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Soliton mode-locked $Yb:Ca_3Gd_2(BO_3)_4$ laser

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Abstract: We report on a soliton mode-locked $Yb:Ca_3Gd_2(BO_3)_4$ laser at ~1.06 µm stabilized by a semiconductor saturable absorber mirror. Pumping with a single-transverse mode, fiber-coupled laser diode at 976 nm, the $Yb:Ca_3Gd_2(BO_3)_4$ laser delivers soliton pulses as short as 39 fs at a central wavelength of 1059.2 nm with an average output power of 70 mW and a pulse repetition rate of ~67.3 MHz.

1. Introduction

Ytterbium (Yb^{3+}) doped calcium rare-earth orthoborate crystals with the general chemical formula $Yb:Ca_3RE_2(BO_3)_4$, where RE = Y, La, Gd, and Lu are passive host-forming ions, represent one of the disordered borate crystal classes which exhibit "glassy-like" spectroscopic properties. Indeed, they possess broad, flat and smooth gain profiles at ~1 µm which are attractive for broadband wavelength tuning and generation of femtosecond (fs) pulses from mode-locked (ML) lasers [1–3]. Besides, these crystals melt congruently at a relatively low temperature (~1400°C) and thus can be easily grown by the conventional Czochralski method with large volume for laser applications [1].

As a member of the above orthoborate crystal family, Yb^{3+}-doped calcium gadolinium borate, i.e., $Yb:Ca_3Gd_2(BO_3)_4$ (abbreviated Yb:GdCB), crystallizes in the orthorhombic class with a centrosymmetric space group D_{2h}^{16} - P_{nma}. Yb:GdCB is a disordered multi-site crystal exhibiting three non-equivalent cationic sites which are statistically occupied by the host-forming Ca^{2+} and Gd^{3+}, and the dopant Yb^{3+} ions. The structural disorder results in considerable inhomogeneous spectral line broadening for Yb:GdCB (a "glassy-like" behavior). As for other borate crystals such as $Yb:Ca_4REO(BO_3)_3$, Yb^{3+} ions in GdCB experience a strong crystal field leading to a relatively large ground-state ($^2F_{7/2}$) splitting. The low-temperature spectroscopic study of the Yb:GdCB crystal performed in [4] indicated the value of $\Delta E(^2F_{7/2})$ to be ~735 cm^{-1}, which is beneficial for low-threshold laser operation and weak temperature sensitivity. In addition, Yb:GdCB shows a relatively broad zero-phonon line (ZPL) absorption width, which is almost three times broader compared to other well-known Yb^{3+}-doped disordered borates, e.g., $Yb:Ca_4YO(BO_3)_3$ (FWHM

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of ~2.5 nm) and Yb:$Ca_4GdO(BO_3)_3$ (FWHM of ~2.2 nm) [5]. This property will significantly release the spectral bandwidth requirement for power scalable operation of Yb:GdCB lasers pumped with high-power and highly multi-transverse mode InGaAs laser diodes. Although the Yb:GdCB crystal exhibits a relatively low thermal conductivity of only ~0.92 W/mK [6], it is still very attractive due to its excellent potential for minimizing the pulse duration achievable from ML oscillators utilizing its extremely broad, flat and smooth gain spectral profiles.

Very recently, we demonstrated the first passively ML operation of a Yb:GdCB laser. Using a commercial SEmiconductor Saturable Absorber Mirror (SESAM) as a saturable absorber, 96 fs pulses were directly generated from the Yb:GdCB laser at 1045 nm with an average output power of 205 mW [7]. In the present work, we focus on exploiting the broadband gain profiles of the Yb:GdCB crystal for further pulse shortening via the soliton pulse shaping technique stabilized by a SESAM. Pumped with a single-transverse mode, fiber-coupled laser diode, sub-40 fs pulse generation is demonstrated from a soliton ML Yb:GdCB laser, for the first time, to the best of our knowledge.

2. Experimental setup

As a gain material, we have used a 5 at.% Yb^{3+}-doped GdCB crystal grown by the Czochralski method. The actual Yb^{3+} ion density in the crystal N_{Yb} was 4.15×10^{20} cm^{-3}. A rectangular laser element was cut for light propagation along the crystallographic $\boldsymbol{a}$-axis ($\boldsymbol{a}$-cut). The laser element was polished to laser quality from both sides with good parallelism and remained uncoated. Its aperture was 4×4 mm^2 and its thickness was 3 mm. The crystal orientation was selected to ensure access to the high-gain laser polarization $\boldsymbol{E} \parallel \boldsymbol{c}$.

