Appl. Phys. B 68, 1147–1149 (1999) / DOI 10.1007/s003409900006

Applied Physics B
Lasers
and Optics

Rapid communication

Slope efficiency of up to 73% for Yb:$Ca_4YO(BO_3)_3$ crystal laser pumped by a laser diode

H. Zhang[1], X. Meng[1], P. Wang[2], L. Zhu[1], X. Liu[1], R. Cheng[1], J. Dawes[2], P. Dekker[2], S. Zhang[1], L. Sun[1]

[1] National Laboratory of Crystal Materials and Institute of Crystal Materials, Shandong University, Jinan, 250100, P.R. China
(Fax: +86-531/8565-403, E-mail: xlmeng@icm.sdu.edu.cn)
[2] Center for Lasers and Applications, Macquarie University, NSW2109, Australia

Received: 16 December 1998/Revised version: 4 February 1999/Published online: 7 April 1999

Abstract. Yb:$Ca_4YO(BO_3)_3$ (Yb:YCOB) crystal with good quality and large size has been grown by the Czochralski method. The polarization absorption and fluorescence spectra have been measured. The laser action of the Yb:YCOB crystal has been demonstrated when it is pumped by a fiber-coupled laser diode (LD) at the wavelength of 976.4 nm. The pumping threshold is 55 mW, the light-light conversion efficiency is 58.7%, and a slope efficiency of up to 73% is thus calculated.

PACS: 42.55.Rz

The Yb^{3+} ion in a laser host crystal is the simplest example of electronic energy levels in an impurity-doped solid, since Yb possesses only two electronic states: the $^2F_{7/2}$ ground state and the $^2F_{5/2}$ excited state. The two energy levels are split under the crystal field, which means that all Yb lasers are quasi-three-level systems. The Yb-doped crystals display some advantages over Nd-doped crystals: the Yb-doped media generally have longer radiative lifetimes (there is no concentration quenching effect for high Yb doping concentration) and higher quantum efficiency than their counterpart Nd doped materials; the Yb^{3+} ions in the host materials possess no up-conversion effect or excited state absorption, which will greatly reduce thermal effects in the crystal. The absorption peak of Yb^{3+} ions around 970 nm can couple with the wavelength of InGaAs LD (0.9–1.1 μm). These properties of the Yb-doped laser are the motivation for studying the Yb-doped materials [1].

The monoclinic $Ca_4YO(BO_3)_3$ (YCOB) and its family crystal $Ca_4GdO(BO_3)_3$ (GdCOB) are new and efficient nonlinear optical crystals with a large transparent range, high damage threshold and non-hygroscopicity [2, 3]. Their space group is *Cm* [4]. The Y or Gd ions in YCOB or GdCOB crystals can be replaced by Nd^{3+} or Yb^{3+} ions [5–10]. Yb:YCOB crystal laser emission was first reported by Chai et al. in 1998. They pumped a Yb:YCOB crystal with a cw Ti:sapphire laser at the wavelength of 900 nm, and the laser output wavelength centered at 1090 nm was demonstrated with a pumping threshold as high as 370 mW [8].

In the work reported in this letter, we measured the polarization absorption and fluorescence spectra of the Yb:YCOB crystal, determined the Stark energy level diagram of Yb^{3+} ions in the YCOB crystal, demonstrated laser output when the Yb:YCOB crystal was pumped by a fiber-coupled LD at the wavelength of 976.4 nm, and found the slope efficiency of up to 73%.

The Yb:YCOB crystal was grown by the Czochralski method in a 2 kHz radio frequency furnace heating an iridium (Ir) crucible (5.6 cm in diameter and 4 cm high) containing Yb:YCOB polycrystalline material. The growth atmosphere was N_2 or Ar. A b-axis Yb:YCOB single crystal bar with dimensions $3 \times 3 \times 25\ mm^3$ was used as seed. The concentration of Yb doped in the Yb:YCOB polycrystalline material was 20 at %. The pulling rate was 1–4 mm/h, the rotation rate 10–30 rpm. After growth, the crystal was cooled to room temperature at a rate of 200 °C/h. The diameter of the as-grown Yb:YCOB crystal boule is 25 mm, its height 80 mm, and its weight 139 g.

The polarization absorption spectra of the Y-cut Yb:YCOB crystal at room temperature are shown in Fig. 1. From this figure, we can see that there are three main absorption peaks in our measuring range, whose wavelengths are centered at 900 nm, 949 nm and 976.4 nm. The absorption intensity at the wavelength of 976.4 nm is the strongest in the measuring wavelength range. The absorption coefficient is $8.43\ cm^{-1}$. So the LD with 976 nm wavelength is ideal for use as a pumping source for the crystal.

