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Mode-locked and Q-switched laser operation of the Yb-doped $Li_6Y(BO_3)_3$ crystal

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ABSTRACT We report for the first time pulsed laser operation of the Yb-doped $Li_6Y(BO_3)_3$ (Yb-LYB) crystal in the nanosecond as well as in the femtosecond regime. Pulse durations as short as 355 fs have been obtained in passively mode-locked operation and pulse energies up to 140 μJ in Q-switched operation.

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1 Introduction

In the recent years many ways to find new solid-state laser materials have been explored to obtain efficient and compact high energy ultrafast laser sources. Ytterbium-doped materials are popular as active laser media because of their absorption spectrum which is suitable for direct diode-pumping and their large emission bandwidth permitting short pulse generation. Moreover, because of their small quantum defect and thus low thermal load, Yb-doped materials offer the potential for high average power short pulse lasers and amplifiers [1–5]. Up to now, pulses as short as 47 fs [6] and millijoule pulse energies [7] have been reported from Yb-doped laser materials.

Yb-doped crystals that combine long fluorescence lifetimes with good thermo-optical properties are especially interesting for the development of high energy, high peak-power laser sources as used, e.g., for material processing or scientific high-field experiments [8]. Yb-doped borate compounds have proven to be attractive materials for these kinds of laser sources [9–12]. The Yb^{3+}:$Li_6Y(BO_3)_3$ (Yb-LYB) crystal, is especially interesting because of its long fluorescence lifetime of 1.1 ms and the broad fluorescence spectrum [13], which are promising for high energy laser systems and short pulse generation, respectively. The Yb-doped LYB can be grown fast and easily in quite large dimensions (typically 15–20 cm^3). Moreover, the crystal has quite high emission cross sections of $\approx 0.5 \times 10^{-20}\,cm^2$ along all three axes and absorption cross sections of up to $1.74 \times 10^{-20}\,cm^2$ (along the Z-axis). The emission (positive values) and absorption (negative values) cross sections along the X-axis used in the following experiments are shown in Fig. 1.

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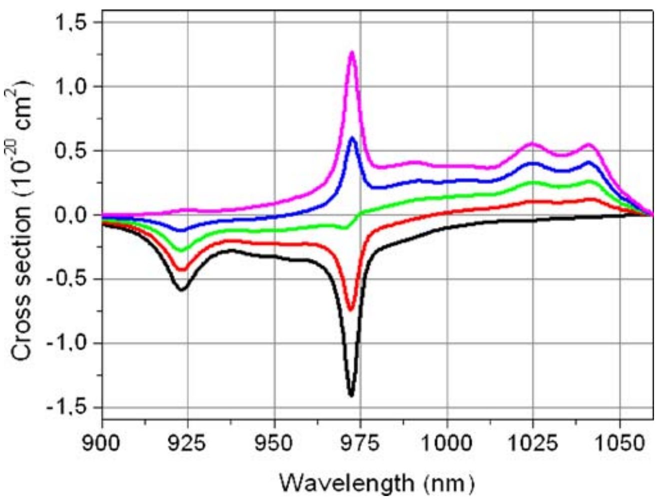

FIGURE 1 Absorption (negative values) and emission (positive values) cross sections along the X-axis of the crystal for an inversion rate of 0 (*black*), 0.25 (*red*), 0.5 (*green*), 0.75 (*blue*) and 1 (*magenta*), respectively

In this paper, we present for the first time the tuning range and pulsed laser operation of the Yb-LYB crystal in the passively mode-locked as well as in the Q-switched regime.

2 Continuous wave laser operation and tunability

The used laser crystal was grown by the Czochralski method and was doped at a high, 26 at. % Yb-concentration. We opted for this concentration in accordance with the results in our previous work [13]. Note that such high doping concentration could be realized without observing any shortening of the fluorescence lifetime. The thermal conductivity for this Ytterbium concentration is about 2.6 $Wm^{-1}K^{-1}$. This has been measured by heating the crystal at one end and recording the temperature difference at two different points along the crystal length. To our knowledge, on undoped LYB crystals no measurements of the thermal conductivity have been reported so far.

