Continuous-wave and modelocked Yb:YCOB thin disk laser: first demonstration and future prospects

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Abstract: Yb:YCOB is a very attractive material for femtosecond pulse generation given its broad emission bandwidth. We demonstrate continuous-wave power scaling in the thin disk geometry to the 100-W level with a 40% optical-to-optical efficiency in multi-mode operation. Furthermore, we present initial modelocking results in the thin disk geometry, achieving pulse durations as short as 270 fs. The modelocked average power is, however, limited to less than 5 W because of transverse mode degradation. This is caused by anisotropic thermal aberrations in the 15% Yb-doped thin disks which were 300 to 400 µm thick. This result confirms the potential of Yb:YCOB to generate short femtosecond pulses in the thin disk geometry but also makes clear that significantly thinner disks are required to overcome the thermal limitations for high power operation.

OCIS codes: (140.0140) Lasers and laser optics; (140.3380) Laser materials.

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1. Introduction

The power scalable concept of the thin disk laser [1] has led to kilowatt continuous-wave (cw) power levels with high beam quality and high efficiencies [2] directly out of an oscillator. Furthermore, it is also highly suitable for ultrafast pulse generation using Semiconductor Saturable Absorber Mirrors (SESAMs) [3,4]. Nowadays, femtosecond thin disk lasers generate higher average output powers (i.e. >140 W) [5] and pulse energies (i.e. >10 µJ) [6,7] than any other type of modelocked laser oscillator. The output power can be scaled up by increasing the pump power and mode areas on both the gain medium and the SESAM by the same factor. Successful power scaling recently resulted in 141 W average output power [5] directly from a femtosecond SESAM modelocked thin disk laser oscillator.

The shortest pulses in the thin disk laser setup have been obtained with Yb:$LuScO_3$. The large gain bandwidth of this material supported pulse durations as short as 227 fs at 7.2 W average power. The output power was in this case limited by the crystal quality of the first manufactured disks [8]. For many application areas such as high harmonic generations at MHz repetition rates with pulse energies in the microjoule range [9,10] even shorter pulse durations are crucial. There are several other Yb-doped gain materials with larger bandwidths, which appear attractive for the thin disk configuration [11]. One of these materials is the monoclinic material Yb:$YCa_4O(BO_3)_3$ (Yb:YCOB). It can be grown by the Czochralski

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method, which simplifies the growth process in comparison to other promising materials like Yb:KYW [12]. The first modelocked Yb:YCOB laser delivered 210 fs [13] pulses with an average output power of 16 mW. Very recently, SESAM modelocking of this material has supported the shortest pulses from any modelocked Yb-doped oscillator so far: 46 fs at 46 mW of average output power [14]. This was further reduced to 42 fs with external compression, demonstrating the extremely broad gain bandwidth of Yb:YCOB. To date, however, the highest average output power in modelocked operation was limited to 275 mW [15].

In this paper we discuss Yb:YCOB thin disk laser operation. First we discuss cw power scaling up to the 100-W level, then we present the first modelocking results, discuss their thermal challenges and give recommendations for optimized thin disk laser material parameters. Average power scaling of Yb:YCOB lasers is challenging because of the low thermal conductivity of this material, which is about 5 times smaller than for Yb:YAG ($\kappa_{\mathrm{Yb:YCOB}}$ = 1.9 W/(m·K) [16]). The excellent heat management in the thin disk laser geometry is therefore highly attractive for this material. Recently, a cw thin disk laser generated up to 26 W in transverse multi-mode operation at 58% optical-to-optical efficiency (η_{opt}) with E||**Z**-polarized output [17]. So far, modelocked operation of an Yb:YCOB thin disk laser has not been reported. This requires a laser cavity with a nearly diffraction-limited output beam, because the presence of higher order modes usually destabilizes the pulse formation.

