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Passive Q-switching at 1.54 μm of an Er–Yb: $GdCa_4O(BO_3)_3$ laser with a Co^{2+}: $MgAl_2O_4$ saturable absorber

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ABSTRACT We report, for the first time to our knowledge, efficient passive Q-switching of the 1.54-μm laser transition in an Er–Yb-doped crystalline medium. The laser configuration is a compact microchip design that is suitable for a range of practical applications such as range finding and lidar. The slope efficiency of 11.6%, pulse duration of 5–6 ns and average output power of 88 mW are all comparable with standard Er–Yb:glass lasers.

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1 Background

The family of $LnCa_4O(BO_3)_3$ (Ln = Y, La, Gd) crystals has proven to be interesting nonlinear optical materials as well as hosts for Nd- and Yb-activated lasers [1, 2]. Recently, 1.5-μm laser action has also been obtained in Er–Yb co-doped $YCa_4O(BO_3)_3$ (YCOB) [3] and $GdCa_4O(BO_3)_3$ (GdCOB) crystals [4]. The latter two papers are the first demonstrations of 1.5-μm laser action in Er–Yb crystalline media where slope efficiencies close to that of Er–Yb:glass lasers were obtained [5]. This is due to efficient energy transfer to the Er^{3+} upper laser level in these crystals. The main advantage of crystalline hosts over Er–Yb glasses is the higher thermal conductivity, which leads to a higher thermal damage threshold and potentially higher output powers. The thermal conductivity of non-activated GdCOB was reported as 2.18, 1.32 and 2.40 W/(m K) in the different dielectric (crystallophysic) directions X, Y and Z, respectively [6]. The same parameter in an Er–Yb-doped glass that was especially designed for high average power microchip lasers [5] was 0.83 W/(m K). Despite the above-mentioned advantageous properties, the practical realization of high average power laser action in GdCOB crystals meets a number of obstacles. A major one is the multiphonon 1.5-μm luminescence quenching. According to Ref. [7], the room-temperature quantum yield is 15.4%. This corresponds to an upper laser level lifetime of ∼ 1.2 ms only, in comparison to 7–8 ms for phosphate Er–Yb laser glasses. Furthermore, the low quantum yield leads to a high lasing threshold. Another obstacle is the narrow (∼ 2 nm) spectral width of the Yb absorption peak at 975 nm, which can be impractical for diode pumping as the narrow absorption peak requires precise selection and temperature stabilization of the pump diodes.

The reports on LnCOB crystals so far have only dealt with continuous-wave (cw) lasing. Still, most applications of miniature diode-pumped 1.5-μm lasers, such as range finding and lidar, require Q-switched operation. Even for Er–Yb-doped crystalline hosts in general, we have not been able to find any investigations of passively Q-switched operation. For erbium glass lasers on the other hand, Co^{2+}:$MgAl_2O_4$ (Co:MALO or spinel) is well known to be an efficient passive Q-switching material [8]. Er–Yb:GdCOB shows a smooth emission spectrum in the 1.5-μm range that is rather similar to the spectrum of Er ions in phosphate glasses and with similar values of the cross section. Furthermore, much less green upconversion is visible in the GdCOB crystals than in glass, which could indicate less upconversion losses. This should be an advantage for the high population inversion levels that are common in the Q-switching regime, because the upconversion losses scale as the square of the inversion.

As can be seen from the spectra in Fig. 1, the Co:MALO absorption spectrum peak is close to 1.54 μm, which is the emission spectrum peak of Er–Yb:GdCOB. The value of the absorption cross section at this peak is about $3.5 \times 10^{-19}\,\mathrm{cm}^2$, which is more than a magnitude higher than the emission cross section of Er in GdCOB. This enables Q-switching without intracavity focusing, which in turn enables a compact microchip configuration. At the same time, the excited-state absorption cross section is relatively low at this wavelength (σ_{ESA} at 1.54 μm $= 1 \times 10^{-20}\,\mathrm{cm}^2$) [9], a fact that further reduces losses. The relaxation time of the bleached state in Co:MALO was measured by Yumashev to be ∼ 350 ns [9]. Taking all this into account, one can expect that Co:MALO can be used for generating short Q-switched pulses in Er–Yb:GdCOB lasers also.

