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► **To cite this version:**

Shijia Sun, Huang-Jun Zeng, Zhang-Lang Lin, Wen-Ze Xue, Ge Zhang, et al.. SESAM mode-locked Yb:Sr₃Y₂(BO₃)₄ laser. Optics Express, 2022, 30 (7), pp.11861. 10.1364/OE.449833 . hal-03858655

HAL Id: hal-03858655

<https://hal.science/hal-03858655>

Submitted on 17 Nov 2022

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To be published in Optics Express:

Title: SESAM mode-locked Yb:Sr₃Y₂(BO₃)₄ laser

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Accepted: 17 March 22

Posted 18 March 22

DOI: <https://doi.org/10.1364/OE.449833>

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OPTICA
PUBLISHING GROUP
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SESAM mode-locked Yb:Sr₃Y₂(BO₃)₄ laser

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Abstract: We demonstrate the first sub-40 fs soliton pulse generation from a diode-pumped Yb:Sr₃Y₂(BO₃)₄ laser passively mode-locked by a semiconductor saturable absorber mirror. Pulses as short as 38 fs at a central wavelength of 1051.7 nm were achieved with an average output power of 115 mW and a pulse repetition rate of 67.7 MHz. The maximum average output power reached 303 mW at 1057.8 nm with a slightly longer pulse duration of 52 fs, which corresponded to a peak power of 76.9 kW and an optical efficiency of 25.3%.

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1. Introduction

Borate crystals doped with ytterbium (Yb³⁺) are well-known gain media for continuous-wave (CW) and mode-locked (ML) lasers emitting at ~1 μm. The two representative examples are: (i) crystals with non-centrosymmetric structures, i.e., Yb³⁺-doped trigonal Yb:YAl₃(BO₃)₄ (abbreviated: Yb:YAB) and monoclinic Yb:Ca₄YO(BO₃)₃ (Yb:YCOB) [1-4], and (ii) crystals with non-centrosymmetric structures, i.e., Yb³⁺-doped Yb:Sr₃Y(BO₃)₃ (Yb:BOYS) [5-7]. There exists another class of double borate Yb-host crystal with a general chemical formula Yb:M₃RE₂(BO₃)₄, where M stands for Ca, Sr and Ba, and RE = Gd, Y, Lu and La. These tetragonal crystals belong to the orthorhombic class with centrosymmetric space group *Pnma* (*D*¹⁶_{2h}). They melt congruently and thus can be easily grown by the conventional Czochralski (Cz) method. In the M₃RE₂(BO₃)₄ structure, the cations (M³⁺ and RE³⁺) statistically occupy three non-equivalent crystallographic sites, denoted as M1, M2 and M3. The crystal structure is composed of three sets of M-oxygen distorted polyhedra (MO₈) and three sets of isolated BO₃ planar triangles. The Yb³⁺ dopant ions are expected to replace for the RE³⁺ cations in the M1 – M3 sites. Therefore, Yb:M₃RE₂(BO₃)₄ are disordered multi-site crystals. The structure disorder determines a significant inhomogeneous spectral broadening for the Yb³⁺ ions leading to smooth and broad absorption and emission bands at ~1 μm similar to those found in amorphous materials (“glassy-like” spectroscopic behavior). This is promising for broad tuning of the laser wavelength and generation of ultrashort pulses from ML lasers [8, 9].

So far, Yb-doped calcium borate crystals of the Yb:Ca₃RE₂(BO₃)₄ type, where RE = Gd, Y, Lu and La, have been mainly exploited for efficient laser applications in the CW and especially ML regimes, namely Yb:Ca₃Gd₂(BO₃)₄ (Yb:GdCB) [10-13], Yb:Ca₃La₂(BO₃)₄ (Yb:LaCB)