Room-temperature (RT) absorption (σ_{abs}) and stimulated-emission (SE, σ_{SE}) cross-section spectra for $\boldsymbol{E} \parallel \boldsymbol{c}$ light polarization is shown in Fig. 1(a). The maximum σ_{abs} is 0.74×10^{-20}/cm^2 at 976.8 nm corresponding to the ZPL the so-called zero-phonon line (ZPL) at RT and the absorption bandwidth (determined at the FWHM) is as broad as 7.5 nm. The gain cross-section, $\sigma_{gain} = \beta\sigma_{SE} - (1 - \beta)\sigma_{abs}$, spectra of Yb:GdCB for the same polarization were also calculated at different inversion ratios, $\beta = N_2(^2F_{5/2})/N_{Yb}$, as shown in Fig. 1(b), to estimate the gain bandwidth. The gain profiles are broad, smooth and almost flat (especially for small β). The maximum in the gain spectra experiences a blue-shift with the inversion ratio β due to reduced reabsorption (increased bleaching of the ground-state); a typical behavior for quasi-three-level Yb^{3+} lasers. The luminescence lifetime of the upper laser level ($^2F_{5/2}$) of Yb^{3+} ions in GdCB is $\tau_{lum} = 644$ µs. These spectroscopic data indicate an excellent potential for sub-50-fs pulse generation from passively ML lasers.

The configuration of the ML Yb:GdCB laser is shown in Fig. 2. An X-folded astigmatically compensated standing-wave cavity was employed. The $\boldsymbol{a}$-cut laser crystal was placed at Brewster's angle between the two concave folding mirrors M_1 and M_2 (radius of curvature, RoC = -100 mm) to fulfill the minimum loss condition for the laser beam in $\boldsymbol{E} \parallel \boldsymbol{c}$ polarization and mounted in a copper holder without active cooling. The unpolarized pump source was a single-transverse-mode fiber-coupled InGaAs laser diode that operated with a maximum incident power of 1.29 W at 976 nm and emitted a nearly diffraction-limited beam with a propagation factor (M^2) of ~1.02. The wavelength of the diode laser was locked by a fiber Bragg grating (FBG) with a spectral linewidth (FWHM) of 0.2 nm. Thus, the pump radiation spectrally well matched the maximum of the ZPL of Yb^{3+} ions in GdCB. The pump beam was collimated by an aspherical lens L_1 (focal length: $f = 26$ mm) and then focused into the laser crystal with an achromatic doublet lens L_2 ($f = 100$ mm) yielding a beam waist (radius) of 18.7 µm × 37.5 µm in the sagittal and tangential planes, respectively.

For ML operation, a commercial SESAM (BATOP, GmbH) with a modulation depth of ~1.2% at 1040 nm, a relaxation time of ~1 ps and a non-saturable loss of ~0.8% was used to initiate and stabilize the soliton ML operation. A curved mirror M_3 (RoC = -100 mm) was implemented to

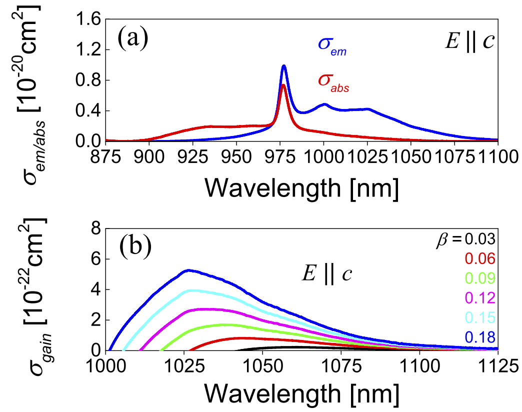

Fig. 1. Room-temperature spectroscopy of the Yb:GdCB crystal for light polarization $\boldsymbol{E} \parallel \boldsymbol{c}$: (a) absorption ($\sigma_{\mathrm{abs}}$) and stimulated-emission (SE, σ_{SE}) cross-sections; (b) gain cross-sections (σ_{gain}), β is the inversion ratio.