The fluorescence of the Yb:YCOB crystal in the infrared range was recorded by using an optical spectrum analyzer (Anritsu Co. MS9030A). Figure 2 shows the polarization fluorescence spectra of Yb:YCOB when the crystal is pumped by a LD with the wavelength of 963 nm. From Fig. 2 we can see that there are five peaks in the fluorescence spectrum of Yb:YCOB crystal from 930 to 1130 nm. The wavelengths of the five peaks are centered at 976.4 nm, 1002 nm, 1019 nm,

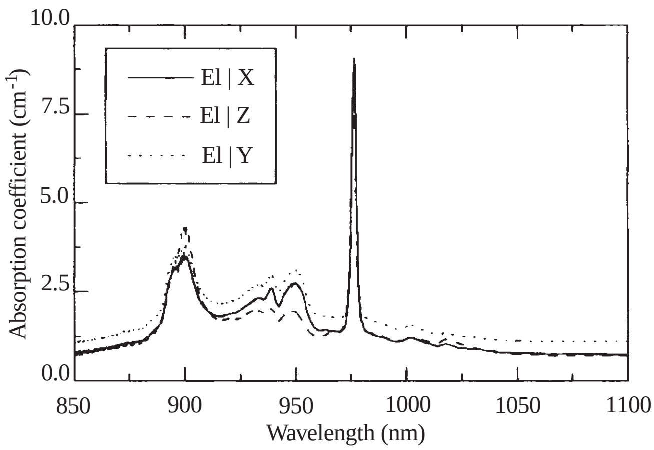

Fig. 1. Polarization absorption spectra of Yb:YCOB crystal

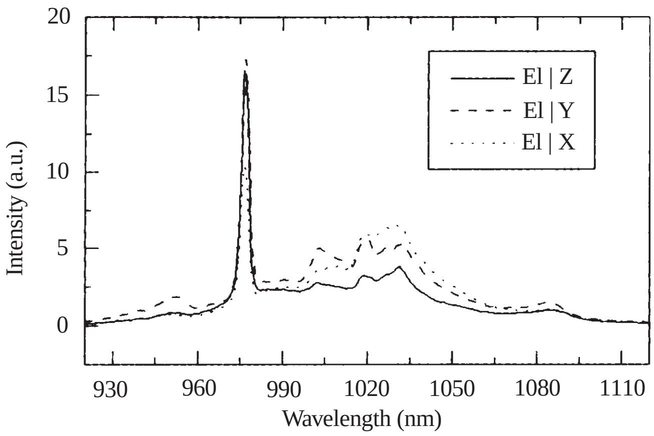

Fig. 2. Polarization fluorescence spectra of Yb:YCOB crystal

1032.4 nm and 1084.7 nm. The peak around 976 nm is the strongest of these, but the wavelength is the same as that of the strongest absorption peak, so this wavelength cannot be used in practice for laser output. The peak around 1032 nm is the second strongest and this is a useful wavelength for laser output. The peak around the wavelength of 1084.7 nm is also useful for laser output.

The fluorescence lifetime of the upper level of 20 at % Yb^{3+} ions in Yb:YCOB is measured to be 2.28 ms when the Yb:YCOB crystal is pumped by a pulsed LD. The lifetime is much longer than that in Nd:YCOB crystal (96 μs for Nd doping concentration of 5 at %).

The Stark energy level of the Yb^{3+} ion in YCOB is determined by the absorption and fluorescence spectra. Figure 3 shows the Stark energy level diagram of the $^2F_{5/2}$ and $^2F_{7/2}$ manifold of the Yb^{3+} ion in YCOB at room temperature.

A Y-cut crystal sample (1.86 mm) was used for the laser experiment. Pumping light of a 1.6 W fiber-coupled LD at the wavelength of 977 nm was tuned to 976.4 nm by controlling the temperature. The crystal temperature was controlled by a Peltier cooler. A plane-concave cavity was used in this optical system. The flat input mirror was coated for a high reflectivity (HR > 99.5%) at 1030–1100 nm and its transmission was 92% at 976 nm. The output coupler had a 1 cm radius of curvature, and transmission at 1030–1100 nm was 1.6%.

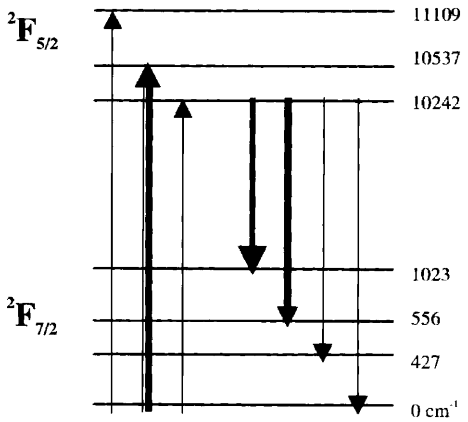

Fig. 3. The Stark energy level diagram of the $^2F_{5/2}$ and $^2F_{7/2}$ manifold of the Yb^{3+} ion in YCOB