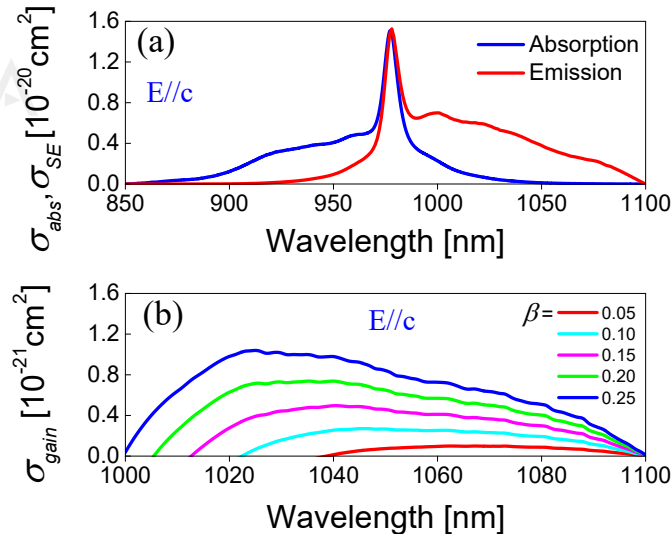
48 [14-18], and Yb:Ca₃Y₂(BO₃)₄ (Yb:YCB) [19-22]. The main drawback of such crystal is the
 49 relatively low thermal conductivity of disordered crystal structures. However,
 50 Yb:M₃RE₂(BO₃)₄ crystals could be very interesting for minimizing the pulse duration in laser
 51 systems based on seeded ultrafast amplifiers.

52 Recently, an Yb³⁺-doped strontium yttrium borate, Yb:Sr₃Y₂(BO₃)₄ (Yb:YSB) crystal was
 53 grown by the Cz method [23]. It melts congruently at a relatively low temperature (1400°C)
 54 which simplifies its growth. As a member of the same family, Yb:YSB exhibits “glassy-like”
 55 spectroscopic properties leading to extremely broad and flat gain profiles. The thermal
 56 conductivity of YSB is in the 0.67 – 1.0 Wm⁻¹K⁻¹ range depending on the direction [24]. The
 57 laser performance of Yb:YSB has been already studied both in the CW and the passively ML
 58 regimes. Pumping with a multi-transverse mode fiber-coupled laser diode at 977 nm, the
 59 maximum achieved output power was 3.47 W in the CW regime with a slope efficiency of 29%
 60 and an optical efficiency of 24% [25]. An Yb:YSB laser passively ML by a Semiconductor
 61 Saturable Absorber Mirror (SESAM) delivered pulses as short as 116 fs at 50 MHz with an
 62 average output power of 1.08 W[26]. Even shorter pulse duration of 58 fs was achieved via
 63 SESAM assisted Kerr-lens mode-locking (KLM) [27].

64 The favorable spectroscopic features, as well as the previous mode-locking results obtained
 65 with this disordered double borate crystal motivated us to further explore the potential of
 66 Yb:YSB for sub-40 fs pulse generation.

67 2. Experimental setup

68 A high-quality Yb:YSB crystal was grown by the Cz method. The actual doping level (in the
 69 crystal) was determined to be 11 at.% (ion density: $8.6 \times 10^{20} \text{ cm}^{-3}$). The crystal was oriented
 70 by single-crystal X-ray diffraction. A rectangular sample was cut for light propagation along
 71 the crystallographic *a*-axis (*a*-cut) with an aperture of 4 mm × 4 mm; it was 3 mm-thick. The
 72 laser crystal was double-side polished to laser-grade quality and left uncoated. The orientation
 73 was selected to ensure access to the *E* ∥ *c* laser polarization with highest gain cross-section
 74 (lattice parameters: *a* = 7.41 Å, *b* = 16.00 Å, *c* = 8.71 Å, and *Z* = 4).



