Research Article | Vol. 30, No. 7 / 28 Mar 2022 / Optics Express 11861

Optics EXPRESS

SESAM mode-locked Yb:$Sr_3Y_2(BO_3)_4$ laser

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Abstract: We demonstrate the first sub-40 fs soliton pulse generation from a diode-pumped Yb:$Sr_3Y_2(BO_3)_4$ 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%.

1. Introduction

Borate crystals doped with ytterbium (Yb^{3+}) 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., Yb^{3+}-doped trigonal Yb:$YAl_3(BO_3)_4$ (abbreviated: Yb:YAB) and monoclinic Yb:$Ca_4YO(BO_3)_3$ (Yb:YCOB) [1–4], and (ii) crystals with non-centrosymmetric structures, i.e., Yb^{3+}-doped Yb:$Sr_3Y(BO_3)_3$ (Yb:BOYS) [5–7]. There exists another class of double borate Yb-host crystal with a general chemical formula Yb:$M_3RE_2(BO_3)_4$, 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 $M_3RE_2(BO_3)_4$ structure, the cations (M^{3+} and RE^{3+}) 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 (MO_8) and three sets of isolated BO_3 planar triangles. The Yb^{3+} dopant ions are expected to replace for the RE^{3+} cations in the M1 – M3 sites. Therefore, Yb:$M_3RE_2(BO_3)_4$ are disordered multi-site crystals. The structure disorder determines a significant inhomogeneous spectral broadening for the Yb^{3+} 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].

#449833 https://doi.org/10.1364/OE.449833
Journal © 2022 Received 29 Nov 2021; revised 4 Mar 2022; accepted 17 Mar 2022; published 24 Mar 2022

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So far, Yb-doped *calcium* borate crystals of the Yb:$Ca_3RE_2(BO_3)_4$ 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:$Ca_3Gd_2(BO_3)_4$ (Yb:GdCB) [10–13], Yb:$Ca_3La_2(BO_3)_4$ (Yb:LaCB) [14–18], and Yb:$Ca_3Y_2(BO_3)_4$ (Yb:YCB) [19–22]. The main drawback of such crystal is the relatively low thermal conductivity of disordered crystal structures. However, Yb:$M_3RE_2(BO_3)_4$ crystals could be very interesting for minimizing the pulse duration in laser systems based on seeded ultrafast amplifiers.

Recently, an Yb^{3+}-doped strontium yttrium borate, Yb:$Sr_3Y_2(BO_3)_4$ (Yb:YSB) crystal was grown by the Cz method [23]. It melts congruently at a relatively low temperature (1400°C) which simplifies its growth. As a member of the same family, Yb:YSB exhibits "glassy-like" spectroscopic properties leading to extremely broad and flat gain profiles. The thermal conductivity of YSB is in the 0.67–1.0 $Wm^{-1}K^{-1}$ range depending on the direction [24]. The laser performance of Yb:YSB has been already studied both in the CW and the passively ML regimes. Pumping with a multi-transverse mode fiber-coupled laser diode at 977 nm, the maximum achieved output power was 3.47 W in the CW regime with a slope efficiency of 29% and an optical efficiency of 24% [25]. An Yb:YSB laser passively ML by a SEmiconductor Saturable Absorber Mirror (SESAM) delivered pulses as short as 116 fs at 50 MHz with an average output power of 1.08 W [26]. Even shorter pulse duration of 58 fs was achieved via SESAM assisted Kerr-lens mode-locking (KLM) [27].

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

2. Experimental setup

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

Room-temperature (RT) absorption (σ_{abs}) and stimulated-emission (SE, σ_{SE}) cross-section spectra for light polarization $\boldsymbol{E} \parallel \boldsymbol{c}$ is shown in Fig. 1(a). The maximum σ_{abs} is 1.52×10^{-20} cm^{-2} at 977 nm [the zero-phonon line (ZPL) at RT] and the corresponding absorption bandwidth (determined at the full width at half maximum, FWHM) is 10 nm. Such a broad absorption linewidth will considerably release the wavelength requirements for using high-power InGaAs laser diodes as pump sources. The gain cross-sections [$\sigma_{gain} = \beta\sigma_{SE} - (1-\beta)\sigma_{abs}$, where $\beta = N_2(^2F_{5/2})/N_{Yb}$ is the inversion ratio] were calculated for the same light polarization to estimate the gain bandwidth, as shown in Fig. 1(b). The spectra are smooth and broad; their maxima experience a blue-shift with the inversion ratio, from 1065 nm for small $\beta = 0.05$ to 1025 nm for high $\beta = 0.25$. For an intermediate $\beta = 0.15$, the spectral bandwidth (FWHM) is ~66 nm indicating excellent potential for the generation of sub-50 fs optical pulses from passively ML lasers.

