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SESAM mode-locked Yb:GdYCOB femtosecond laser

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Abstract: We report a detailed characterization of the diode-pumping operation of the mixed crystal $Yb_{0.1}$:$Gd_{0.5}Y_{0.4}$COB, including cw, tunable and femtosecond laser regimes. This crystal was recently proposed as a promising candidate for high-power as well as femtosecond operation. Our results show that the crystal quality and performance is comparable to the more deeply investigated and closely related calcium yttrium oxoborate and calcium gadolinium oxoborate laser crystals.

OCIS codes: (140.3380) Laser materials; (140.3615) Lasers, ytterbium; (140.7090) Ultrafast lasers.

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1. Introduction

The mixed crystal Yb:Gd_xY_{1-x}COB has been proposed and investigated as a potential alternative to calcium yttrium oxoborate Yb:$YCa_4O(BO_3)_3$ (Yb:YCOB) and calcium gadolinium oxoborate Yb:$GdCa_4O(BO_3)_3$ (Yb:GdCOB), since the random distribution of Y and Gd ions can broaden the emission and absorption band making this material even more suitable to high-power diode pumping [1–3].

Indeed, it was shown [3] that a favorable broadening occurs for the pump absorption band near 977 nm, keeping emission cross section, lifetime and emission bandwidth comparable to those of

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Yb:GdCOB and Yb:YCOB. A brief report on a laser experiment was also included in that article, however a detailed investigation of laser performance of the mixed crystal Yb:Gd_xY_{1-x}COB is long overdue.

An interesting application area of this new crystal is generation and amplification of femtosecond pulses, owing to the broad fluorescence bandwidth. For comparison, diode-pumped ultrafast oscillators based on Yb:YCOB and Yb:GdCOB were reported to generate pulses as short as 35 fs [4] and 90 fs [5], respectively. However, information on femtosecond oscillators based on Yb:Gd_xY_{1-x}COB is still missing to date. High power operation at 100 W output was already reported for a thin-disk Yb:YCOB oscillator, with pulses as short as 270 fs [6].

In this article we report, for the first time to our knowledge, the following investigations of a Yb:Gd_xY_{1-x}COB diode-pumped oscillator:

- detailed Caird [7] analysis of continuous wave (cw) operation, showing that the crystal quality is certainly comparable to most available Yb-doped crystals, as well as the performance in terms of slope efficiency and threshold power;
- broad-band tunable operation of the cw laser;
- femtosecond operation of oscillators employing semiconductor saturable absorber mirrors (SESAMs).

2. Experimental details

The experimental setup for both cw and mode-locking experiments, is shown in Fig. 1.

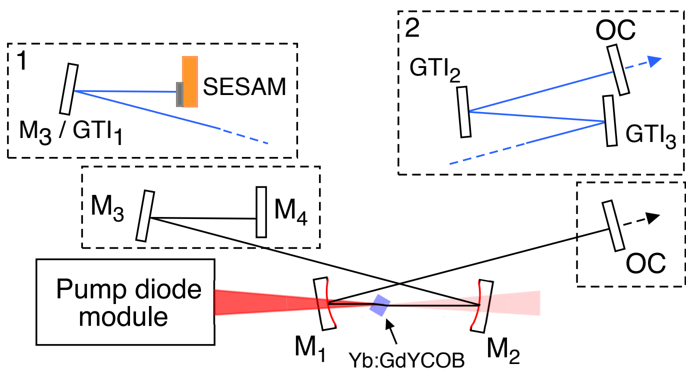

Fig. 1. The experimental setup for cw and mode-locking experiments. M_1: spherical pump mirror (R = 50 mm), Anti-Reflection (AR) coated at 976 nm, High-Reflectivity (HR) at 1000-1100 nm; M_2: spherical mirror (R = 100 mm), AR coated at 976 nm, HR at 1000-1100 nm; M_3: plane mirror AR coated at 976 nm and HR at 1000-1100 nm, M_4: plane mirror HR at 1000-1100 nm; OC: output coupler, 30' wedged. For mode-locking operation (see insets 1 and 2): GTI: Gires-Tournois interferometer mirrors: GTI_1 = -550 fs^2, GTI_2, GTI_3 = -375 fs^2.