The crystal was cut along the optical Y-axis, which was also chosen as the propagation direction of the laser beam. The high doping concentration results in significant single pass pump absorption for short crystal lengths, which is beneficial for diode-pumping of quasi-three-level materials because a good modal overlap inside the gain medium between the diffraction limited laser beam and the highly diffracting pump beam can be obtained. Despite the biaxial crystal symmetry of Yb-LYB the pump light can be arbitrarily polarized as the absorption cross sections are quite similar along the axes perpendicular to the optical Y-axis. This is a very interesting property of the Yb-LYB crystal in comparison to other biaxial laser crystals as, e.g., Yb-doped tungstates [14], as it permits the use of fiber coupled laser diodes as efficient pump sources. Together with the high amplification coefficient this makes the Yb-LYB an interesting candidate for high average power lasers.

The crystal was AR-coated on both faces by a single material pulverization. However, this was a first test of the coating, far from being perfect, and we measured a residual reflection of about 1.5% for each interface when using the crystal close to normal incidence.

We first characterized the laser crystal in continuous wave operation. The cavity was formed by two curved folding mirrors M1 and M2, a flat end mirror, a 10% output coupler, and a dichroic folding mirror which allowed pumping the crystal at normal incidence with an intensity of 22 kW/cm^2. The 1.3 mm thick Yb-LYB crystal is mounted on a water-cooled heatsink and pumped by an unpolarized 200-μm-fiber coupled diode laser with an emission wavelength centered at 972 nm and delivering a maximum output power of 7 W. The pump spot diameter in the crystal is $\approx$ 200 μm. About 75% of the incident pump power is absorbed when preventing the cavity from lasing operation; this value was determined by measuring the residual transmission of the pump beam after the crystal. The emission wavelength of the laser was centered at 1042 nm, and the output power was as high as 2 W at a pump power of 7 W. At this power level the laser performances showed no degradation due to thermal effects. The laser threshold was at 0.8 W of incident pump power, and the laser output is linearly polarized along the X-axis.

By inserting a prism into the cavity we could tune the laser operation wavelength from 1018 to 1055 nm which corresponds to a tuning range of over 35 nm. This is in good agreement with the emission spectrum of the material (see Fig. 1). The results are depicted in Fig. 2, and for these experiments a 5% output coupler was used.

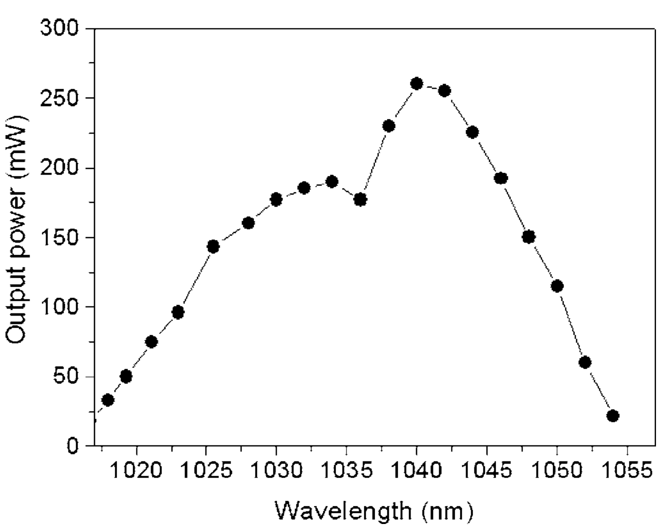

FIGURE 2 Tuning range of the Yb:LYB with a 5% output coupler and using a prism for wavelength selection

3 Q-switched cavity-dumped laser operation

For Q-switched cavity-dumped laser operation, we inserted a thin film polarizer and a KD*P Pockels cell as switching element into the laser cavity (see Fig. 3). The Pockels cell was adjusted for static quarter-wave retardation in order to inhibit laser action of the cavity when no high-voltage is applied to the cell. Once the quarter-wave voltage is applied to the Pockels cell the Q-switched pulse develops inside the resonator until it is cavity-dumped by switching the high-voltage to zero again. The round-trip small signal gain was estimated from the Q-switched pulse build-up to be about 1.4. The round-trip resonator losses were estimated to be about 12%, predominantly due to the imperfect AR-coatings of the crystal (6%).