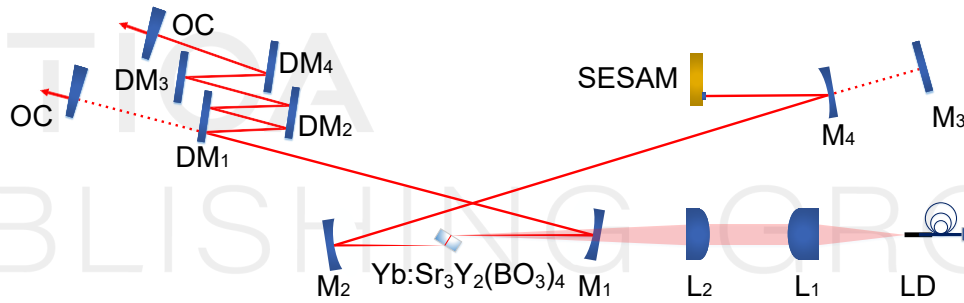
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76 **Fig. 1.** RT spectroscopy of the Yb:YSB: (a) absorption (σ_{abs}) and stimulated-emission (SE, σ_{SE})
 77 cross-sections; (b) gain cross-sections (σ_{gain}), β is the inversion ratio.

78 Room-temperature (RT) absorption (σ_{abs}) and stimulated-emission (SE, σ_{SE}) cross-section
 79 spectra for light polarization *E* ∥ *c* is shown in Fig. 1(a). The maximum σ_{abs} is $1.52 \times 10^{-20} \text{ cm}^{-2}$
 80 at 977 nm [the zero-phonon line (ZPL) at RT] and the corresponding absorption bandwidth
 81 (determined at the full width at half maximum, FWHM) is 10 nm. Such a broad absorption

82 linewidth will considerably release the wavelength requirements for using high-power InGaAs
 83 laser diodes as pump sources. The gain cross-sections [$\sigma_{\text{gain}} = \beta\sigma_{\text{SE}} - (1 - \beta)\sigma_{\text{abs}}$, where
 84 $\beta = N_2(2F_{5/2})/N_{\text{Yb}}$ is the inversion ratio] were calculated for the same light polarization to
 85 estimate the gain bandwidth, as shown in Fig. 1(b). The spectra are smooth and broad; their
 86 maxima experience a blue-shift with the inversion ratio, from 1065 nm for small $\beta = 0.05$ to
 87 1025 nm for high $\beta = 0.25$. For an intermediate $\beta = 0.15$, the spectral bandwidth (FWHM) is
 88 ~ 66 nm indicating excellent potential for the generation of sub-50 fs optical pulses from
 89 passively ML lasers.

90 The cavity design of the Yb:YSB laser is shown in Fig. 2. An X-shaped astigmatically
 91 compensated linear resonator was used to evaluate the laser performance both in the CW and
 92 ML regimes. The crystal was placed at Brewster's angle between the two concave folding
 93 mirrors M_1 and M_2 (radius of curvature, $\text{RoC} = -100$ mm). It was mounted in a copper holder
 94 without active cooling. An unpolarized, single-transverse mode, fiber-coupled InGaAs laser
 95 diode delivering a maximum incident power of 1.29 W was employed as a pump source. It had
 96 a fiber Bragg grating (FBG) for wavelength locking at 976 nm with a spectral linewidth
 97 (FWHM) of ~ 0.2 nm and a nearly diffraction-limited intensity profile with a beam propagation
 98 factor (M^2) of ~ 1.02 . An aspherical lens L_1 (focal length: $f = 26$ mm) and an achromatic doublet
 99 lens L_2 ($f = 100$ mm) were employed to reimagine the pump beam into the laser crystal yielding
 100 a beam waist (radius) of $18.7 \mu\text{m} \times 37.8 \mu\text{m}$ in the sagittal and tangential planes, respectively.



