Efficient and tunable continuous-wave diode-pumped Yb^{3+}:$Ca_4GdO(BO_3)_3$ laser

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A Yb^{3+}:$Ca_4GdO(BO_3)_3$ (Yb:GdCOB) crystal has been diode pumped for the first time to our knowledge. We obtained 47.5% slope efficiency at 6 °C, producing 191 mW of power at 1050 nm, with a 2.4% output coupler. Temperature does not significantly affect the laser performance: At room temperature we still obtained 180 mW of power for the same cavity. We achieved tunability of the Yb:GdCOB laser from 1035 to 1088 nm with a 1.7% output coupler and 100-nm tunability with a low-transmission output coupling ($T = 0.03\%$). © 1999 Optical Society of America

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Diode-pumped solid-state lasers produce efficient laser action and high average power. During recent years the ytterbium ion has found renewed interest, in particular because of the emergence of InGaAs laser diodes as suitable pump sources. The Yb^{3+} ion has numerous advantages. Its simple electronic structure eliminates unwanted processes, such as cross relaxation, upconversion, and excited-state absorption. It offers the possibility of high doping levels without concentration quenching. Its small quantum defects limit thermal problems, and it has a long fluorescence lifetime. Despite its quasi-three-level nature, ytterbium as a dopant for YAG,[1] apatite,[2,3] and glass[4] has been shown to produce efficient cw lasers (even at room temperature), and an efficient tunable femtosecond Yb:glass laser was recently demonstrated.[5]

Recently a new crystal, $Ca_4GdO(BO_3)_3$ (GdCOB), has been developed.[6,7] It has attractive properties compared with other laser hosts when it is doped with ytterbium ions. Its thermal conductivity is twice that of Yb:glass,[8] and the large splitting of the lower laser level strongly limits the reabsorption at the laser wavelength that is usually associated with quasi-three-level lasers. With its broad absorption and emission bandwidths, Yb:GdCOB crystal is an interesting material for use in diode-pumped tunable cw and femtosecond oscillators.

We report what is to our knowledge the first demonstration of a diode-pumped, tunable cw Yb:GdCOB laser. GdCOB is a new material developed in collaboration with the French company Crismatec. GdCOB belongs to the calcium rare-earth oxoborate family. It crystallizes in a monoclinic biaxial crystal system with lattice parameters $a = 0.8095(7)$ nm, $b = 1.6018(6)$ nm, and $c = 0.3558(8)$ nm ($\beta = 101, 17°$). It belongs to the Cm space group, and the number of formula units is $Z = 2$. This crystal has good mechanical properties (hardness of 6.5 on Mohs' scale), permitting easy cutting and polishing, and melts congruently at 1480 °C. In the spectra represented in Fig. 1 we can see a broad absorption band near 901 nm [$\sigma_{abs}(901 \text{ nm}) = 0.5 \times 10^{-20} \text{ cm}^2$, $\Delta\lambda_{abs} = 20$ nm FWHM], which is favorable for diode pumping, and a large emission bandwidth [$\sigma_{em}(1035 \text{ nm}) = 0.46 \times 10^{-20} \text{ cm}^2$, $\Delta\lambda_{em} = 90$ nm], which is a necessary condition for tunability and for production of ultrashort pulses.

Our experimental setup is illustrated in Fig. 2. As the gain material we used various samples of 15-at.% Yb^{3+}-doped GdCOB with cross-sectional areas of 6 mm × 6 mm and lengths of 2, 3, and 4 mm, allowing us to study the influence of the crystal length on laser performance. Each crystal was antireflection coated at 1030 nm. The sample was sandwiched between

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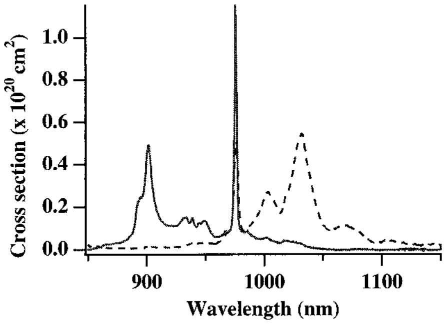

Fig. 1. Yb:GdCOB emission (dashed curve) and absorption (solid curve) spectra.

two copper blocks, and its temperature was controlled by a thermoelectric cooler. With this device we could change the crystal temperature from 6° to 55 °C. The laser host was pumped near 901 nm by a 1.2-W fiber-coupled InGaAs laser diode with a 100-μm-diameter core and a 0.2 numerical aperture. The spectral bandwidth of the diode was ~6 nm. The absorption of the pump light was ~40% for the 2-mm-long crystal, ~56% for the 3-mm-long crystal, and ~60% for the 4-mm-long crystal, which corresponds to an absorption coefficient of 2.7 cm^{-1}.