This paper aims at investigating the possibilities for Q-switching of Er–Yb:GdCOB crystals by use of Co:MALO

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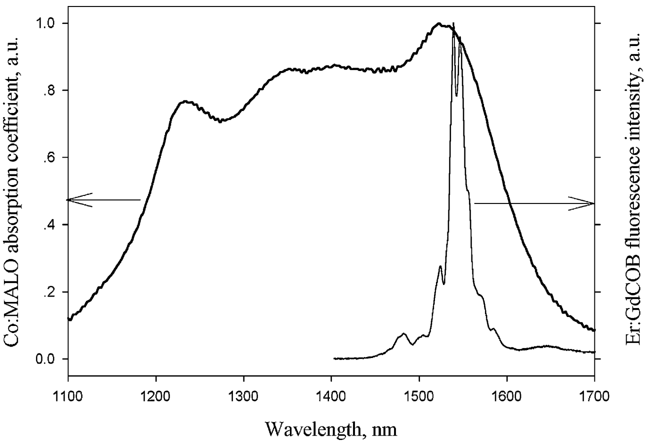

FIGURE 1 The emission spectrum of Er–Yb-doped GdCOB and the absorption spectrum of MALO

crystals as saturable absorbers. Especially, the comparison with glass laser performance is of interest. The main question is to what extent a crystalline host can compete with glass in terms of efficiency and output power in a miniature microchip laser emitting Q-switched pulses of a few nanoseconds duration and several hundreds of watts in peak power. Such a laser configuration is of great interest for a number of applications such as range finding and lidar. Another question is if it might even be possible to achieve higher average output powers than in glass due to the higher thermal conductivity in the crystal.

2 Design of the experimental set-up

The experiments were performed using 6-mm-diameter Er–Yb:GdCOB microchip crystals with a thickness of 1.5 mm, polished with flat parallel surfaces. The crystals were grown by the Czochralski method from platinum crucibles in air. The growth direction was [0 1 0] and the microchips were cut perpendicular to the growth direction. The dopant concentrations in the melt were 28 at.% Yb ($\sim 1.2 \times 10^{21}$ cm^{-3}) and 2.5 at.% Er ($\sim 1 \times 10^{20}$ cm^{-3}), respectively. A high Yb concentration was chosen in order to have a high absorption. The short lifetime of the $^4I_{11/2}$ energy level in Er inhibits energy back-transfer despite this high Yb doping. The input side of the crystal was high-reflection coated for the lasing wavelength around 1.54 μm and transmitted $\sim$ 90% of the pump light at 0.975 μm. The opposite side was uncoated but in optical contact with a 6-mm-diameter Co:MALO plate, which was also polished to optical finish. This Co:MALO plate was 0.7-mm thick, rendering a single-pass saturable loss of 2%. The unsaturable insertion loss due to Fresnel reflections should be negligible because the refractive index of Co:MALO ($n \approx 1.7$) roughly equals the refractive index of GdCOB. The opposite side of the Co:MALO crystal was coated as an output coupler with 97.5% reflection at the lasing wavelength while transmitting $\sim$ 90% of the pump light, for single-pass pumping, to avoid back reflections into the pump diode. This microchip assembly was mounted using indium-foil gaskets in a copper heat sink consisting of two copper plates on opposite sides of the assembly. The copper plates had 3-mm-diameter holes for the pump and laser beams to pass through.

The pump laser was a laser diode system from LIMO GmbH (HLU25D/100-978/KTH1). This laser system consisted of a diode bar without any fiber coupling and a set of optics that was designed to focus the diode-bar emission into a slightly elliptical spot of 97 μm × 95 μm (FWHM) or 125 μm × 175 μm ($1/e^2$). The microchip assembly was positioned so that the pump laser focus was centered in the Er–Yb:GdCOB crystal. The designed emission wavelength was 978 nm with a spectral width of 2.4 nm (FWHM) but could be temperature tuned to coincide with the absorption center of Yb close to 975 nm. This resulted in an absorption of 67% of the incident power in the crystal and a maximum absorbed peak power of just above 5.7 W. The diode system was operated in quasi-continuous-wave (quasi-cw) regime with square pulses of 1–2-ms duration and variable pulse-repetition rate. In this paper, the absorbed power during the pulses is referred to as the absorbed peak power while the term ‘absorbed average power’ refers to the absorbed energy per second from the repetitive pump pulses.

3 Free-running laser performance of Er–Yb:GdCOB

In the free-running regime, Er–Yb:GdCOB crystals have been evaluated earlier under continuous-wave (cw) Ti:sapphire pumping, continuous-wave diode pumping and pulsed diode pumping [4]. Continuous-wave Ti:sapphire pumping and pulsed diode pumping achieved slope efficiencies of 14–15% and an average output power of 80 mW that was limited by available pump power. Continuous-wave diode pumping produced a slope efficiency of 7% only, presumably because in this case there was no way to control the thermal lens. The thresholds were relatively high, around 750 mW of absorbed power. This is mostly due to the short lifetime of the $I_{13/2}$ energy level of Er in GdCOB.