The resonator was a standard anastigmatic X-folded cavity [8]. The pump module consisted of a single transverse-mode, fiber-coupled (FC) laser diode (JDSU S27-7602-400) emitting 400 mW at 976 nm (wavelength stabilized with a fiber Bragg grating).

The polarization of pump beam was manipulated by properly coiling the pig-tail fiber to induce a strongly elliptical polarization with a ratio about 13:1 between the two axes. The maximum pump power incident on the laser crystal was 375 mW. The diode laser beam was collimated by means of an aspherical lens (f = 15.3 mm, NA = 0.16) and focused into the laser crystal to a spot radius $w \approx 12$ μm (measured in air, intensity at $1/e^2$) by means of a spherical lens with 50 mm focal length.

A half-wave plate at 976 nm was used to adjust the pump polarization principal axis in the horizontal plane. The active medium was a 3×3×3 mm^3, $Yb_{0.1}Gd_{0.5}Y_{0.4}Ca_4O(BO_3)_3$ (Yb:GdYCOB for brevity). The residual pump not absorbed by the crystal was transmitted by dichroic mirror M_2 (see Fig. 1) and monitored with a power meter. Under lasing conditions, the sample absorbed 66% of the incident pump.

Details about crystal growth and spectroscopic characterization can be found in [1–3]. The crystal facets were optically polished and uncoated. In order to minimize crystal insertion losses, we placed the crystal at Brewster angle. According to the notation used in [2], in laser experiments we exploited the laser polarization along the Y-axis, taking advantage of the higher values of the emission cross section with respect to X- and Z-axis crystal orientation [2]. XYZ is the dielectric frame whose position relative to the crystallographic frame of this monoclinic crystal can be found in [2].

In the cw regime, the cavity arm lengths were as follows: M_2-M_4 = 200 mm; M_1-M_2 = 91 mm, and M_1-OC = 450 mm. The results obtained in the cw regime for a set of different output couplers (OCs) with transmission T are shown in Fig. 2(a). With the optimum output coupler T = 5%, we obtained up to 117 mW output power at an absorbed pump power of 236 mW.

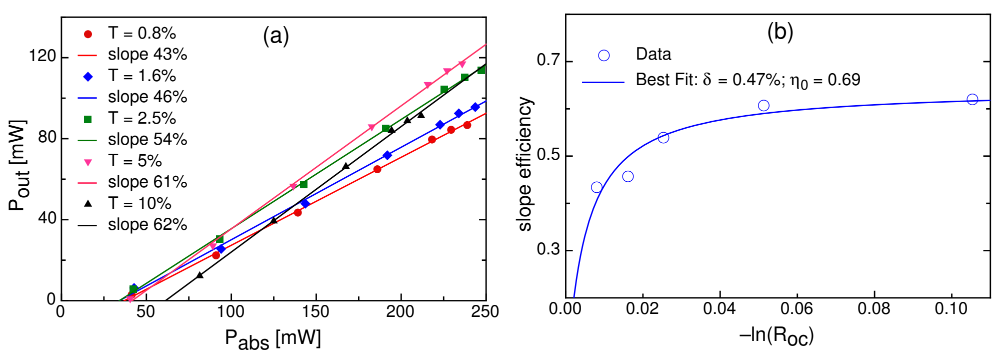

Fig. 2. Cw laser performance with different OCs (a) and slope efficiency as a function of the different OCs (b).