The cavity design of the Yb:YSB laser is shown in Fig. 2. An X-shaped astigmatically compensated linear resonator was used to evaluate the laser performance both in the CW and ML regimes. The crystal was placed at Brewster's angle between the two concave folding mirrors M_1 and M_2 (radius of curvature, RoC = -100 mm). It was mounted in a copper holder without active cooling. An unpolarized, single-transverse mode, fiber-coupled InGaAs laser diode delivering a maximum incident power of 1.29 W was employed as a pump source. It had a fiber Bragg grating (FBG) for wavelength locking at 976 nm with a spectral linewidth (FWHM) of ~0.2 nm and a

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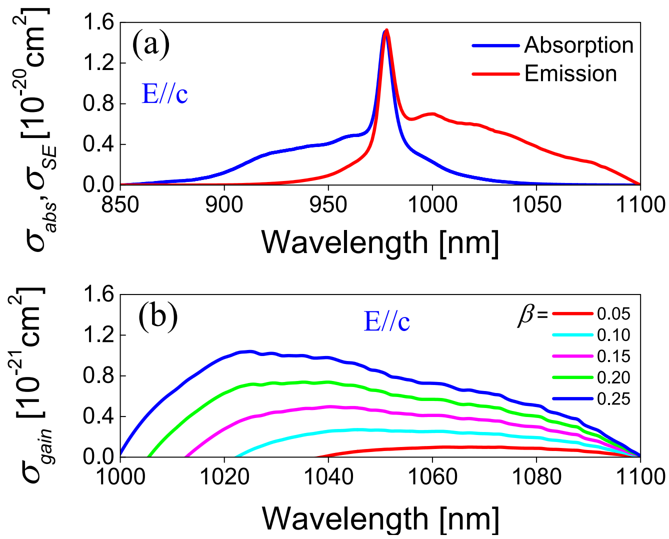

Fig. 1. RT spectroscopy of the Yb:YSB: (a) absorption (σ_{abs}) and stimulated-emission (SE, σ_{SE}) cross-sections; (b) gain cross-sections (σ_{gain}), β is the inversion ratio.

nearly diffraction-limited intensity profile with a beam propagation factor (M^2) of ~1.02. An aspherical lens L_1 (focal length: f = 26 mm) and an achromatic doublet lens L_2 (f = 100 mm) were employed to reimage the pump beam into the laser crystal yielding a beam waist (radius) of 18.7 µm × 37.8 µm in the sagittal and tangential planes, respectively.

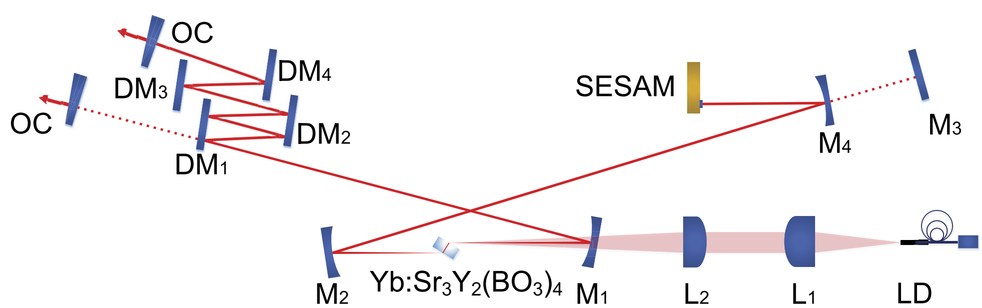

Fig. 2. Experimental configuration of the Yb:YSB laser. LD: fiber-coupled laser diode; L_1: aspherical lens; L_2: achromatic doublet lens; M_1, M_2 and M_4: concave mirrors (RoC = -100 mm); M_3: flat rear mirror used in the CW regime; DM_1 - DM_4: flat dispersive mirrors; OC: output coupler; SESAM: SEmiconductor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

