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New green self-frequency-doubling diode-pumped Nd:$Ca_4GdO(BO_3)_3$ laser

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Abstract. Results on green laser performances are reported for a new efficient self-frequency-doubling (SFD) oxoborate crystal: Nd^{3+}:$Ca_4GdO(BO_3)_3$ (Nd:GdCOB). 21 mW of green cw laser emission for an absorbed pump power of 820 mW were achieved under laser diode-pumping. 64 mW of green cw laser output were obtained with 1 W of absorbed pump power under titanium-sapphire pumping. Its availability in large-size crystals with good optical quality makes Nd:GdCOB a true challenger to the best SFD laser crystal reported so far: Nd:$YAl_3(BO_3)_4$ (Nd:YAB or NYAB).

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During the last years, there has been a great interest in nonlinear optical materials. These materials have contributed to the broadening of the available laser wavelengths by frequency conversion. For example, the infrared laser emission of Nd:YAG can be converted into visible laser emission. The simplest way to produce a visible laser beam through second-harmonic generation would be the use of SFD laser materials. Then, these lasers would be more compact and low cost. Up to now, NYAB [1] was the only efficient system reported to produce cw self-frequency-doubling in the green spectral region. Unfortunately, NYAB shows significant self-absorption at the second-harmonic wavelength. Efforts to overcome this drawback have led to undesirable effects such as difficulties in growing large crystals of good optical quality, free of impurities, or to a reduction of the Nd ion concentration. Recently, self-frequency-doubling under Ti:sapphire pumping has been observed in a nonlinear crystal called GdCOB ($Ca_4GdO(BO_3)_3$) [2–4] doped with neodymium ions [5]. More recently, Nd:YCOB [6], Yb:YCOB [7], and Yb:GdCOB [8] have shown the same property, always under Ti:sapphire pumping. In this paper, we present what is, to our knowledge, the first self-frequency doubling diode-pumped Nd:GdCOB laser [9].

1 Nd:GdCOB properties

GdCOB belongs to the calcium rare-earth oxoborate family and crystallizes in a monoclinic biaxial crystal system. Its lattice parameters are: $a = 0.8095(7)$ nm, $b = 1.6018(6)$ nm, $c = 0.3558(8)$ nm. It belongs to the Cm space group and the number of formula units is $Z = 2$. GdCOB melts congruently at 1480 °C so the Czochralski pulling method is employed to grow large single crystals (up to 50 mm in diameter and 120 mm long) with good optical quality. It is absolutely insensitive to moisture and exhibits easy cutting and polishing. Gd^{3+} ions can be substituted by different lanthanide ions such as Nd^{3+} or Yb^{3+} in order to obtain an optical amplifier. This work focuses on a Nd^{3+}-doped GdCOB crystal and presents the results under laser diode-pumping for the neodymium infrared laser emission at 1061 nm and its second-harmonic generation at 530.5 nm. For the sake of comparison, some laser experiments were also performed under Ti:sapphire pumping.

The nonlinear properties of GdCOB are comparable to those of LBO. Second-harmonic generation of the 1061-nm laser emission of Nd ions is allowed only for type I phase-matching in the ZX ($\phi = 0°$, $\theta = 19.7°$) and XY ($\phi = 90°$, $\theta = 46°$) principal planes [4]. The nonlinear coefficients in the ZX and XY planes are around 1 pm/V and 0.5 pm/V, respectively. The angular acceptance is 2.2 mrad cm. Nd-doped GdCOB crystal has the following emission and absorption cross sections for the three crystallophysic axes x, y, and z: $\sigma_e\ (x, 1061\,\text{nm}) = 4.2 \times 10^{-20}\,\text{cm}^2$, $\sigma_e\ (y, 1061\,\text{nm}) = 2.1 \times 10^{-20}\,\text{cm}^2$, $\sigma_e\ (z, 1061\,\text{nm}) = 1.9 \times 10^{-20}\,\text{cm}^2$, and $\sigma_\text{abs}\ (x, 812\,\text{nm}) = 2.3 \times 10^{-20}\,\text{cm}^2$, $\sigma_\text{abs}\ (y, 812\,\text{nm}) = 1.57 \times 10^{-20}\,\text{cm}^2$, $\sigma_\text{abs}\ (z, 812\,\text{nm}) = 1.86 \times 10^{-20}\,\text{cm}^2$ [5]. The fluorescence lifetime of Nd ions in GdCOB is 98 µs and the damage threshold of the crystal is up to 1 GW/cm^2 with 6-ns pulses at 1064 nm.