Several kinds of cavity (plano–concave and concave–concave) were tested with different output couplers (T = 0.1%, T = 1.7%, T = 2.4%, T = 3.2%, and T = 7.2%) and mirrors of different radii of curvature (50 and 100 mm). The best results were obtained for each crystal with plano–concave cavities, and the best output power was obtained with a concave output coupler of 100-mm radius of curvature and a transmission of 2.4% (Fig. 3). The pump waist in the crystal had a 60-μm radius, whereas the cavity waist was estimated to ~50 μm when the cavity was optimized. At 6 °C an output of 191 mW at 1050 nm for 600 mW of absorbed pump power was demonstrated, with a slope efficiency of 47.5% and a 116-mW laser threshold (absorbed pump power) with the 3- and 4-mm-long crystals. Those results are encouraging compared with the performances of Yb:YAG [slope efficiency of 68% (Ref. 9)] and Yb:glass [slope efficiency of 38% (Ref. 5)]. In fact, for a quasi-three-level laser we could find an optimal crystal length L_{opt} to yield a low pump threshold associated with a high output power. This length is a balance between two conditions: if the laser medium is too short, little pump power is absorbed, and we cannot

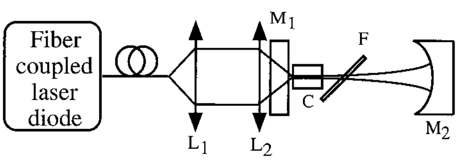

Fig. 2. Diode-pumped Yb:GdCOB laser experimental setup: L_1, L_2, lenses of 60-mm focal length; M_1, plane input mirror, highly reflecting at 1064 nm; M_2, concave output coupler; C, Yb:GdCOB crystal; F, Lyot filter.

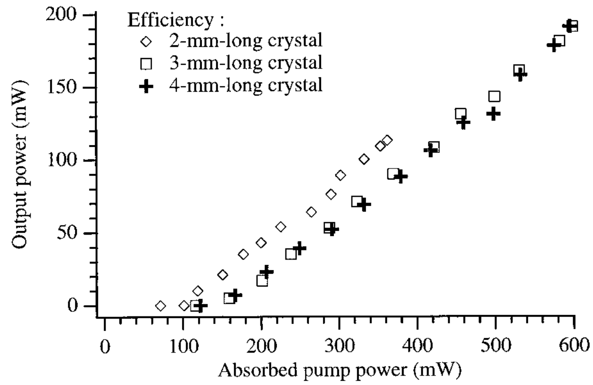

Fig. 3. Output power of the Yb:GdCOB laser versus absorbed pump power for three crystal lengths.

obtain high output power; if it is too long, there is a strong reabsorption of the laser light by Yb^{3+} ions at the ground-state level and an increase of the pump threshold. Several authors[10,11] have established that a good approximation of this length is to take it to be $1/\alpha$, where α is the absorption coefficient. For Yb:GdCOB, L_{opt} should be 3.7 mm. Figure 3 shows similar results for 3- and 4-mm crystals, in agreement with the fact that the optimal length lies between those two values. All the additional results given in this paper apply to the 3-mm-thick crystal.

Internal losses of the laser were determined by the Findlay–Clay method.[12] In this method one calculates losses by measuring the pump power threshold as a function of the output coupler's reflectivity. The internal losses of our crystals were determined to be ~1%/cm.

As Yb:GdCOB is a quasi-three-level laser crystal, the temperature is an important parameter to take into account to optimize the laser performance. The increase in the temperature causes the population inversion to decrease. As illustrated in Fig. 4, increasing the temperature by 50 °C led to a loss of only 30% in the output power and to an increase in the threshold by a factor of 1.6. At room temperature the laser still yielded 180 mW for 600 mW of absorbed pump power with a laser threshold of 150 mW. For

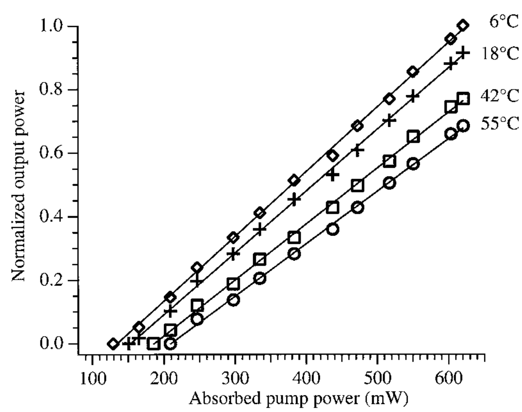

Fig. 4. Output power versus absorbed pump power for four temperatures of the crystal.