The maximum slope efficiency of 62% was achieved with T = 10% OC. Laser emission occurred around the fluorescence peak at 1035 nm with all the tested OCs. According to Caird analysis [7], we could estimate the intra-cavity non-saturable losses δ per round trip and the intrinsic slope efficiency η_0 by fitting the measured slope efficiency as a function of the laser OC reflectivity with the equation

$$\eta = \frac{\lambda_p}{\lambda_l}\eta_0\frac{-\ln(R_{oc})}{\delta-\ln(R_{oc})} \tag{1}$$

The corresponding results are shown in Fig. 2(b). The best fit yields a high intrinsic slope efficiency (accounting for mode-matching efficiency and quantum efficiency) of η_0 = 69% and total resonator losses, excluding the re-absorption losses in the laser crystal, $\delta \approx 0.47\%$. This total loss value, mostly due to mirror coating scattering and generic loss, is rather typical of these resonators also with high optical quality commercial crystals, either Brewster-cut or AR-coated, then we can safely state that the optical quality of the Yb:GdYCOB sample is definitely comparable.

As it is shown in Fig. 3(a), as the inversion level increases (e.g. when output coupling is increased), the gain spectrum tends to peak around 1035 nm. This may explain why the emitted wavelength in cw experiments occurred at this wavelength regardless of the OC transmission. The only exception was the T = 0.8% OC that provided a slightly shifted emission wavelength of 1040 nm.

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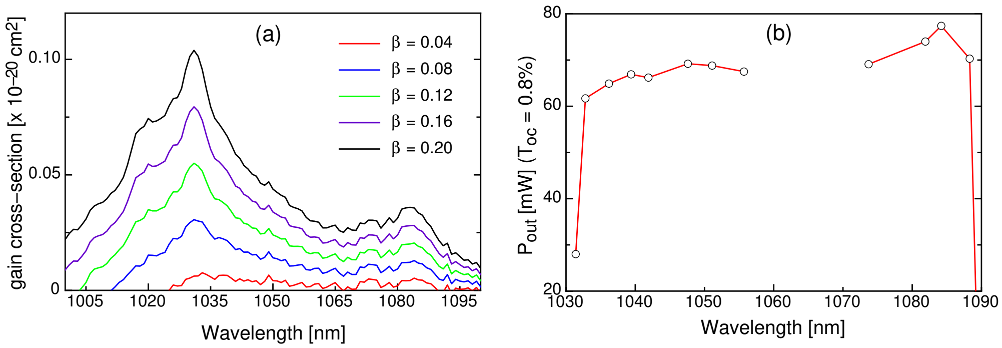

Fig. 3. Gain cross-section spectrum at different values of inversion factor β for laser polarization along Y-axis (a), and tuning curve in cw regime with T = 0.8% OC (230 mW absorbed pump power) (b).

In order to investigate the tuning range of the output wavelength in cw regime, we inserted a fused silica prism in the arm M_1-OC. Employing the T = 0.8% OC, the output wavelength could be readily tuned in the range 1031-1056 nm and 1074-1090 nm, as shown in Fig. 3(b). This experimental result is in good qualitative agreement with the gain cross-section spectrum that can be calculated for E // Y-axis polarization as a function of the inversion factor $\beta = n_2/n_{tot}$ (see Fig. 3(a)).

It is expected that higher pump power would extend the tuning range further, filling the gap between 1056 and 1074 nm.

In mode-locking experiments, referring to Fig. 1, we employed three GTI mirrors for intracavity group delay dispersion (GDD) compensation, and we replaced mirror M_4 with a SESAM specified for a modulation loss of 3% and a saturation fluence of 140 μJ/cm^2. Given the GTI mirrors specifications, the total amount of negative GDD introduced per roundtrip was -2600 fs^2. In the modified cavity configuration, the total distance between mirror M_1 and OC was about 610 mm. Stable and self-starting soliton mode-locking was obtained with this setup, both with T = 0.8% OC and T = 0.4% OC. The average output power was about 20 mW and 14 mW, respectively. Thanks to the slightly higher intracavity pulse energy, the shortest pulses of 161 fs duration were obtained with T = 0.4% OC. The pulse autocorrelation trace and the 7.5 nm FWHM optical spectrum centered at 1033 nm, are shown in Fig. 4. The corresponding time bandwidth product was 0.34, close to the Fourier-Transform limit of 0.32 for sech^2 shaped soliton pulses. One of the main drawbacks of the otherwise very practical GTI mirrors is the discretization of the amount of negative GDD introduced. Given the available GTI mirrors, in our experiments the minimum reduction-step consisted in the removal of mirror GTI_2, accounting for -750 fs^2 per roundtrip. In these conditions, corresponding to a total negative GDD of -1850 fs^2 per roundtrip, negative dispersion was not sufficient to stabilize the soliton Mode-Locking regime.