2 Infrared laser experiments

We have first investigated the infrared performances of this new Nd-doped host under diode-pumping. The experimental setup is illustrated in Fig. 1. The 9.5-mm-long $1.8 \times 10^{20}\,\mathrm{Nd/cm^3}$ doped crystal was pumped at 812 nm with a polarization parallel to the x axis, where the absorption and emission cross section are maximum. The crystal was AR coated at 1064 nm. Only 86% of the pump light was absorbed because of the spectral bandwidth of the laser diode. Nd:GdCOB oscillates preferentially with a polarization parallel to the x axis (maximum emission cross section). Two kinds of cavities have been tested: plano-concave and concave-concave cavities. For each type of laser architecture, three different output couplers were investigated ($T = 0.1\%$, $T = 2\%$, $T = 4\%$). We used an SDL 2362-P1 diode with an emitting surface area of $100\,\mu\mathrm{m} \times 1\,\mu\mathrm{m}$, producing a 1.2-W cw output power at 812 nm. The best results (105-mW cw infrared laser output for an absorbed pump power of 780 mW) were obtained with a concave-concave cavity ($R = 100$ mm). In this configuration, the pump beam waist was measured to be $70\,\mu\mathrm{m} \times 50\,\mu\mathrm{m}$ and the cavity waist is around $70\,\mu\mathrm{m}$. The slope efficiency was 15% and the laser threshold 120 mW (absorbed pump power). In order to estimate the ultimate performances of our crystal, we have pumped it with the diffraction-limited beam of a cw Ti:sapphire laser. In the same experimental conditions (cavity, waist sizes, absorbed pump power), 135-mW cw infrared laser output was obtained with a slope efficiency of 19% and a threshold at 37 mW (absorbed pump power).

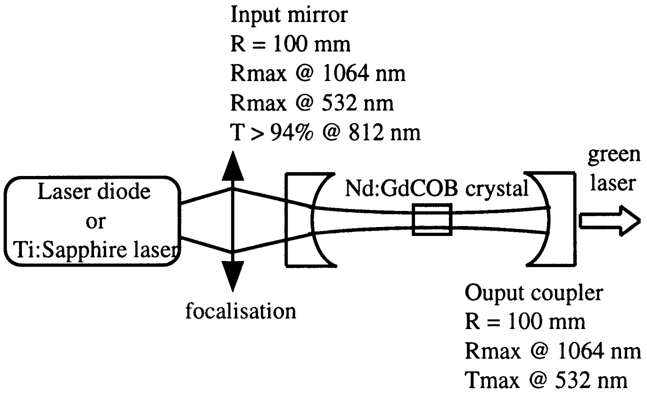

Fig. 1. Experimental setup for laser test for the two schemes of pumping

3 Self-frequency-doubling experiments

These results for infrared laser emission were obtained for pump and laser polarizations parallel to the x axis. But the self-frequency-doubling process can be obtained only for type I phase-matching in ZX and XY planes, i.e. for 1061-nm laser emission polarized along the y or z axis, respectively. If the pump polarization is parallel to the z axis, infrared emission is also polarized along the z axis, whereas y-axis polarized emission has never been observed [5]. So we have investigated the XY configuration and a new crystal, cut with the corresponding phase-matching angles, was needed. This crystal was 8 mm long, AR coated at 1064 and 532 nm and was a $3.2 \times 10^{20}\,\mathrm{Nd/cm^3}$-doped GdCOB. We chose a slightly higher doped crystal to improve the overlap between the pump and cavity modes. 90% of the pump light was then absorbed. Figure 2 shows that the reabsorption cross section at 530.5 nm is remarkably weak: only half of that for a NYAB crystal ($2.28 \times 10^{-21}\,\mathrm{cm^2}$ for Nd:GdCOB versus $4.95 \times 10^{-21}\,\mathrm{cm^2}$ for NYAB). The infrared polarization was along the z axis where the emission cross section was lower than along the x axis. Therefore we have first tested the infrared performances of the new crystal under laser diode-pumping in the same experimental setup as previously. The concave-concave cavity ($R = 100$ mm) with an output coupler of 2% gave us 98 mW at 1061 nm for an absorbed pump power of 780 mW and a laser threshold of 140 mW.