The cavity length was 95 cm which resulted in a Q-switched cavity-dumped pulse duration of about 6.5 ns. The used high-voltage switch permitted operation of the laser up to repetition rates as high as 80 kHz. Figure 4 shows the extracted pulse energy as well as the average output power as a function of the repetition rate.

The extractable pulse energy was limited by the damage threshold of the crystal's AR-coating. We therefore limited the pump power to 5 W and obtained a maximum pulse energy of 140 μJ for pulse repetition rates below 1 kHz. The rela-

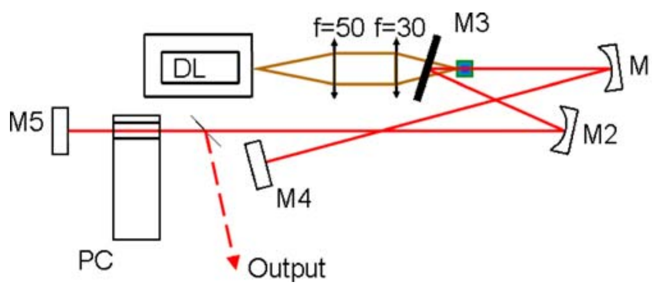

FIGURE 3 Cavity setup for Q-switching; M1 and M2 are curved mirrors (M1: 20 cm ROC; M2 : 25 cm ROC), M3 is a dichroic pump mirror, M4 and M5 are flat high reflecting mirrors, PC Pockels cell

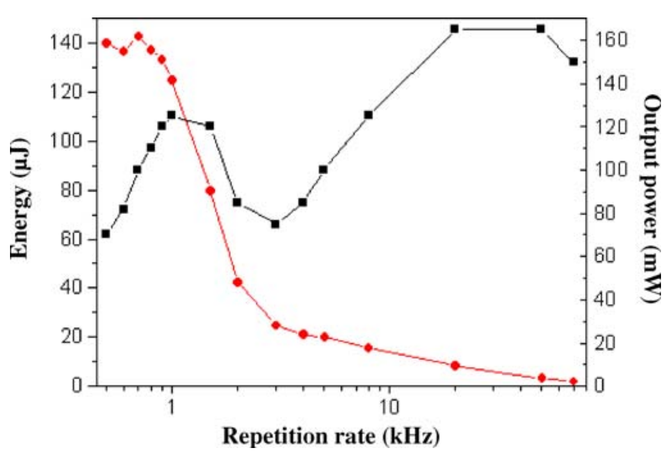

FIGURE 4 Output average power (*black*) and energy (*red*) as a function of the repetition rate at 5 W pump power