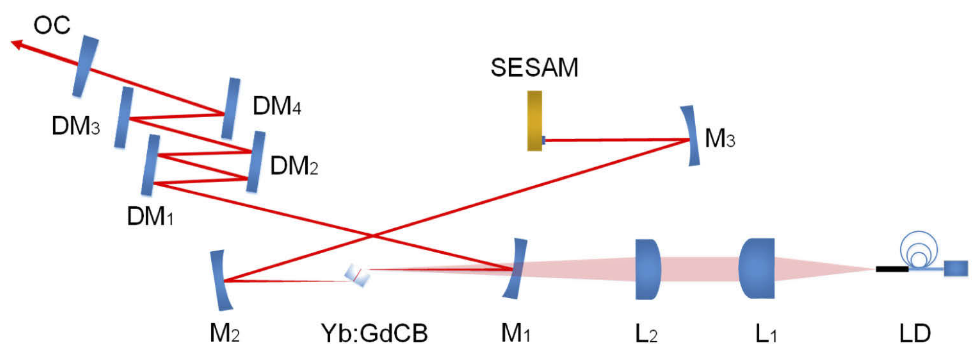

Fig. 2. Experimental setup of the ML Yb:GdCB laser. LD: fiber-coupled laser diode; L_1: aspherical lens; L_2: achromatic doublet lens; M_1 - M_3: concave mirrors; DM_1 – DM_4: flat dispersive mirrors; OC: output coupler; SESAM: SEmiconductor Saturable Absorber Mirror.

create a second beam waist on the SESAM with a beam radius of ~65 µm to ensure its efficient bleaching. Four flat dispersive mirrors (DMs) were applied in the other cavity arm with a negative group delay dispersion (GDD) per bounce of: $DM_1 = DM_2 = -55$ fs^2, $DM_3 = DM_4 = -250$ fs^2 to compensate the material dispersion inside the resonator and to balance the self-phase modulation (SPM) induced by the Kerr nonlinearity of the crystal for soliton pulse shaping. The physical cavity length of the ML Yb:GdCB laser was ~2.2 m which corresponded to a pulse repetition rate of ~67 MHz.

3. Mode-locked laser operation

In passively ML lasers, a trade-off is usually sought between pulse duration and average output power since the pulses gets shorter decreasing the OC transmission. In the case of Yb-lasers, lowest total cavity loss is overcome by lowest gain (smallest β) whereas such small inversion ratios result in flattened and broadened gain spectra shifted to longer wavelength, thus supporting very short pulse durations, cf. Figure 1(b). Contrary, higher output-coupling results in higher average output power at the expense of longer pulse duration. In the present work, we tested three different OCs with transmission T_{OC} of 1.6%, 2.6% and 4%.

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Initially, stable and self-starting ML operation was readily achieved by applying the highest $T_{OC} = 4\%$ and all four DMs ($DM_1 - DM_4$) providing a total negative roundtrip GDD of -1440 fs^2. The measured optical spectrum of the soliton pulses had a sech^2-shaped spectral intensity profile with an emission bandwidth of 21 nm at a central wavelength of 1054 nm, see Fig. 3(a). The pulse duration (FWHM) derived from the recorded second-harmonic generation (SHG) based background free intensity autocorrelation trace assuming a sech^2-shaped temporal profile, see Fig. 3(b). The time-bandwidth product (TBP) of 0.34 indicated a pulse duration slightly above the Fourier-transform limit (0.315). The long-scale autocorrelation scan of 50 ps confirmed single-pulse operation without any pedestal or multi-pulsing, see the inset in Fig. 3(b). The pulse train from the ML Yb:GdCB laser was characterized by a radio-frequency (RF) spectrum analyzer. The recorded fundamental beat-note was located at 67.3 MHz with a relatively high extinction ratio above the noise level exceeding 74 dBc, see Fig. 3(c). A wide-span frequency measurement up to 1-GHz confirmed the stable single-pulse steady-state mode-locking without any spurious modulation or multi-pulsing instabilities, see Fig. 3(d). The average output power amounted to 88 mW at an absorbed pump power of 637 mW for a pulse repetition rate of 67.3 MHz, and thus corresponded to a peak power of 19 kW.