The set-up used in this paper is quite similar to those used in the earlier work. The difference is a larger output coupling, R = 97.5% instead of R = 98%, and a somewhat larger focus of the pump beam that is also slightly elliptical as opposed to circular in shape. This should give a slightly increased threshold as compared with the earlier work, but otherwise the free-running performance should be about the same. However, as the output coupler in our set-up was coated on to the MALO crystal, we had no possibility to measure the free-running performance directly.

4 Q-switched laser performance of Er–Yb:GdCOB

With the set-up described in Sect. 2, an irregular train of Q-switched pulses was obtained. The duration of the individual Q-switched pulses varied between 5 and 6 ns, attributed to shifting thermal conditions and different output modes. The pulse energy also varied but was in the order of 2.8 ± 0.3 μJ, with a resulting peak power of $\sim$ 0.5 kW. Pulse duration and energy remained at these levels at all pump powers. Due to the irregularity of the pulse train, the time interval between adjacent pulses varies and it is difficult to speak of a true repetition rate. An average repetition rate is best calculated from pulse energy and output power.

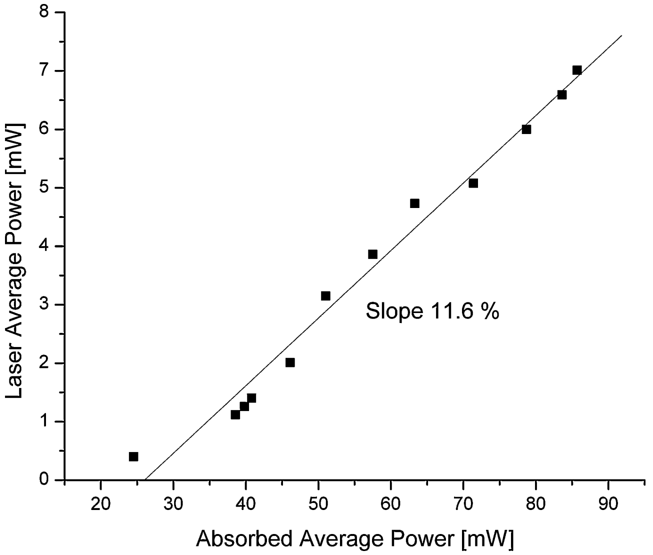

FIGURE 2 The input–output characteristics of the Q-switched laser when altering pump peak power at constant pump pulse frequency

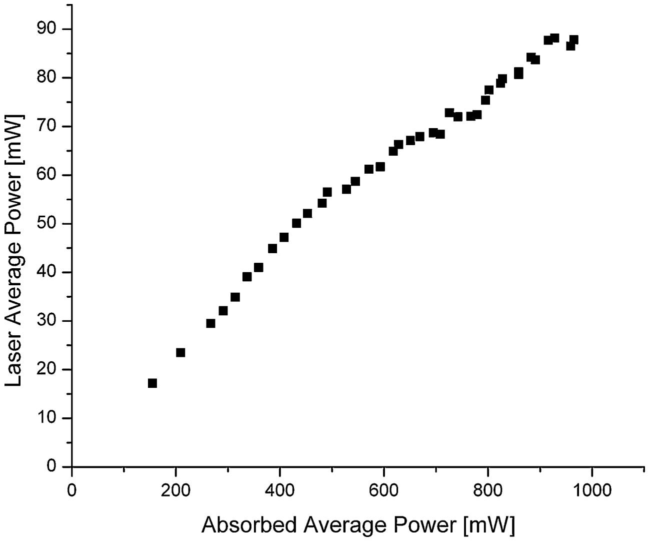

FIGURE 3 The input–output characteristics of the Q-switched laser when altering pump pulse frequency at constant pump peak power

The emission was centered around 1538 nm with a FWHM line width of 2 nm. The anisotropy of the gain in different polarization directions in GdCOB is significant enough to give polarized output in the free-running regime. In the Q-switched regime, however, both polarization directions are lasing simultaneously and polarized output could not be achieved. Still, the different polarization directions showed different mode structures. Another polarization feature is that the different polarization states of different Q-switched spikes experience different gains. This contributed to the variations in pulse energy and duration between the individual spikes of the pulse train.