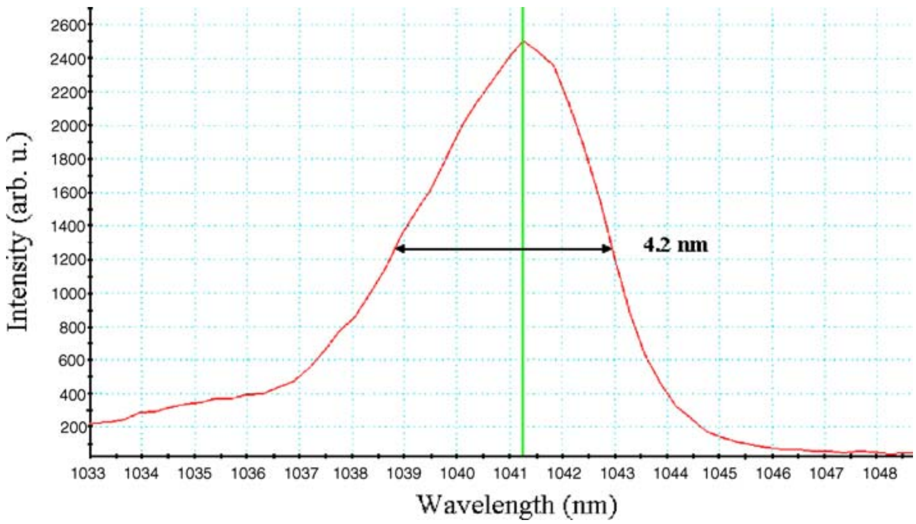

FIGURE 5 Q-Switched spectrum obtained at 1 kHz repetition rate and 100 μJ pulse energy

tively low extraction efficiency (< 5%) and the rather strong energy roll-off for repetition rates exceeding 0.8 kHz can be explained by the high resonator losses and the photo-acoustic ringing effect in the KD*P Pockels cell. The latter results in several quarter-wave transitions of the Pockels cell during the low-Q cycle of the laser thus limiting the stocked energy in the amplifier medium. Within the investigated range of pulse repetition rates we even observed some resonance frequencies of the photo-acoustic ringing prohibiting stable operation of the Q-switched cavity-dumping. The extraction efficiency can significantly be improved by reducing the intracavity losses of the laser, e.g., by optimizing the crystal's AR-coating and by using a BBO-Pockels cell instead of KD*P because BBO shows a significantly lower absorption around 1 μm.

The first results from the Yb-LYB laser show the potential for pulse energies in the millijoule region at kHz pulse repetition rates. Moreover, the FWHM bandwidth of > 4 nm of the Q-switched cavity-dumped laser (Fig. 5) shows the potential for amplifying ultrashort pulses around 300 fs.

4 Passively mode-locked laser operation

In order to explore the properties for short pulse generation of the Yb-doped LYB crystal, we modified the laser cavity to achieve passive mode-locking. We removed the thin film polarizer and the Pockels cell and replaced the flat end mirror by a curved folding mirror that focused onto a semiconductor saturable absorber mirror (SESAM) [15]. The main challenge of Yb-doped mode-locked oscillators using a SESAM is to efficiently suppress the Q-switching instabilities of the mode-locked pulse train. The stability condition as derived in [16] can be achieved by increasing the intracavity pulse energy in order to sufficiently saturate both the gain medium as well as the saturable absorber. Therefore we lengthened the cavity arms thus lowering the pulse repetition rate from 125 to 59 MHz. This leads to a longer storage time and therefore to higher pulse energy. The cavity setup is shown in Fig. 6.

Without inserting any negative dispersion into the laser cavity we obtained stable cw mode-locking operation with a pulse duration of 1.3 ps. These pulses were not transform limited and had a time bandwidth product of 1.05. We obtained 300 mW of output power behind a 5% output coupling mirror and measured 5 to 6% additional coupling loss due to the residual reflections of the crystal's AR-coating. This means that the total output power corresponds to 600 mW at an incident pump power of 5.5 W. This output power can be obtained in one output beam if a 10% output coupler is used together with an optimized crystal coating.

Inserting a chirped mirror with a negative dispersion of $-400\,fs^2$ allowed to minimize the frequency chirp within the cavity and led to nearly transform limited soliton-like pulses of 355 fs duration. The output coupler in this experiment had 1% transmission at the lasing wavelength. The pulse spectrum and the autocorrelation trace are reported in Fig. 7. The average power for these values was 75 mW behind the output coupler at a pump power of 6 W.