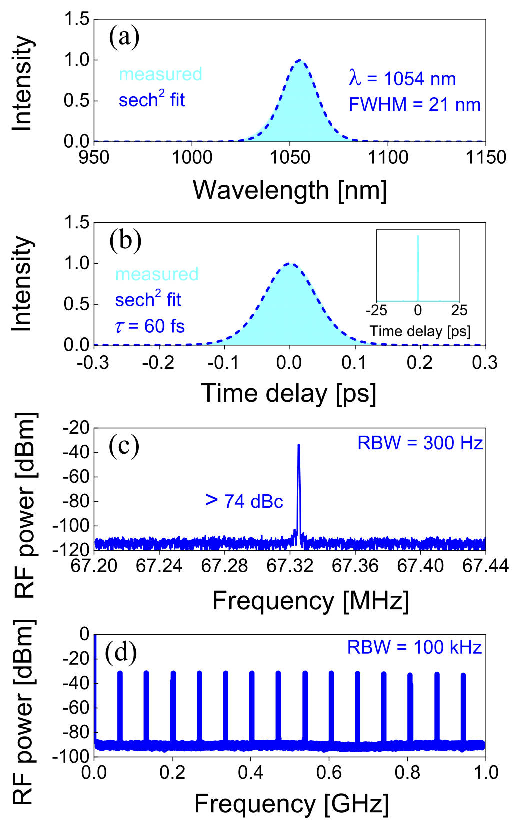

Fig. 3. ML Yb:GdCB laser with $T_{OC} = 4\%$. (a) Optical spectrum and (b) SHG-based intensity autocorrelation trace. *Inset*: autocorrelation trace on a time span of 50 ps. RF spectra: (c) first beat note at ~67.3 MHz recorded with a resolution bandwidth (RBW) of 300 Hz, and (d) harmonics on a 1-GHz frequency span, RBW = 100 kHz.

The pulse duration could be further shortened by reducing the transmission of the OC to 2.5% while maintaining the same total negative roundtrip GDD. The spectrum of the ML laser centered at 1062 nm with a sech^2-shaped spectral intensity profile (emission bandwidth: 23 nm) is shown

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in Fig. 4(a). The recorded SHG-based autocorrelation trace can be almost perfectly fitted with a $sech^2$-shaped temporal profile, resulting in an estimated pulse duration of 52 fs, see Fig. 4(b). The corresponding TBP was 0.318, very close to the Fourier-transform limited value, which indicated almost chirp-free soliton pulses. 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 these conditions, the average output power of the ML Yb:GdCB laser was 77 mW at an absorbed pump power of 675 mW and a pulse repetition rate of 67.2 MHz, thus corresponding to a peak power of 19 kW. The recorded RF spectra exhibited a relatively high extinction ratio of >72 dBc above the noise level for the fundamental beat note at ~67.3 MHz, see Fig. 4(c), and uniform harmonics recorded on a 1-GHz frequency wide-span, see Fig. 4(d).

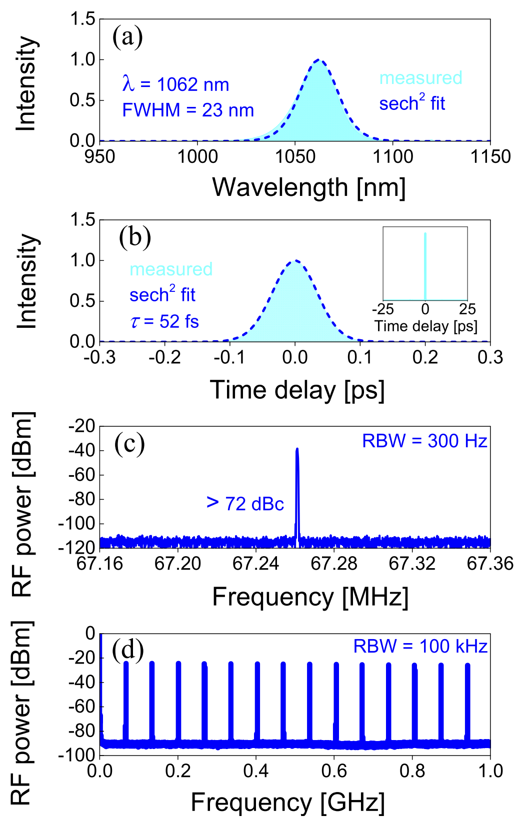

Fig. 4. ML Yb:GdCB laser with $T_{OC} = 2.5\%$. (a) Optical spectrum and (b) SHG-based intensity autocorrelation trace. *Inset*: autocorrelation trace on a time span of 50 ps. RF spectra: (c) first beat note at ~67.2 MHz recorded with an RBW of 300 Hz, and (d) harmonics on a 1-GHz frequency span, RBW = 100 kHz.

Finally, the shortest pulse duration was achieved by using the smallest $T_{OC} = 1.6\%$. After careful alignment, the spectrum of the Yb:GdCB laser experienced a substantial spectral broadening reaching an emission bandwidth of 32 nm (FWHM) at a central wavelength of 1059.2 nm assuming a $sech^2$-shaped intensity profile, see Fig. 5(a). Sub-40 fs soliton pulses were generated from the ML Yb:GdCB laser as confirmed by the SHG-based intensity autocorrelation measurement, see Fig. 5(b). Assuming a $sech^2$-shaped temporal shape, the almost perfect fit yielded a deconvolved pulse duration of 39 fs (FWHM), which led to a TBP of 0.318, very close to the Fourier-transform-limited value for $sech^2$-shaped pulses. Still, the SHG-based autocorrelation trace on a long-time span of 50 ps clearly revealed single-pulse mode-locking without multiple pulse instabilities, as shown in the inset of Fig. 5(b). The RF spectra corresponding to the shortest pulses were measured to verify the stability of the ML operation. The fundamental beat-note of the ML Yb:GdCB laser was located at 67.3 MHz with a very high extinction ratio of >74 dBc, indicating the absence of Q-switching instabilities, see Fig. 5(c). The wide-span RF spectrum measurement up to 1-GHz frequency range shown in Fig. 5(d) again revealed uniform harmonic beat notes which are an evidence for single pulse ML operation of the Yb:GdCB laser.