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

For ML operation, the flat rear mirror M_3 was substituted by a curved mirror M_4 (RoC = -100 mm) for creating a second beam waist on the SESAM with a beam radius of ~76 µm to ensure its efficient bleaching. A commercially available SESAM (BATOP, GmbH) with a modulation depth of 1.2%, a relaxation time of ~1 ps, a saturation fluence of 60 µJ/cm^2 and a non-saturable

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loss of ~0.8% was implemented to start and stabilize the ML operation. Four flat dispersive mirrors (DMs) were implemented in the other cavity arm with a negative GDD per bounce of: DM_1 = -55 fs^2, DM_2 = -100 fs^2, DM_3 = -250 fs^2 and DM_4 = -250 fs^2 to compensate the material dispersion inside the resonator and balance the self-phase modulation (SPM) induced by the Kerr nonlinearity of the crystal for soliton pulse reshaping. The cavity length of the ML Yb:YSB laser was 2.22 m which corresponds to a pulse repetition of ~67 MHz.

3. Continuous-wave laser operation

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

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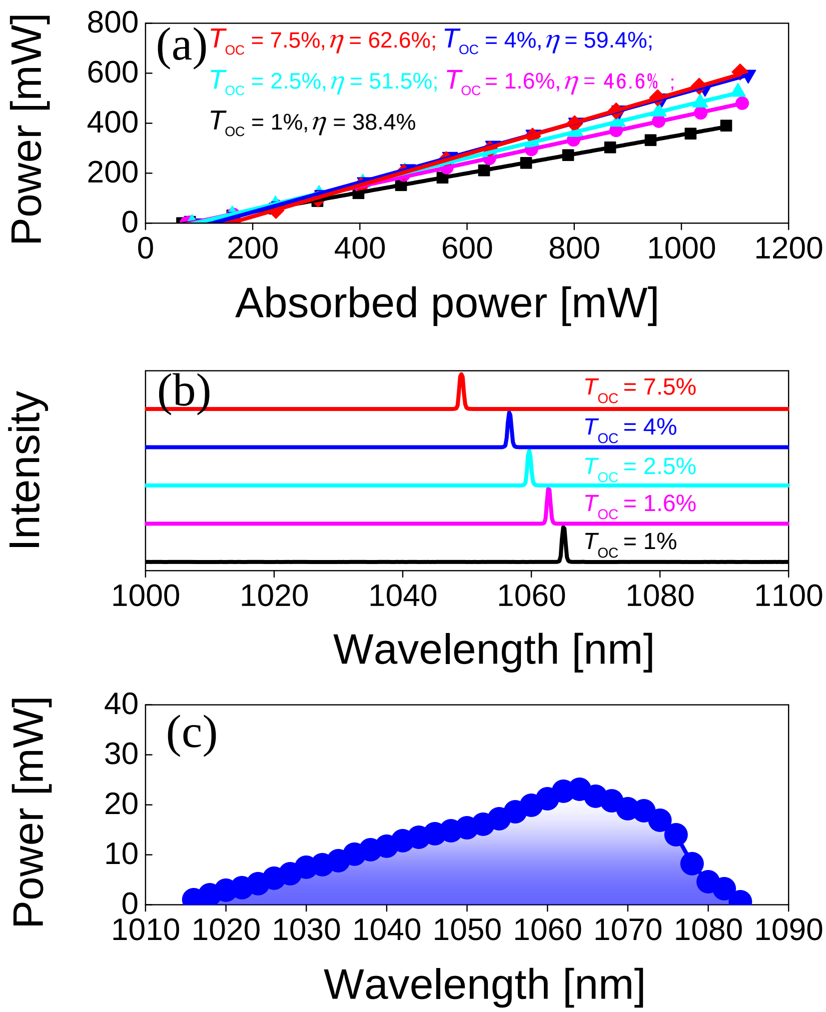

Fig. 3. (a) CW diode-pumped Yb:YSB laser: (a) input-output dependences for different OCs, η – slope efficiency; (b) typical laser spectra; (c) spectral tuning curve obtained with an intracavity SF10 prism and an OC with $T_{OC} = 0.4\%$.