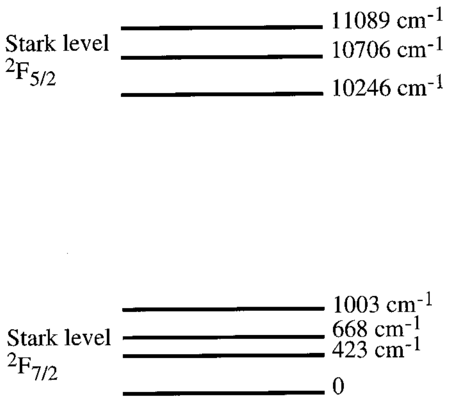

Fig. 5. Stark levels of the Yb^{3+} ^2L_j manifold in GdCOB.

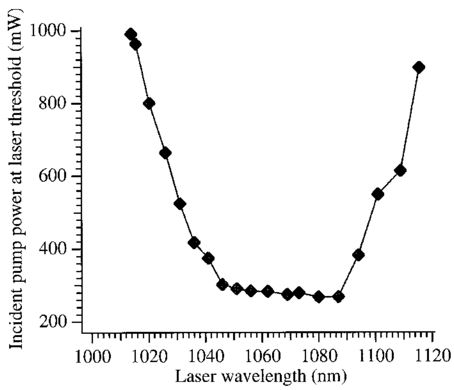

Fig. 7. Influence of laser wavelength on the laser threshold. These measurements were made with a high-reflection output coupler.

Yb:YAG, such a rise in temperature led to a loss of 50% of the performance,[13] whereas the output power of a Yb:S-FAP [$Yb:Sr_5(PO_4)_3F$] laser decreased by 38% when the temperature changed by only 20 °C.[2] The small effect of the temperature on Yb:GdCOB laser performance could be explained by the large splitting of the $^2F_{7/2}$ level. In fact, the lower laser level is the uppermost of four crystal field components of the $^2F_{7/2}$ level and is separated by 1003 cm^{-1} (compared with 628 cm^{-1} for Yb:YAG and ~600 cm^{-1} for Yb:S-FAP) from the lower component of the same level (Fig. 5). The lower laser level population increases with temperature, providing an increase in laser threshold and a decrease in the slope efficiency. In fact, 1003 cm^{-1} is a relatively strong value for a quasi-three-level laser, and it explains the slight effect of temperature on laser efficiency.

We demonstrated the tunability of the Yb:GdCOB laser by inserting a Lyot filter into a plano–concave cavity with a 1.7% output coupler (a 2.4% output coupler did not give good results because of losses induced by the Lyot filter). We achieved a tuning range of 53 nm from 1035 to 1088 nm (Fig. 6), with a maximum output power of 120 mW at 1082 nm. This tuning range, which is smaller than the emission bandwidth, was limited at the shortest wavelengths by reabsorption and by the mirror coatings. Using a high-reflection mirror instead of the output coupler, we observed laser emission from 1013 to 1115 nm. This 100-nm tunability is to our knowledge the largest range obtained in ytterbium-doped crystal, even larger than that reported by Shah *et al.* for Yb:YCOB.[14] The influence of the emission wavelength on the pump power necessary for reaching laser threshold was also studied and is shown in Fig. 7.

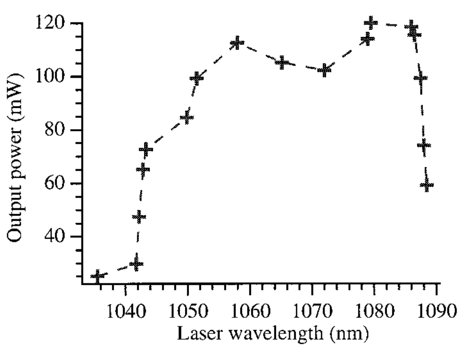

Fig. 6. Output power versus wavelength.

We conducted a preliminary experiment to Q switch the Yb:GdCOB laser. We inserted an acousto-optic modulator into the cavity described previously (Fig. 2). Using a 1.7% output coupler, we obtained an energy of 125 μJ/pulse with a pulse duration of 1 μs at a repetition rate of 200 Hz.

In conclusion, we believe this to be the first demonstration of an efficient, tunable cw diode-pumped Yb:GdCOB laser. Output power of 191 mW was obtained at 6 °C with a slope efficiency of 47.5%. Tunability over a 53-nm range was observed [compared with 46 nm in Yb:YAG (Ref. 15) and 40 nm in Yb: glass (Ref. 5)]. A decrease in performance of only 30% was observed when the crystal temperature rose to 55 °C (compared with 50% for Yb:YAG under the same conditions). Experiments are currently under way to improve the laser efficiency by pumping the crystal at 976 nm, a wavelength at which the absorption cross section is stronger [σ_{abs}(976 nm) = 1.15×10^{-20} cm^2] and the quantum defect is minimal. Research is also under way to develop a femtosecond laser source based on the Yb:GdCOB crystal. Moreover, because of its nonlinear properties, Yb:GdCOB could be an interesting self-frequency-doubling crystal for use in developing a tunable green laser.

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