In comparison to YAG, YCOB has a lower density of Y-sites. This means that the Yb doping concentration of 15at.% used in our experiments corresponds to an active ion concentration of only 4.85% in Yb:YAG. Furthermore, the emission cross section $\sigma_{\mathrm{em,L}}$ of Yb:YCOB peaks at 1034 nm and is only $0.3\cdot10^{-20}$ cm^2. This is more than seven times lower than for Yb:YAG ($\sigma_{\mathrm{em,\ YAG}} = 2.2\cdot10^{-20}$ cm^2) which leads to a stronger tendency for Q-switching instabilities with a higher Q-switched modelocking (QML) threshold [18].

The absorption cross sections in Yb:YCOB at 940 nm are also much lower than in Yb:YAG. The recent progress on Volume Bragg Grating (VBG) [19] stabilized pump diodes allows for pumping in the much narrower but stronger zero-phonon absorption line around 975 nm. The corresponding absorption cross sections are $\sigma_{\mathrm{abs,\ E\|X}} = 0.91\cdot10^{-20}$ cm^2, $\sigma_{\mathrm{abs,\ E\|Y}} = 1.4\cdot10^{-20}$ cm^2 and $\sigma_{\mathrm{abs,\ E\|Z}} = 0.91\cdot10^{-20}$ cm^2, which are comparable to those of Yb:YAG. Therefore efficient pump absorption can in principle be achieved in Yb:YCOB thin disk lasers. We used relatively thick Yb:YCOB disks in the range of 300-400 µm because the doping concentration of the available crystals was limited to 15at.%. This limited the average output power in the fundamental mode to less than 10 W due to strong anisotropic thermal effects, but still allowed for power scaling to more than 100 W in multi-mode operation.

2. Continuous-wave multi-mode laser experiments

The simple linear multi-mode resonator for the cw experiments was formed by the thin disk and an output coupler with a radius of curvature of 500 mm. The disk has an anti-reflective coating on the front side and a highly reflective coating for both the pump and the laser wavelength on the backside. It is soldered with indium-tin on a water cooled copper heat sink. The pump source is a fiber coupled VBG-stabilized pump diode [20] delivering up to 400 W of output power and emitting at 976.4 nm with an emission bandwidth of 0.55 nm.

The highest power was obtained with a **Z**-cut Yb:YCOB thin disk crystal. The disk was 400 µm thick, 15at.%-doped and had an aperture of 6.3 mm × 7.0 mm cut perpendicular to the **Z**-axis (**Z**-cut). Despite the moderate density of the active ions as discussed in the introduction, the crystal absorbed 93% of the incident pump power due to the relatively large disk thickness and the 24 pump passes through the disk.

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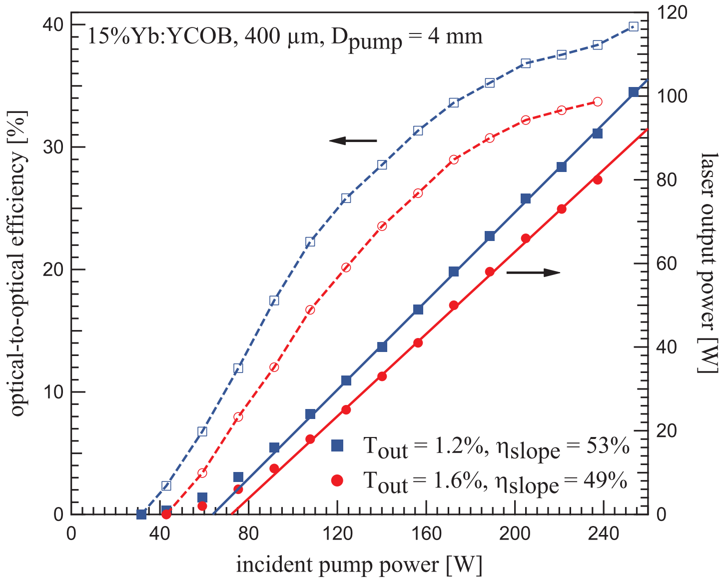

Fig. 1. Yb:YCOB thin disk laser cw multi-mode output power (solid lines) and optical-to-optical efficiency (dashed lines). The 15at.% Yb:YCOB disk is 400 µm thick, and oriented in (**Z**)-cut with a pump spot diameter of 4 mm. Results are presented for two different output couplers.