The laser input–output characteristic for quasi-cw pumping is plotted in Fig. 2. This measurement was taken at a constant pump pulse duration of 1 ms and a repetition rate of 15 Hz, while the absorbed peak power was stepwise increased from zero to 5.7 W. As measured from the figure, the slope efficiency is 11.6%, which compares well with the data for Q-switched Er–Yb:glass lasers. The absorbed peak power at threshold was found to be 1.65 W, which corresponds to 25 mW of absorbed average power. The average repetition rate reached 100 kHz at 60 mW of absorbed average power and the maximum average output power was 7 mW at 85.7 mW of average pump power. This corresponds to an absolute efficiency of 8.2%.

A second input–output experiment had the purpose of estimating the maximum average power that is obtainable from a GdCOB crystal in the passively Q-switched regime. In this experiment the pump pulse duration was fixed at 2 ms and the absorbed peak power at 5.2 W. The pump repetition rate was increased from 20 Hz to 100 Hz, where the crystal fractured. Figure 3 represents the dependence of the laser average power on the absorbed average power. The figure shows a linear dependence on input power for absorbed average powers lower than ~ 500 mW, corresponding to laser average powers of less than ~ 55 mW. After this point the thermal effects degrade the performance of the crystal until it finally fractures at an average absorbed pump power of ~ 1 W. The maximum output power, 88.2 mW, was achieved at 928 mW of absorbed average power. This first demonstration of passive Q-switched laser action in a crystalline Er–Yb microchip laser is thus comparable to glass lasers in average output power. The amount of absorbed average power at fracture is also comparable to glass lasers. Because a higher thermal conductivity should give lower steady-state temperature gradients in the crystal, it seems that the fracture limit of GdCOB might be lower than in glass. One possible reason for this could be the significant anisotropy of the thermal expansion coefficients in the crystal. These coefficients are 10.2×10^{-6}, 8.3×10^{-6} and $14.3 \times 10^{-6}\,K^{-1}$ in the a, b and c crystallographic directions, respectively [6], which are also slightly higher than in glass. The maximum amount of absorbed power prevented continuous-wave pumping in the Q-switched regime.

In another experimental design aiming at shorter, more intense pulses a Co:MALO plate with 3% single-pass saturable loss was used. With this set-up the pulse duration dropped to about 1.6 ns FWHM. Unfortunately, the high peak power of these pulses damaged the partially reflective coating on the Co:MALO plate. However, no damage to any of the crystals could be seen and the coating on the GdCOB surface also seemed to be in good condition. When the Co:MALO plate was translated so that the laser spot hit a fresh area of the coating, it was damaged again and we believe that the coating on the Co:MALO surface was not of acceptable quality.

5 Conclusions

We have demonstrated Q-switched lasing of an Er–Yb:GdCOB microchip laser using a Co:MALO crystal as the passive Q-switch. To the best of our knowledge this is the first demonstration of passively Q-switched laser action in crystalline Er–Yb microchip lasers.

The lasing threshold is higher than for Er–Yb phosphate glass, but using a quasi-cw high power pump system this drawback can be overcome. Important properties such as the pulse duration, average output power, slope efficiency and absolute efficiency are comparable to those of Er–Yb:glass lasers in the compact microchip configuration used in this report. Furthermore, some polarization effects could be seen even though the gain anisotropy was not enough for complete polarization of the output. The high threshold calls for high pump power, which in turn means a high-power diode system, normally resulting in a low-quality focus that is either large or highly divergent. Either case makes it difficult to achieve a single-mode, single-polarization and single-frequency output in a compact configuration.

Even though the thermal conductivity is higher than in glass, it seems that the maximum amount of absorbed average power is about the same. It seems reasonable that anisotropy of the thermal expansion coefficients in combination with higher absolute values of said coefficients lead to a lower thermal fracture limit compared to glass. This limit countered the effect of a higher thermal conductivity and inhibited continuous-wave pumping in the Q-switched regime.

The results show that the performance of the Er–Yb:GdCOB and Co:MALO microchip configuration is primarily limited by the high threshold in combination with the thermal fracture limit of the GdCOB crystal. A solution that could increase performance would therefore be to decrease the Er content of the crystal. The Yb → Er energy transfer in GdCOB has proved to be very efficient and a decrease of the Er concentration to about 1.5% or even less would probably not change this fact significantly. On the other hand, the 1.54-μm lasing transition in erbium is close to a true three-level system, which means that reabsorption losses would drop significantly and the threshold would be reduced.

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