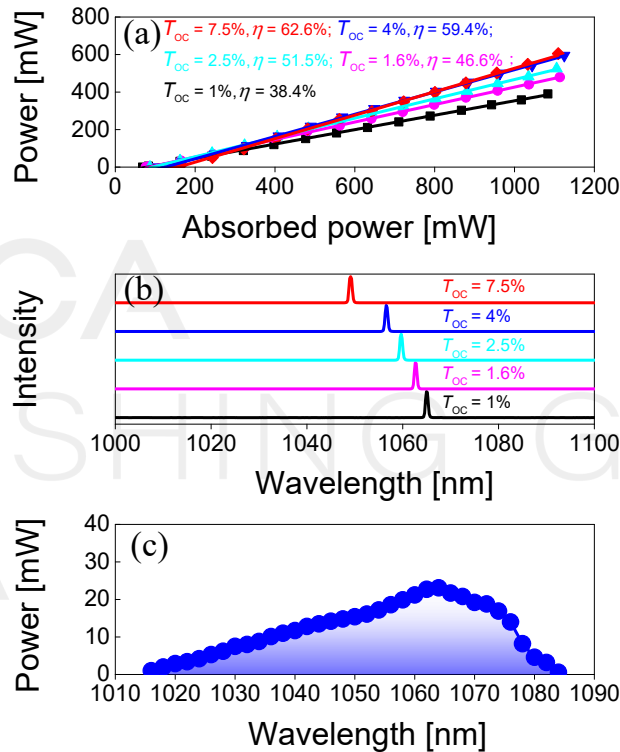
101
 102 **Fig. 2.** Experimental configuration of the Yb:YSB laser. LD: fiber-coupled laser diode; L_1 :
 103 aspherical lens; L_2 : achromatic doublet lens; M_1 , M_2 and M_4 : concave mirrors ($\text{RoC} = -100$ mm);
 104 M_3 : flat rear mirror used in the CW regime; DM_1 - DM_4 : flat dispersive mirrors; OC: output
 105 coupler; SESAM: SEmiconductor Saturable Absorber Mirror.

106 In the CW regime, a four-mirror cavity was used. One cavity arm was terminated by a flat
 107 rear mirror M_3 and the other arm – by a flat output coupler (OC) having a transmission at the
 108 laser wavelength T_{OC} in the range 1% - 7.5%. The corresponding cavity mode size in the laser
 109 crystal was estimated using the ABCD formalism yielding radii of $22 \mu\text{m} \times 40 \mu\text{m}$ in the
 110 sagittal and the tangential planes, respectively. The measured single-pass pump absorption
 111 under lasing conditions depended on the transmission of the OC ranging from 84.1% to 87.3%.

112 For ML operation, the flat rear mirror M_3 was substituted by a curved mirror M_4
 113 ($\text{RoC} = -100$ mm) for creating a second beam waist on the SESAM with a beam radius of
 114 $\sim 76 \mu\text{m}$ to ensure its efficient bleaching. A commercially available SESAM (BATOP, GmbH)
 115 with a modulation depth of 1.2%, a relaxation time of ~ 1 ps, a saturation fluence of $60 \mu\text{J}/\text{cm}^2$
 116 and a non-saturable loss of $\sim 0.8\%$ was implemented to start and stabilize the ML operation.
 117 Four flat dispersive mirrors (DMs) were implemented in the other cavity arm with a negative
 118 GDD per bounce of: $\text{DM}_1 = -55 \text{ fs}^2$, $\text{DM}_2 = -100 \text{ fs}^2$, $\text{DM}_3 = -250 \text{ fs}^2$ and $\text{DM}_4 = -250 \text{ fs}^2$ to
 119 compensate the material dispersion inside the resonator and balance the self-phase modulation
 120 (SPM) induced by the Kerr nonlinearity of the crystal for soliton pulse reshaping. The cavity
 121 length of the ML Yb:YSB laser was 2.22 m which corresponds to a pulse repetition of ~ 67 MHz.