When using a 5% output coupler, we achieved a total output power of 660 mW at a pump power of 6.8 W and soliton-like pulses of 400 fs. The FWHM of the spectrum is about 3.8 nm. As the measured pulse spectrum in Q-switched operation was even broader, we expect shorter pulses if the self-phase-modulation inside the laser crystal is increased. This can be achieved once a new run of crystal growth has been made and the AR-coating on the crystal is optimized. More-

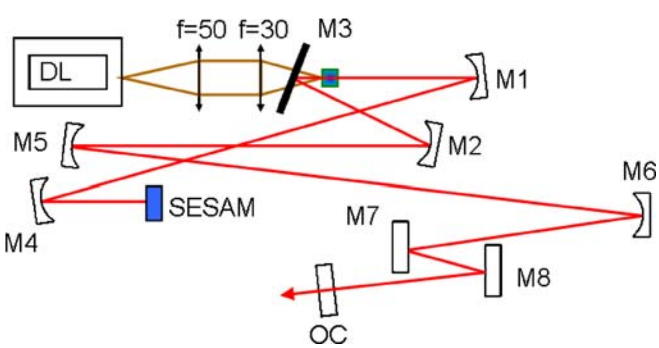

FIGURE 6 Cavity setup for passive mode-locking. M1, M2, M4, M5 and M6 are curved mirrors (M1: 20 cm ROC; M2 : 25 cm ROC, M4: 15 cm ROC; M5 and M6: 75 cm ROC), M3 is a dichroic pump mirror, M7 is a flat high reflecting mirror, M8 is a chirped mirror, OC output coupler

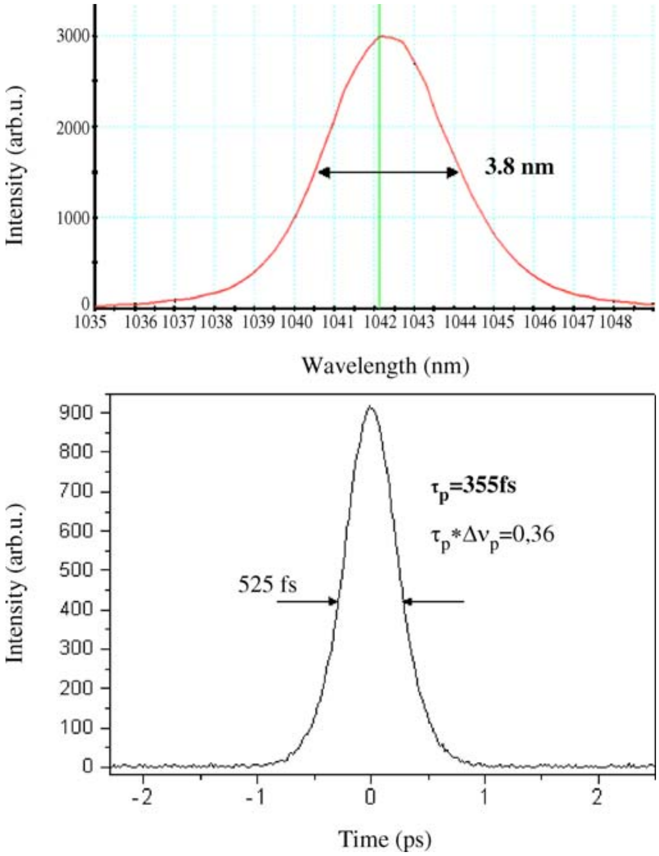

FIGURE 7 Spectrum and autocorrelation trace for passive mode-locking operation using a 1% output coupler

over, the self-phase-modulation can be increased by adding an AR-coated glass plate in or close to an intracavity beam focus.

5 Conclusion

In conclusion, we have demonstrated for the first time Q-switched and mode-locked laser operation of the $Li_6Y(BO_3)_3:Yb^{3+}$ crystal showing the interesting potential of this material for high energy and short pulse generation. Pulse energies up to 140 μJ have been extracted in Q-switched operation and pulse durations as short as 355 fs have been obtained in passive mode-locking. The average power and the extraction efficiency can be considerably improved by optimizing the AR-coating of the crystal. These results show that this Yb-doped borate-compound is a very interesting material for high energy laser amplifier systems in the femtosecond regime.

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