4. Mode-locked laser operation

Stable and self-starting SESAM ML operation was readily obtained by implementing the four flat DMs (DM_1 – DM_4) in the cavity arm terminated by the OC, see Fig. 2, which provided a total round-trip negative GDD of -1620 fs^2.

For the 7.5% OC, the measured optical spectrum and the background-free second-order autocorrelation trace are shown in Fig. 4(a) and (b), respectively. The measured optical spectrum exhibited a $sech^2$-shaped spectral bandwidth (FWHM) of 23.6 nm at a central wavelength of 1057.8 nm, see Fig. 4(a). The pulse duration was 52 fs by assuming a $sech^2$-shaped temporal intensity profile, see Fig. 4(b). The resulting time-bandwidth product (TBP) was 0.329 indicating nearly Fourier-transform limited pulses (0.315). The inset in Fig. 4(b) shows an autocorrelation trace on a longer time scale of 50 ps revealing single-pulse mode-locking without multiple pulse instabilities. In this condition, the maximum average output power amounted to 303 mW for an absorbed pump power of 1.19 W, which corresponded to a peak power of 76.9 kW and an optical efficiency of 25.3%. The recorded radio frequency (RF) spectra of the laser pulses are shown in Fig. 4(c) and (d). The photodetector using for RF measurements is EOT ET-3600 (InGaAs) with 22-GHz bandwidth (rise time/fall time, 16 ps/16 ps). The fundamental beat note located at ~67.7 MHz exhibits a high extinction ratio of >78 dBc above the noise level. The uniform harmonics on a 1-GHz frequency span reveal high stability of the ML operation.

A shorter pulse duration was obtained by reducing the output coupling, $T_{OC} = 4\%$. After careful alignment, the ML Yb:YSB laser delivered soliton pulses with a duration of 47 fs at 1060.7 nm for a spectral bandwidth (FWHM) of 25.3 nm by assuming $sech^2$-shaped temporal and spectral intensity profiles, see Fig. 5. The corresponding TBP of 0.317 was even closer to the Fourier-transform limit. The average output power amounted to 222 mW at an absorbed pump power of 1.11 W, which corresponds to an optical efficiency of 20%. The long-time autocorrelation trace [Fig. 5(b), inset] and the RF spectra, Fig. 5(c) and (d), confirmed the stable and single pulse mode-locking performance.

Figure 6 shows the characterization of the shortest pulses from the SESAM ML Yb:YSB laser with a 2.5% OC. Soliton mode-locking operation was stabilized by a SESAM, and the ML laser delivered pulses as short as 38 fs at 1051.7 nm by assuming $sech^2$-shaped temporal intensity profiles. The average output power dropped to 115 mW at an absorbed pump power of 1.07 W and a pulse repetition of 67.7 MHz. This corresponds to an optical efficiency of 10.7%. The optical spectrum of the ML laser revealed an emission bandwidth (FWHM) of 32.7 nm assuming a $sech^2$-shape spectral intensity profile, see Fig. 6(a). The observed satellite peaks above 1100 nm could be explained by the non-optimized GDD of the DMs at long wavelengths above 1100 nm as well as the non-perfect reflectivity bands of the laser mirrors. The resulting TBP was 0.337, very close to the Fourier transform limit. The steady-state ML pulse train corresponding to the shortest pulse duration was characterized by a long scale (50 ps) autocorrelation trace, inset Fig. 6(b), and RF spectra, as shown in Fig. 6(c) and (d). The sharp fundamental beat note at ~67.7 MHz with a high signal-noise-ratio of >77 dBc, and the uniform harmonics again proved stable CW mode-locking without any Q-switched instabilities.

The dominant mode-locking mechanism was confirmed via monitoring the far-field beam profiles before and after initiating mode-locked operation by the SESAM. The almost unchanged beam diameter revealed that the dominant mode-locking mechanism was soliton pulse shaping stabilized by the SESAM without Kerr-lensing. The estimated total phase shift due to the self-phase modulation according to our experimental results was in the range of 88.7 - 173.6 mrad per roundtrip. Therefore, the resulting spectral phase could be compensated by the negative second-order GDD introduced by the used DMs. The measured beam propagation factors (M^2) of the ML Yb:YSB laser were less than 1.05.