122 3. Continuous-wave laser operation

123 In the CW regime, the laser generated a maximum output power of 605 mW at 1049.1 nm
 124 for an absorbed pump power of 1.11 W with a laser threshold of 143 mW, which corresponded
 125 to a slope efficiency of 62.6% for the highest tested $T_{OC} = 7.5\%$, see Fig. 3(a). The laser
 126 threshold gradually increased with the transmission of the OC, from 68.3 mW ($T_{OC} = 1\%$) to
 127 143 mW ($T_{OC} = 7.5\%$). The laser wavelength monotonously decreased with the output coupling
 128 in the range 1049.1 - 1065 nm, as shown in Fig. 3(b). Such a blue-shift of the laser wavelength
 129 with increasing output-coupling losses is typical for quasi-three-level Yb^{3+} lasers with inherent
 130 reabsorption at the laser wavelength and it agrees well with the gain spectra of $\text{Yb}:\text{YSB}$ for
 131 light polarization $\mathbf{E} \parallel \mathbf{c}$, see Fig. 1(b). The spectral tunability in the CW regime was studied
 132 with a SF10 prism and a 0.4% OC at an absorbed pump power of 0.8 W. The laser wavelength
 133 was continuously tunable between 1016 and 1084 nm, i.e., across 68 nm at the zero-level, see
 134 Fig. 3(d).



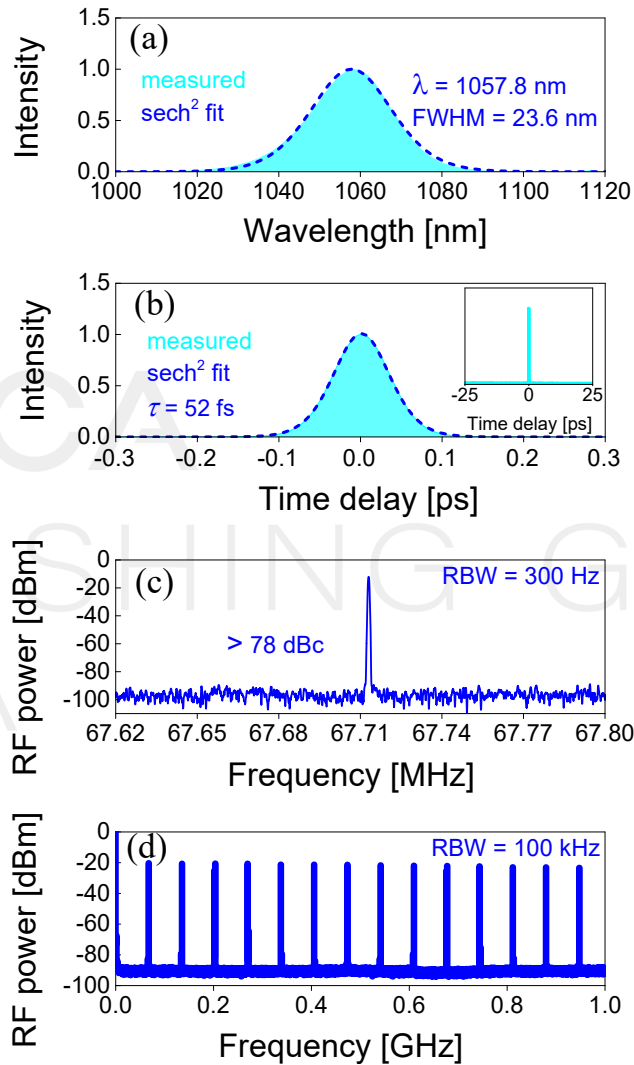
135
 136 **Fig. 3.** (a) CW diode-pumped $\text{Yb}:\text{YSB}$ laser: (a) input-output dependences for different OCs,
 137 η – slope efficiency; (b) typical laser spectra; (c) spectral tuning curve obtained with an
 138 intracavity SF10 prism and an OC with $T_{OC} = 0.4\%$.

139 4. Mode-locked laser operation

140 Stable and self-starting SESAM ML operation was readily obtained by implementing the four
 141 flat DMs ($\text{DM}_1 - \text{DM}_4$) in the cavity arm terminated by the OC, see Fig. 2, which provided a
 142 total round-trip negative GDD of -1620 fs^2 .