With a 1.2% output coupler we obtained a cw multi-mode output power of 101 W with 254 W of incident pump power, resulting in an optical-to-optical efficiency of 40% and a slope efficiency of 53% (see Fig. 1). No correction was applied for the unabsorbed pump power. With a higher output coupler of 1.6% a maximum output power of 80 W with a slightly lower slope efficiency of 51% was achieved.

A thinner 300-µm **Z**-cut Yb:YCOB thin disk laser with a 2.4-mm pump spot diameter delivered a cw multi-mode output power of 35 W with 80 W of incident pump power, resulting in an optical-to-optical efficiency of 43% and a slope efficiency of 43% even though only 86% was absorbed (Fig. 2, blue line). The reduced pump spot diameter of 2.4 mm was chosen according to the size and quality of the disk.

With a **X**-cut Yb:YCOB thin disk we observed better efficiency (Fig. 2, red line), but since the available **X**-cut crystals were too small we could only use a 1.9-mm pump spot diameter. The crystal thickness of 350 µm led to a pump absorption of 90%. The good efficiency which we obtained with this crystal also indicates that a further decrease in crystal thickness should be possible.

The pump threshold for the smaller pump diameters is about 2 times better than expected from simple power density scaling (compare Fig. 1 and 2). We assume that this is due to some residual crystal inhomogeneity and that with a smaller laser mode on the crystal a pump spot with higher quality could be selected.

The latter two Yb:YCOB crystals and pump geometries were used for the subsequent modelocking experiments and hence we stopped measuring output slopes before we reached a thermal rollover and before we risk damage of the disks.

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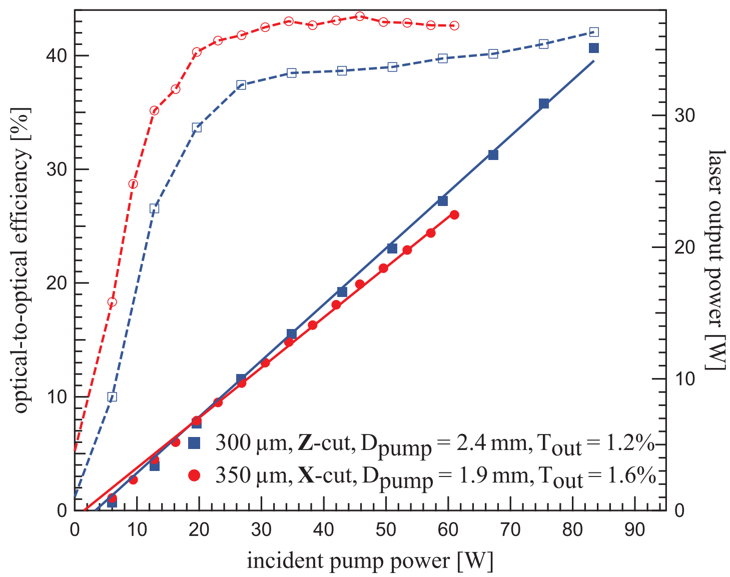

Fig. 2. CW multi-mode output power (solid lines) and optical-to-optical efficiency (dashed lines) vs. incident pump power for a 350-µm thick, (**X**)-cut (red) and a 300-µm thick, (**Z**)-cut (blue) 15at.% doped Yb:YCOB disks. These are the same disks that were used for the modelocking experiments. The pump spot diameters were chosen to be 2.4 mm for the (**Z**)-cut disk and 1.9 mm for the (**X**)-cut disk. The thinner thickness led to a pump absorption of 86% for the 300 µm, and 90% for the 350 µm thick crystal.