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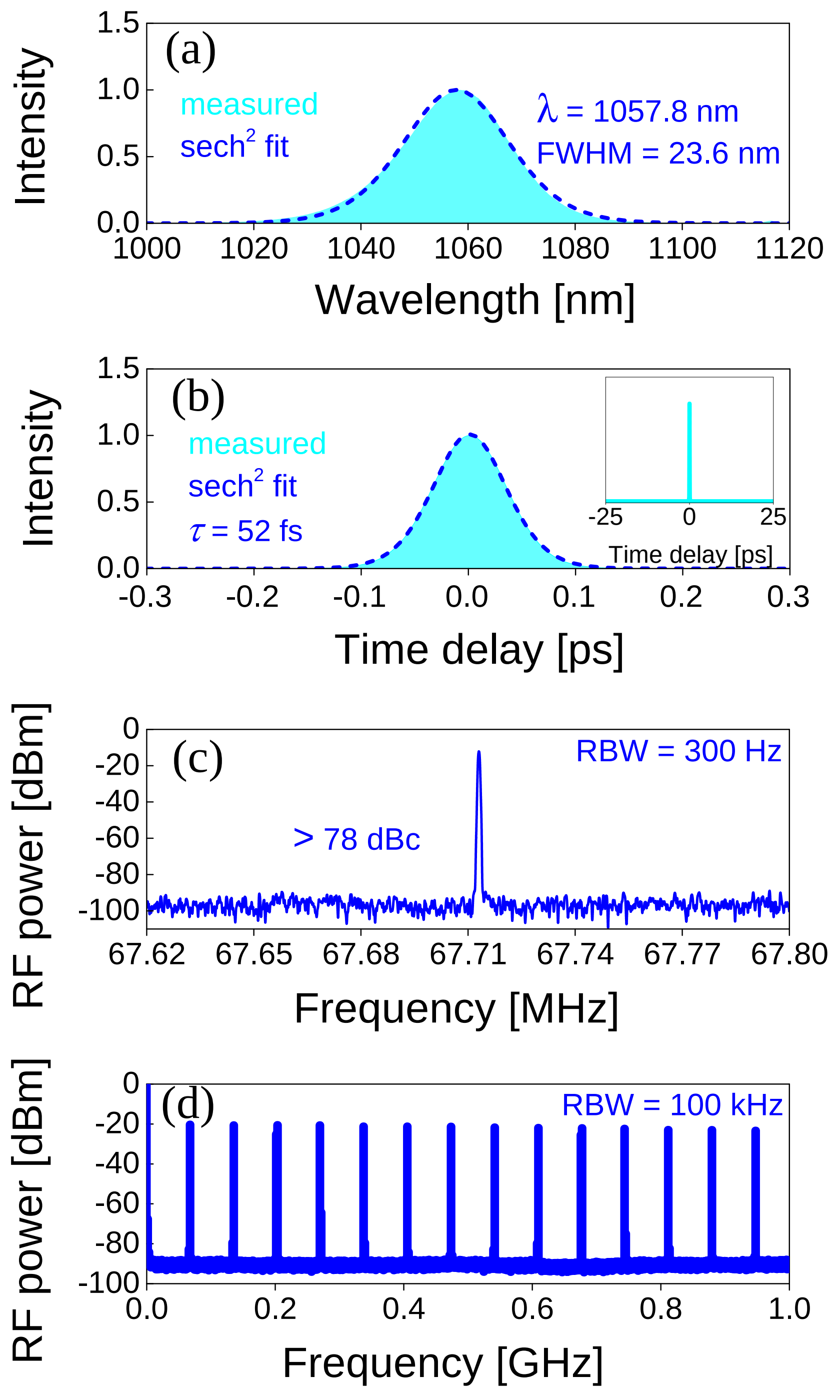

Fig. 4. SESAM ML Yb:YSB laser with $T_{OC} = 7.5\%$. (a) Optical spectrum and (b) SHG-based intensity autocorrelation trace. *Inset*: autocorrelation trace on a time span of 50 ps. RF spectra: (c) fundamental beat note at ~67.7 MHz recorded with a resolution bandwidth (RBW) of 300 Hz, and (d) harmonics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