143 For the 7.5% OC, the measured optical spectrum and the background-free second-order
 144 autocorrelation trace are shown in Fig. 4(a) and (b), respectively. The measured optical
 145 spectrum exhibited a sech^2 -shaped spectral bandwidth (FWHM) of 23.6 nm at a central
 146 wavelength of 1057.8 nm, see Fig. 4(a). The pulse duration was 52 fs by assuming a sech^2 -
 147 shaped temporal intensity profile, see Fig. 4(b). The resulting time-bandwidth product (TBP)
 148 was 0.329 indicating nearly Fourier-transform limited pulses (0.315). The inset in Fig. 4(b)
 149 shows an autocorrelation trace on a longer time scale of 50 ps revealing single-pulse mode-

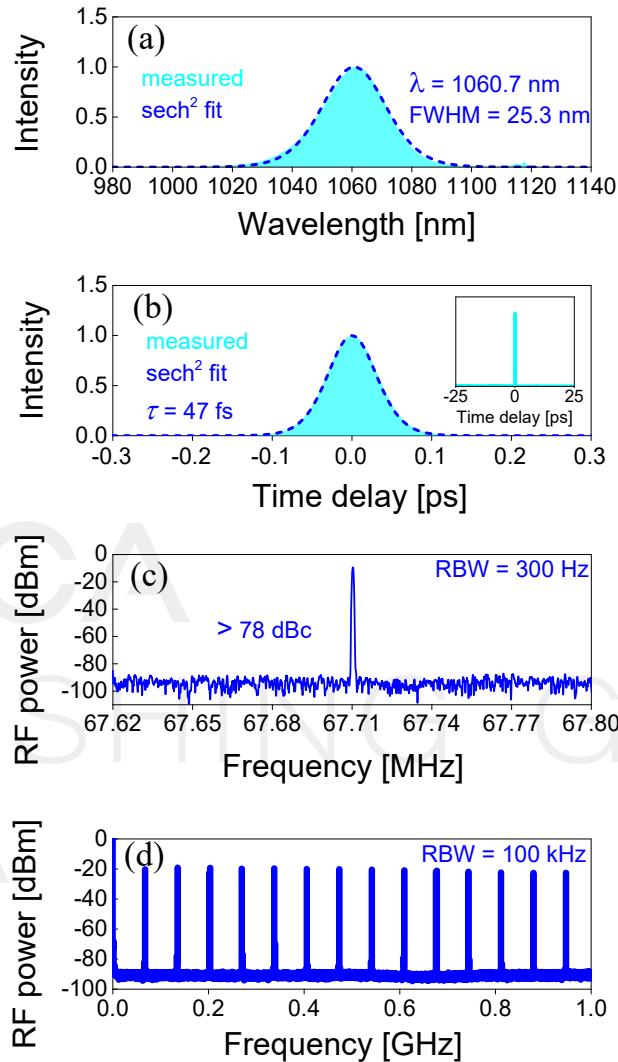
150 locking without multiple pulse instabilities. In this condition, the maximum average output
 151 power amounted to 303 mW for an absorbed pump power of 1.19 W, which corresponded to a
 152 peak power of 76.9 kW and an optical efficiency of 25.3%. The recorded radio frequency (RF)
 153 spectra of the laser pulses are shown in Fig. 4(c) and (d). The photodetector used for RF
 154 measurements is EOT ET-3600 (InGaAs) with 22-GHz bandwidth (rise time/fall time, 16 ps/16
 155 ps). The fundamental beat note located at ~ 67.7 MHz exhibits a high extinction ratio of >78 dBc
 156 above the noise level. The uniform harmonics on a 1-GHz frequency span reveal high stability
 157 of the ML operation.



158
 159 **Fig. 4.** SESAM ML Yb:YSB laser with $T_{OC} = 7.5\%$. (a) Optical spectrum and (b) SHG-based
 160 intensity autocorrelation trace. *Inset:* autocorrelation trace on a time span of 50 ps. RF spectra:
 161 (c) fundamental beat note at ~ 67.7 MHz recorded with a resolution bandwidth (RBW) of 300 Hz,
 162 and (d) harmonics on a 1-GHz frequency span, RBW = 100 kHz.