3. Modelocking experiments

For the modelocking experiments we compared the performance of two disks cut parallel to the **X**-, and **Z**-axis of the crystal as discussed in the previous section. The corresponding cw multi-mode operation output power curves are shown in Fig. 2. Figure 3 shows the cavity set-up for the modelocking experiments. The large thickness of the crystals led to pronounced thermal aberrations (Fig. 4) which limited our single mode cw output power to 8 W for the **X**-cut crystal (thickness 350 µm, pump spot diameter 1.9 mm) and 10 W for the **Z**-cut crystal (thickness 300 µm, pump spot diameter 2.4 mm). The **X**-cut crystal allows for laser operation polarized E‖**Z,** which is the most promising polarization for modelocking experiments because it has the highest emission cross section [15,17].

As discussed in the introduction, the gain material Yb:YCOB has a stronger tendency for Q-switching instabilities compared to Yb:YAG. Since we were limited in single mode output power, we increased the predicted intracavity pulse energy to overcome the QML threshold [18] with a lower pulse repetition rate. A simple 4-*f* extension was added into the cavity, consisting of two mirrors separated by their radius of curvature R = 2*f*, thus adding a total of 2R to the cavity length (Fig. 3) [21].

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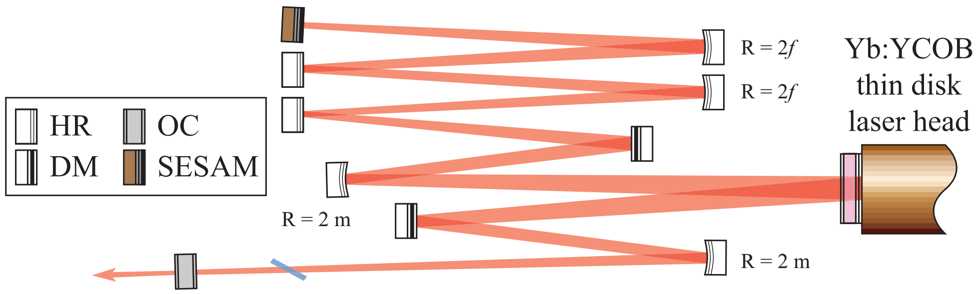

Fig. 3. Schematic Yb:YCOB thin disk laser cavity set-up for single mode and cw modelocking operation. The disk is used as a folding mirror. The Brewster plate close to the output coupler (OC) ensures linearly polarized laser output and provides the required self-phase modulation (SPM) for stable soliton modelocking. The 4-*f* extension which was necessary to obtain stable modelocking was inserted close to the SESAM. Dispersive mirrors (DM), high reflector (HR).

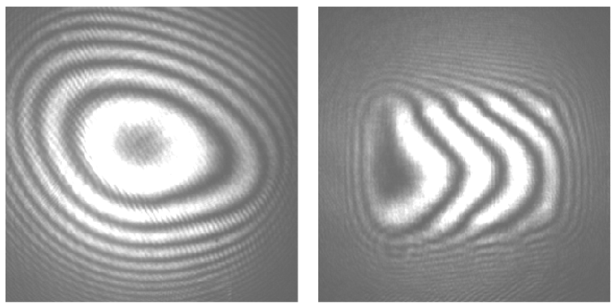

Fig. 4. Interferograms of the two 15at.% doped Yb:YCOB disks used for modelocking, left (**Z**)-cut (300 µm thick), right (**X**)-cut (350 µm thick). The interferograms were recorded without incident pump light and show significant aberrations of the available disks. The anisotropy of the disks increased with the pump power due to the anisotropic thermal properties. These images were recorded at a wavelength of 1064 nm.