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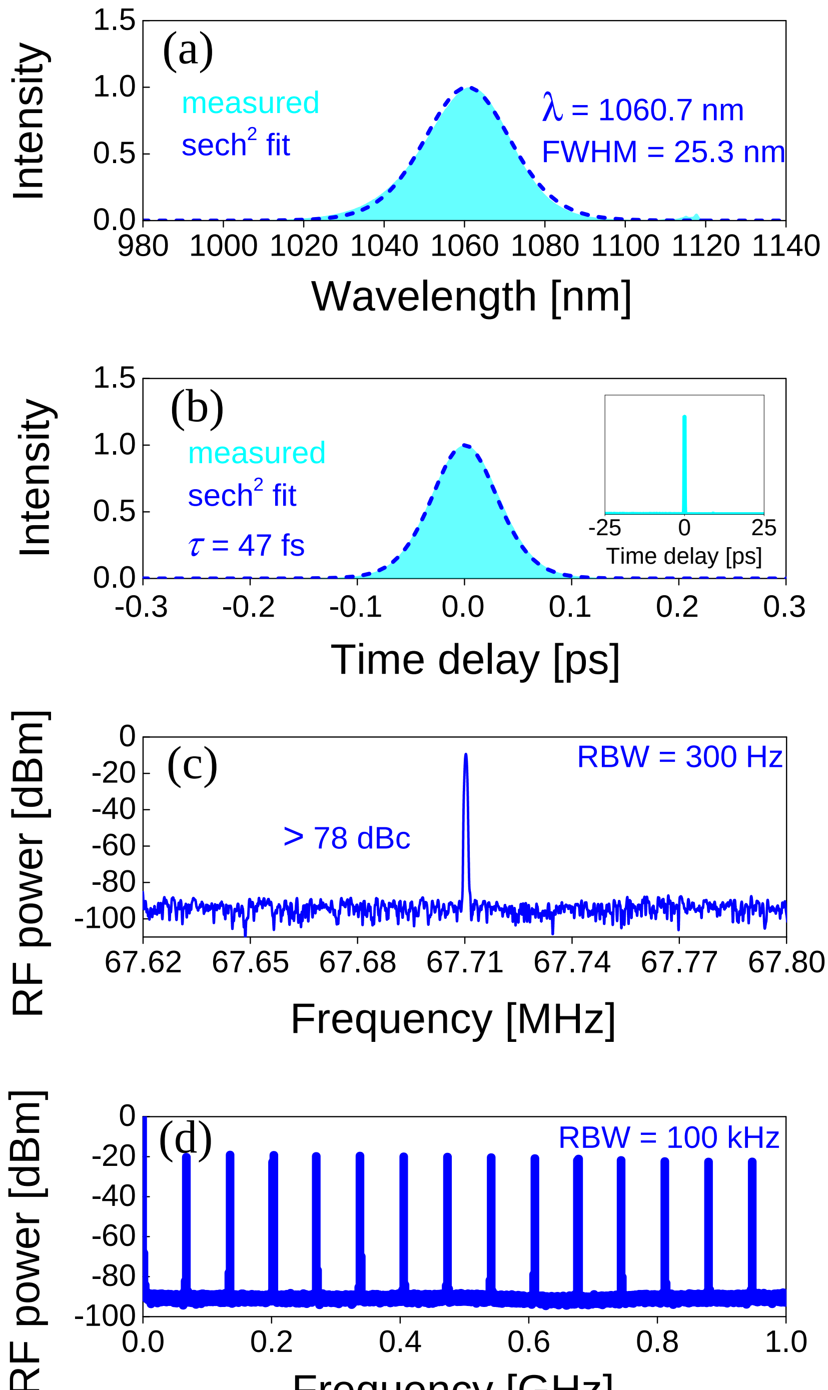

Fig. 5. SESAM ML Yb:YSB laser with $T_{OC} = 4\%$. (a) Optical spectrum and (b) SHG-based intensity autocorrelation trace. *Inset*: autocorrelation trace on a time span of 50 ps. RF spectra: (c) fundamental beat note at ~67.7 MHz recorded with an RBW of 300 Hz, and (d) harmonics on a 1-GHz frequency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