The experimental setup for the self-frequency-doubling process was the same as for infrared tests (cf Fig. 1). The laser emission oscillated at 1061 nm (reflexion coefficient > 99% for both mirrors) in order to get the best conversion efficiency. We tried different kinds of cavities and, as before, the concave-concave one ($R = 100$ mm) gave the best results. A green cw output power of 21 mW for 820 mW absorbed pump power was achieved with a laser threshold of 47 mW. Ti:sapphire pumping gave 64 mW green output for 1 W of absorbed pump power and a threshold of 25 mW. The laser output versus pump power is plotted in Fig. 3.

Comparison between Ti:sapphire and laser diode-pumping results indicated that the GdCOB performances should be improved by the use of a brighter diode. A 500-mW pump laser diode at 812 nm with an emitting surface of $50\,\mu\mathrm{m} \times 1\,\mu\mathrm{m}$ was employed to confirm this hypothesis. In the same experimental conditions (cavity, waist sizes, and 300 mW of absorbed pump power) as for the previous laser diode, 0.67 mW of 530.5-nm emission and a laser threshold of 29 mW have been obtained, whereas only 0.27 mW of 530.5-nm radiation and a threshold of 47 mW were measured with the previous laser diode for the same absorbed pump power.

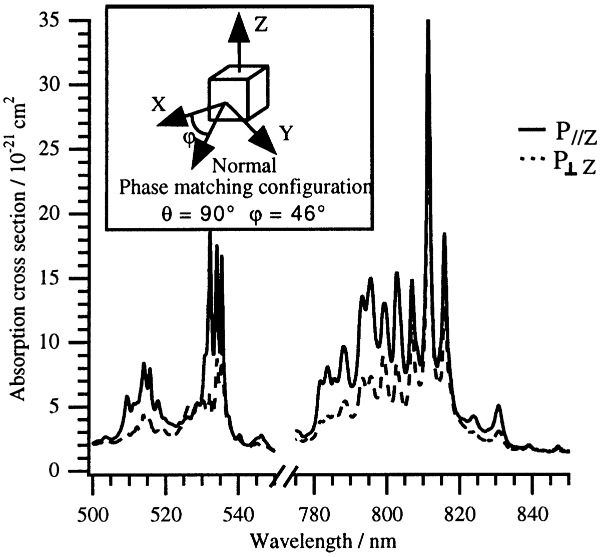

Fig. 2. Absorption cross section for Nd:GdCOB cut in phase-matching direction around the second-harmonic and pump wavelengths

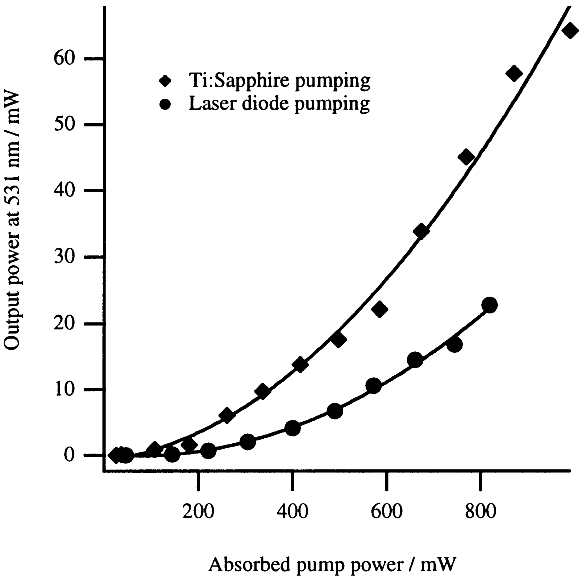

Fig. 3. Output power for the second-harmonic generation versus absorbed pump power

4 Conclusion

We have demonstrated that Nd:GdCOB crystal is an efficient self-frequency-doubling diode-pumped laser material. About 21 mW of green laser radiation at 530.5 nm was obtained for 820 mW of 812-nm absorbed power. Even if it is still less efficient than NYAB for self-frequency-doubling, Nd:GdCOB is, to our knowledge, the best substitute for self-frequency-doubling thanks to its good performances and its availability in large-size crystals. It is also a good candidate to realize low-cost microchip lasers emitting in the green. Moreover, phase-matching conditions exist in this crystal for frequency doubling the $^4F_{3/2} \rightarrow {}^4I_{9/2}$ Nd laser line making the Nd:GdCOB crystal a good candidate for a blue self-frequency-doubling laser.

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Note added in proof

Very recent experiments gave us 114 mW of 531-nm laser emission for an absorbed pump power of 1250 mW.

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