163 A shorter pulse duration was obtained by reducing the output coupling, $T_{OC} = 4\%$. After
 164 careful alignment, the ML Yb:YSB laser delivered soliton pulses with a duration of 47 fs at
 165 1060.7 nm for a spectral bandwidth (FWHM) of 25.3 nm by assuming sech²-shaped temporal
 166 and spectral intensity profiles, see Fig. 5. The corresponding TBP of 0.317 was even closer to
 167 the Fourier-transform limit. The average output power amounted to 222 mW at an absorbed

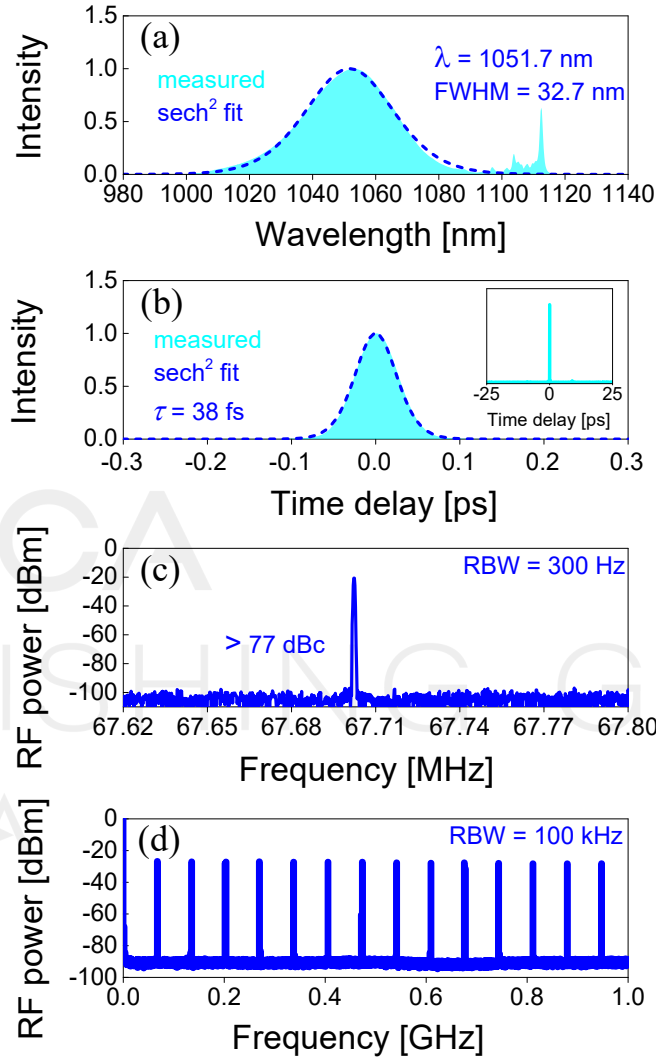
168 pump power of 1.11 W, which corresponds to an optical efficiency of 20%. The long-time
 169 autocorrelation trace [Fig. 5(b), inset] and the RF spectra, Fig. 5(c) and (d), confirmed the stable
 170 and single pulse mode-locking performance.



171
 172 **Fig. 5.** SESAM ML Yb:YSB laser with $T_{OC} = 4\%$. (a) Optical spectrum and (b) SHG-based
 173 intensity autocorrelation trace. *Inset:* autocorrelation trace on a time span of 50 ps. RF spectra:
 174 (c) fundamental beat note at ~ 67.7 MHz recorded with an RBW of 300 Hz, and (d) harmonics
 175 on a 1-GHz frequency span, RBW = 100 kHz.