With 300-µm thick **Z**-cut Yb:YCOB thin disk crystal stable soliton modelocking was achieved by inserting a SESAM with a saturation fluence of F_{Sat} = 28 µJ/cm^2, a modulation depth of ΔR = 0.76% and nonsaturable losses below 0.1%. The size of the laser mode on the disk is estimated to have a radius of $w_0 \approx 500$ µm and on the SESAM of $w_0 \approx 440$ µm, resulting in a QML threshold intracavity power of 29 W taking into account the additional soliton stabilization [18]. The negative group delay dispersion (GDD) in the cavity was obtained with two GTI-type dispersive mirrors accounting for −2200 fs^2 per roundtrip. The Brewster plate had a thickness of 1 mm, providing the required SPM for stable soliton modelocking [18] and was situated close to the output coupler. The low output coupling rate of only 1.4% was chosen because of the low emission cross section of Yb:YCOB in the E‖**X** direction ($\sigma_{em,E\|X}$ = $0.25\cdot10^{-20}$ cm^2) [17]. The final cavity including the 4-*f* extension (f = 1 m) had a total length of 6.15 m resulting in a repetition rate of 24.4 MHz. The average output power was measured to be 4.7 W with an M^2 of below 1.1. The achieved pulse duration was 455 fs with a spectral bandwidth of $\Delta\lambda$ = 2.6 nm (Fig. 5). This results in a time bandwidth product of 0.33 which is close to the ideal case of 0.315 assuming a soliton pulse shape.

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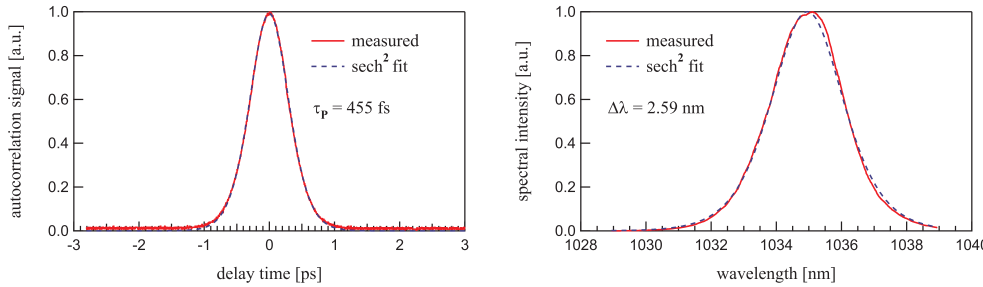

Fig. 5. SESAM modelocked (**Z**)-cut Yb:YCOB thin disk laser: autocorrelation trace and optical spectrum at an average output power of 4.7 W and a pulse repetition rate of 24.4 MHz.

With the slightly thicker **X**-cut Yb:YCOB thin disk crystal we were able to achieve stable soliton modelocking in a modified cavity with a length of 7.6 m, resulting in a repetition rate of 19.7 MHz. In these experiments, the SESAM had a saturation fluence of F_{Sat} = 61 µJ/cm^2, a modulation depth of ΔR = 1.47% and nonsaturable losses around 0.15%. The laser mode size radius on the active medium was again w_0 ≈500 µm, but had a slightly larger diameter of ≈650 µm on the SESAM. Despite the lower repetition rate and the higher cross sections in E‖**Z** polarization, this results in a higher intracavity power threshold for stable modelocking of 73 W because of the larger spot size on the SESAM and its higher saturation fluence. Again, two GTI-type dispersive mirrors introduced the required negative GDD of –2200 fs^2 per roundtrip. The Brewster plate had a thickness of 5 mm and was placed after the 4-*f* extension (*f* = 1.5 m) in front of the SESAM. The laser output was polarized parallel to the **Z**-axis of the crystal. Due to the higher emission cross section a higher output coupler of 2.2% was found to be optimal. With these operation parameters we achieved pulses as short as 270 fs with an optical bandwidth of Δλ = 4.38 nm (Fig. 6), resulting in a time bandwith product (TBP) of 0.33. The output power was 2 W and the beam was almost diffraction limited with an M^2 <1.1. A summary of the continuous wave and modelocking results and parameters can be found in the Tables 1 and 2.