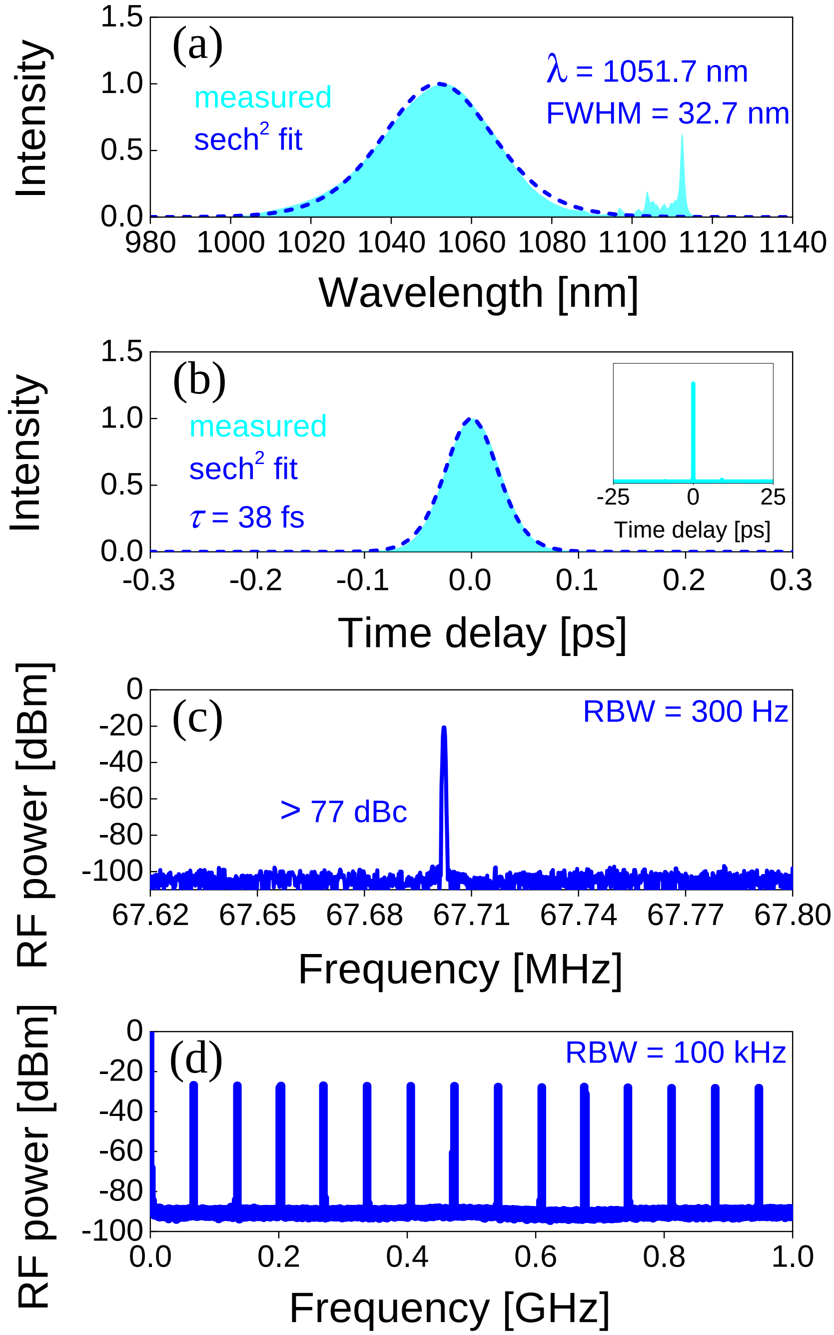

Fig. 6. Characterization of the shortest pulses from the SESAM ML Yb:YSB laser obtained with $T_{OC} = 2.5\%$. (a) Optical spectrum and (b) SHG-based intensity autocorrelation trace with a $sech^2$-fit. *Inset*: simultaneously measured long-scale background free intensity autocorrelation trace for the time span of 50 ps. RF spectra of the ML Yb:YSB laser: (a) fundamental beat note at ~67.7 MHz recorded with a RBW of 300 Hz, and (b) harmonics on a 1-GHz frequency span, measured with a RBW of 100 kHz.

5. Conclusion

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

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

Acknowledgment. Xavier Mateos acknowledges the Serra Húnter program.

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.

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