176 Figure 6 shows the characterization of the shortest pulses from the SESAM ML Yb:YSB
 177 laser with a 2.5% OC. Soliton mode-locking operation was stabilized by a SESAM, and the
 178 ML laser delivered pulses as short as 38 fs at 1051.7 nm by assuming sech^2 -shaped temporal
 179 intensity profiles. The average output power dropped to 115 mW at an absorbed pump power of
 180 1.07 W and a pulse repetition of 67.7 MHz. This corresponds to an optical efficiency of
 181 10.7%. The optical spectrum of the ML laser revealed an emission bandwidth (FWHM) of
 182 32.7 nm assuming a sech^2 -shape spectral intensity profile, see Fig. 6(a). The observed satellite
 183 peaks above 1100 nm could be explained by the non-optimized GDD of the DMs at long
 184 wavelengths above 1100 nm as well as the non-perfect reflectivity bands of the laser mirrors.
 185 The resulting TBP was 0.337, very close to the Fourier transform limit. The steady-state ML

186 pulse train corresponding to the shortest pulse duration was characterized by a long scale (50 ps)
 187 autocorrelation trace, inset Fig. 6(b), and RF spectra, as shown in Fig. 6(c) and (d). The sharp
 188 fundamental beat note at ~ 67.7 MHz with a high signal-noise-ratio of >77 dBc, and the uniform
 189 harmonics again proved stable CW mode-locking without any Q-switched instabilities.



190
 191 **Fig. 6.** Characterization of the shortest pulses from the SESAM ML Yb:YBS laser obtained
 192 with $T_{OC} = 2.5\%$. (a) Optical spectrum and (b) SHG-based intensity autocorrelation trace with a
 193 sech²-fit. *Inset:* simultaneously measured long-scale background free intensity autocorrelation
 194 trace for the time span of 50 ps. RF spectra of the ML Yb:YBS laser: (a) fundamental beat note
 195 at ~ 67.7 MHz recorded with a RBW of 300 Hz, and (b) harmonics on a 1-GHz frequency span,
 196 measured with a RBW of 100 kHz.

197 The dominant mode-locking mechanism was confirmed via monitoring the far-field beam
 198 profiles before and after initiating mode-locked operation by the SESAM. The almost
 199 unchanged beam diameter revealed that the dominant mode-locking mechanism was soliton
 200 pulse shaping stabilized by the SESAM without Kerr-lensing. The estimated total phase shift
 201 due to the self-phase modulation according to our experimental results was in the range of
 202 88.7 - 173.6 mrad per roundtrip. Therefore, the resulting spectral phase could be compensated

203 by the negative second-order GDD introduced by the used DMs. The measured beam
204 propagation factors (M^2) of the ML Yb:YSB laser were less than 1.05.

205 5. Conclusion

206 In conclusion, we demonstrate sub-40 fs pulse generation from a SESAM ML Yb:YSB laser,
207 for the first time, to the best of our knowledge. The Yb:YSB crystal exhibits a variety of cation
208 sites randomly occupied by Sr^{2+} and $\text{Y}^{3+}|\text{Yb}^{3+}$ leading to unique spectroscopic properties for a
209 single-crystal material (a “glassy-like” behavior) supporting the generation of ultrashort pulses.
210 In the present work, an Yb:YSB laser ML by a commercial SESAM directly emitted soliton
211 pulses as short as 38 fs at 1051.7 nm. A slightly longer pulse duration of 52 fs was also achieved
212 with an average output power of 303 mW which corresponded to a peak power of 76.9 kW and
213 an optical efficiency of 25.3%. Our results represent a significant improvement in terms of
214 pulse duration compared to previous work (58 fs) [27], and also reveal a high potential for
215 applications of the Yb:YSB laser for seeding of femtosecond amplifiers. Further pulse
216 shortening of the ML Yb:YSB laser would be possible through optimizing the intracavity GDD
217 management in combination with the KLM technique.

218 **Funding.** National Natural Science Foundation of China (61975208, 61875199, 51761135115, 61850410533,
219 62075090, 52032009); the Science Foundation of Fujian Province (2019J02015); Sino-German Scientist Cooperation
220 and Exchanges Mobility Program (M-0040).

221 **Acknowledgment.** Xavier Mateos acknowledges the Serra Hünter program.

222 **Disclosures.** The authors declare no conflicts of interest.

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

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