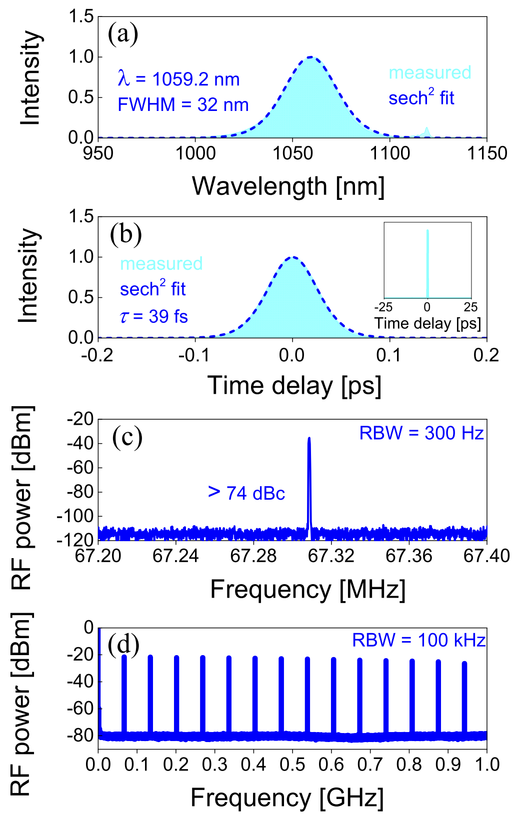

Fig. 5. ML Yb:GdCB laser with $T_{OC} = 1.6\%$. (a) Optical spectrum and (b) SHG-based intensity autocorrelation trace with a sech^2-fit. *Inset*: simultaneously measured long-scale autocorrelation trace for the time span of 50 ps. RF spectra of the Yb:GdCB laser: (c) first beat note at ~67.3 MHz recorded with a RBW of 300 Hz, and (d) harmonics on a 1-GHz frequency span, measured with a RBW of 100 kHz.

In Table 1, we summarize the output characteristics of the ML Yb:GdCB laser achieved in the present work.

Table 1. Output Characteristics[a] of the Mode-Locked Yb:GdCB Laser at 67.3 MHz

T_{OC}, %	P_{out}, mW	P_{abs}, W	η_{opt}, %	$\Delta\tau$, fs	λ_{em}, nm	$\Delta\lambda_{em}$, nm
1.6	70	0.701	9.99%	39	1059.2	32
2.5	77	0.675	11.4	52	1062	23
4	88	0.637	13.8	60	1054	21

[aa] P_{out} – average output power, P_{abs} – absorbed pump power, η_{opt} – optical-to-optical efficiency, $\Delta\tau$ – pulse duration (FWHM), λ_{em} – central emission wavelength, $\Delta\lambda_{em}$ – emission bandwidth (FWHM).

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4. Conclusion

In conclusion, we report on a sub-40 fs pulse generation from a passively ML Yb:GdCB laser, for the first time, to the best of our knowledge. The structurally disordered Yb:GdCB structure of the Yb:GdCB crystal exhibits a significant spectral line inhomogeneous broadening which supports a relatively broad absorption spectra (7.5 nm) and extremely broad, smooth and flat gain profiles. Such a "glassy-like" spectral behavior supports the generation of ultrashort pulses from the ML lasers with sub-40 fs pulse duration. In this work, a soliton ML Yb:GdCB laser stabilized by a commercial SESAM directly emitted pulses as short as 39 fs at 1059.2 nm with an average output power of 70 mW which corresponded to a peak power of 23 kW. This result represents a significant improvement in terms of pulse duration compared to our previous work (96 fs) [7], and also reveals the high potential of the Yb:GdCB laser in applications such as seeding of femtosecond amplifiers. Further power scaling operation of the ML Yb:GdCB laser would be possible through using higher Yb^{3+} doping levels in combination with the Kerr-lens mode-locking technique.

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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.

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