Figure 4 shows the fundamental output power versus the absorbed power of the Yb:YCOB crystal sample. The pumping threshold power is 55 mW. The highest output power of 446.4 mW is achieved at an absorbed power of 760 mW (because of the power loss of the focussing lens, the uncoated crystal, and the about 66% absorptivity of Yb:YCOB crystal, the highest absorbed power is 760 mW), the light–light conversion efficiency is 58.7% and a slope efficiency of up to 73% is obtained from the fitted line. The wavelength of the output laser is tunable from 1045 to 1090 nm. Our experimental results for the highest output power and slope efficiency are higher than the values of Chai et al. [8] (the highest power is about 140 mW, and the slope efficiency is 28.6%). Our pumping threshold (55 mW) is lower than that of Chai et al. for pumping by cw Ti-sapphire (370 mW).

To improve the laser performance of the Yb:YCOB crystal, we need to optimize the cavity design, for example, by adding HR and AR (anti-reflection) coating on the crystal, and by optimizing the curvature and transmission of the output coupler and the crystal length. If the cavity design is optimized, better results for the laser output will be obtained.

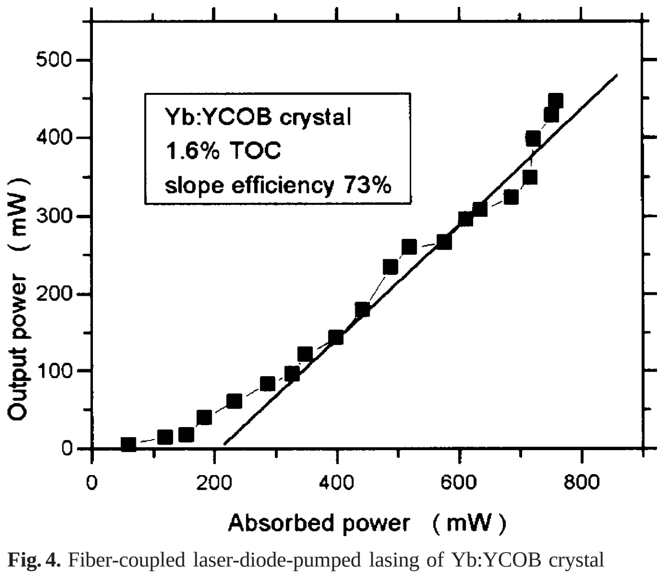

Fig. 4. Fiber-coupled laser-diode-pumped lasing of Yb:YCOB crystal

The broad output wavelength range shows that the Yb:YCOB crystal may be used in a tunable laser.

In conclusion, Yb:YCOB crystals with good quality and large sizes can be grown easily by the Czochralski method. Spectral and laser experimental results show that the YB:YCOB crystal is a potential Yb-doped laser material.

References

1. L.D. DeLoach, S.A. Payne, L.L. Chase, L.K. Smith, W.L. Kway, W.F. Krupke: IEEE J. Quantum Electron. **QE-29**, 1179 (1993)
2. M. Iwai, T. Kobayshi, H. Furuya, Y. Mori, T. Sasaki: Jpn. J. Appl. Phys. **36** (Pt.2, 3A) L276 (1997)
3. G. Aka, A. Kahn-Harari, F. Mougel, D. Vivien, F. Salin, P. Coquelin, P. Colin, D. Pelence, J.P. Damelet: J. Opt. Soc. Am. B **14**, 2238 (1997)
4. R. Norrestam, M. Nygren, J.-O. Bovin: Chem. Mater. **4**, 737 (1992)
5. F. Mougel, G. Aka, A. Kahn-Harari, H. Hubert, J.M. Benitez, D. Vivien: Opt. Mater. **8**, 161 (1997)
6. G. Aka, A. Kahn-Harari, D. Vivien, J.-M. Benitez, F. Salin, J. Godard: Eur. J. Solid State Inorg. Chem. **33**, 727 (1996)
7. M. Martrou, F. Mougel, G. Aka, A. Kahn-Harari, D. Vivien, B. Viana: OSA Topical Conference on Advanced Solid State Lasers (1998) 158/AMFI-1
8. B.H.T. Chai, D.A. Hammons, J.M. Eichenholz, Q. Ye, W.K. Jang, L. Shah, G.M. Luntz, M. Richardson, H. Qiu: OSA Topical Conference on Adv. Solid State Lasers (1998) p. 11–2
9. F. Auge, F. Mougel, G. Aka, A. Kahn-Harari, D. Vivien, F. Balembois, P. Geoges, A. Brun: in Conference on Lasers and Electro-Optics, 1998 Technical Digest Series, CLEO'98, San Francisco, CThA5, 324 (1998)
10. B.H.T. Chai, I Eichenholz, Q. Ye, W.K. Jang, M. Richardson: in Conference on Lasers and Electro-Optics, 1998 Technical Digest Series, CLEO'98, San Francisco, CThA6, 325 (1998)