By observing the fundamental beat note of the radio frequency spectrum of the mode-locked pulse train showing a sharp peak at 166.6 MHz with a high extinction ratio of 50 dB (see Fig. 4(b)), we could exclude the presence of significant amplitude modulations in the cw-Mode-Locked pulse train due to Q-switching instabilities. We also measured clean autocorrelation traces of the laser pulses over a wide delay span (>200 ps) that did not show any sign of multiple pulsing.

3. Conclusions

Diode-pumping of a mixed Yb:GdYCOB crystal, both in cw and femtosecond regime, was investigated for the first time to our knowledge. The setup employed a fiber-coupled low-power single-mode pump laser unit, thus avoiding any thermal issue with the crystal mounting and

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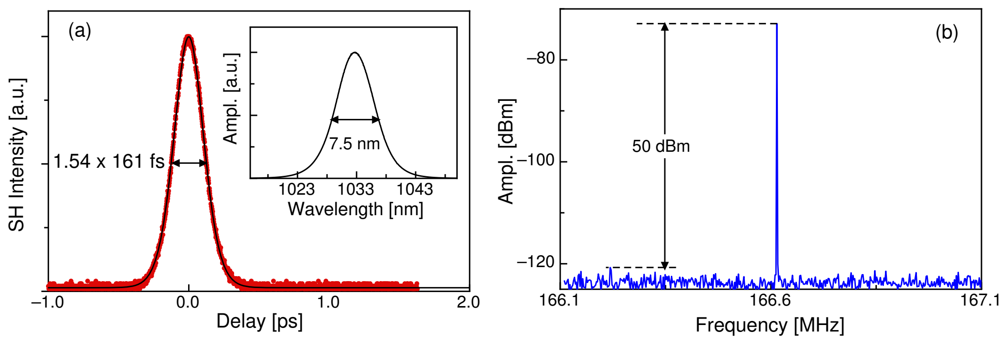

Fig. 4. Autocorrelation trace of the shortest mode-locking pulses (a) and corresponding optical spectrum (inset). Fundamental beat note of the RF spectrum of the pulse train (b).

characterization of the different regimes which permits to assess more clearly the intrinsic laser properties of the material.

Slope efficiency, internal crystal losses and tunability compare well with Yb:YCOB and Yb:GdCOB. This confirms the good optical quality of the mixed crystal. As for the femtosecond results, the shortest pulsewidth measured (161 fs) is certainly far from the best results achieved with Yb:YCOB and Yb:GdCOB. However, the higher pump power available in the experiments described in [4, 5] might have permitted to extend the laser emission spectrum as previously noticed, making it easier to optimize the mode-locking with shortest pulses at longer wavelengths with respect to the fluorescence peak (as usually observed with most femtosecond oscillators emitting near 1 μm). We also attribute the difficulty in optimization of the mode-locking pulses to a progressive slight deterioration of the crystal sample available. This made somehow difficult to recover initial cw performance, with the crystal showing increasing non-homogeneity.

We suspect that Q-switching instabilities, occurring during alignment and dispersion optimization, produced local damage inside the crystal which is not readily visible upon optical inspection. This most often occurs with long-lifetime Yb-doped materials such as fluorides, e.g. Yb:CaF_2 [8] which tend to produce energetic transient pulses in such conditions. The availability of only a single sample made the femtosecond experiment definitely harder than usual. However, we believe our results prove to be a good starting point for a research effort more specifically focused on investigation and optimization of Yb:GdYCOB for ultrafast applications.

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