$YAl_3(BO_3)_4$ laser," Appl. Phys. B **93**(4), 753–757 (2008).
16. J. Li, J. Wang, X. Cheng, X. Hu, and X. Wang, "The influence of Yb^{3+} concentration on Yb:$YAl_3(BO_3)_4$," Cryst. Res. Technol. **38**(10), 890–895 (2003).
17. W. Yang, J. Li, F. Zhang, Y. Zhang, and Z. G. Zhang, "Group delay dispersion measurement of Yb^{3+}:$YAl_3(BO_3)_4$ crystal with white-light interferometry," Opt. Commun. **281**(4), 679–682 (2008).
18. J. A. Caird, S. A. Payne, P. R. Staver, A. Ramponi, and L. Chase, "Quantum electronic properties of the $Na_3Ga_2Li_3F_{12}$:Cr^{3+} laser," IEEE J. Quantum Electron. **24**(6), 1077–1099 (1988).
19. P. Trabs, F. Noack, A. S. Aleksandrovsky, A. I. Zaitsev, N. V. Radionov, and V. Petrov, "Spectral fringes in non-phase-matched SHG and refinement of dispersion relations in the VUV," Opt. Express **23**(8), 10091–10096 (2015).
20. M. Kowalczyk, X. Zhang, X. Mateos, S. Guo, Z. Wang, X. Xu, P. Loiko, J. E. Bae, F. Rotermund, J. Sotor, U. Griebner, and V. Petrov, "Graphene and SESAM mode-locked Yb:CNGS lasers with self-frequency doubling properties," Opt. Express **27**(2), 590–596 (2019).
21. M. Kowalczyk, X. Zhang, V. Petrov, P. Loiko, X. Mateos, S. Guo, Z. Wang, X. Xu, and J. Sotor, "Self-frequency-doubling Yb:CNGS lasers operating in the femtosecond regime," J. Opt. Soc. Am. B **37**(10), 2822–2829 (2020).