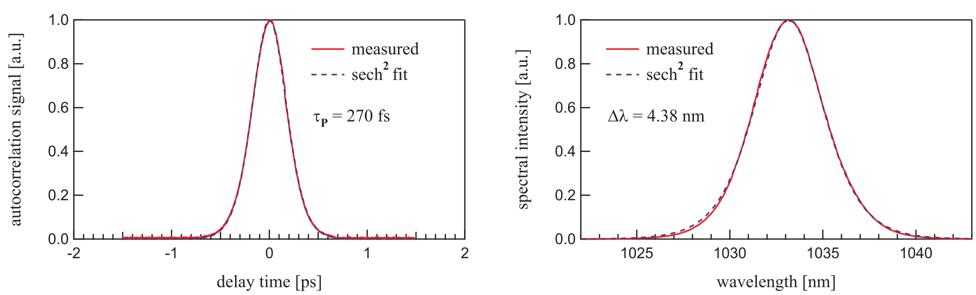

Fig. 6. SESAM modelocked (**X**)-cut Yb:YCOB thin disk laser: autocorrelation trace and optical spectrum of the shortest pulses obtained at an average output power of 2 W and a pulse repetition rate 19.7 MHz.

Yb:YCOB is a self frequency doubling material [22]. Therefore we observed green light in modelocked operation, which was however limited to only 1 mW after the first folding mirror inside the cavity due to the short interaction length with the active medium in our setup. We did not observe any destabilization of the modelocking due to the green light generation [23]. This folding mirror had a >95% transmission for the green light.

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Table 1. Summary of multimode continuous wave results

name	cut	thickness [µm]	polarization	∅ pump spot [mm]	pump absorption	T_{OC}	P_{out}[W]	η_{opt}
CW1	**Z**	400	E‖X	4	93%	1.2%	101	40%
CW1	**Z**	400	E‖X	4	93%	1.6%	80	38%
ML1	**Z**	300	E‖X	2.4	86%	1.2%	35	43%
ML1	**X**	350	E‖Z	1.9	90%	1.6%	26	43%

Parameters of cw multimode lasers presented in Fig. 1 and 2 with T_{OC} being the output coupling rate, P_{out} the average output power and η_{opt} the optical-to-optical efficiency.

Table 2. Summary of modelocking results and parameters

name	P_{out} [W]	T_{OC}	F_{Sat} [µJ/cm^2]	ΔR	f_{rep} [MHz]	Δλ [nm]	τ_P [fs]	TBP	M^2
ML1	4.7	1.4%	28	0.76%	24.4	2.6	455	0.33	<1.1
ML2	2	2.2%	61	1.47%	19.7	4.38	270	0.33	<1.1

Parameters of the modelocked lasers presented in section 3. The output coupling rates changed in comparison to the cw results due to the double passes through the disk in the modelocking cavities along with small additional losses from SESAM, Brewster Plate and additional mirrors.

3. Conclusion

In conclusion, we scaled the output power of a cw multi-mode Yb:YCOB thin disk laser to above 100 W. This encouraging result shows the potential of Yb:YCOB for high power operation in a thin disk laser geometry despite its relatively low thermal conductivity. Thermal effects induced by the relatively large thickness of the available disks limited the power in single mode operation and therefore cw modelocking operation to <10 W. Pulses as short as 270 fs have been generated at 2 W average power and 455 fs at 4.7 W. For operation at higher power levels thinner disks with a higher doping concentration are necessary to reduce thermal lensing and aberrations. The current thin disk laser head provided 24 passes through the gain material, resulting in 93% absorption of the pump light. We expect that efficient operation with 100-150 µm thick disks can be achieved by increasing the doping concentration to more than 30%. Such a disk would still allow for an absorption rate close to 75% and corresponds to a cation density similar to a ≈10% Yb:YAG. Thus the problems reported for highly Yb-doped materials should not occur [24]. This is also supported by previous investigations which did not reveal any concentration quenching of the lifetime even for doping concentrations of 50at.% [25]. In addition, high slope efficiencies of up to 66% with a 35at.% Yb:YCOB crystal were observed [26]. Increasing the doping concentration to more than 30at.% and reducing the thickness of the disk down to 100 µm will result in sufficient absorption and a much better thermal management.

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