15 November 1998

OPTICS COMMUNICATIONS

ELSEVIER

Optics Communications 156 (1998) 327–330

Laser action in Yb^{3+}:YCOB ($Yb^{3+}:YCa_4O(BO_3)_3$)

D.A. Hammons [a], J.M. Eichenholz [a], Q. Ye [a], B.H.T. Chai [a,b], L. Shah [a], R.E. Peale [a], M. Richardson [a,*], H. Qiu [b]

[a] *Center for Research and Education of Optics and Lasers, University of Central Florida, 4000 Central Florida Blvd., Orlando, FL 32816-2700, USA*

[b] *Crystal Photonics Inc., 3403 Technological Ave., Suite 14, Orlando, FL 32817, USA*

Received 12 June 1998; revised 18 August 1998; accepted 18 August 1998

Abstract

Infrared laser action in Yb^{3+}:YCOB ($Yb^{3+}:YCa_4O(BO_3)_3$) is reported for the first time. Maximum output powers of ~ 300 mW with a slope efficiency of 35.8% have been obtained. The observation of self-frequency doubling in this material is also reported. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: Infrared laser; $Yb^{3+}:YCa_4O(BO_3)_3$; Self-frequency doubling

1. Introduction

Ytterbium-ion doped solid-state lasers have received considerable attention because their favorable spectroscopic properties could lead to compact high average power diode pumped laser systems emitting either tunable or ultrashort infrared radiation. Laser action has been demonstrated in a number of Yb^{3+}-doped crystals such as YAG [1–5], S-FAP [6], and S-VAP [7] and in Yb^{3+}-doped glasses [8]. Many of these materials have also been diode pumped using InGaAs laser diodes [1], which are ideal for ytterbium's broad absorption band at 900 nm. The Yb^{3+} ion in these materials has a relatively wide fluorescence bandwidth (~ 100 nm), good for both tunable lasers [2,3], and the generation of femtosecond pulses [9,10]. The smaller quantum defect [11] of Yb^{3+}, compared to Nd^{3+}, makes it ideal for high average power lasers [4,5]. In addition, unlike neodymium, ytterbium does not suffer from concentration quenching, a nonradiative relaxation process that adds to thermal loading.

The recent progress in the growth of the rare earth calcium oxyborate [12,13] crystals has now generated a new class of laser materials that can be used as both a laser host and a nonlinear frequency converter. Previous studies have concentrated on $GdCa_4O(BO_3)_3$ (GdCOB) and $YCa_4O(BO_3)_3$ (YCOB) as materials for second harmonic generation [14–16]. Laser action and self-frequency doubling (SFD) has been observed in Nd:GdCOB [14], Nd:YCOB [17], and Yb:$BaCaBO_3F$ [18]. The self-frequency doubling in these materials are comparable to results obtained in Nd:MgO:$LiNbO_3$ [19] and NYAB [20]. The oxyborates have shown significant SFD results without suffering from photorefractive damage as with Nd:MgO:$LiNbO_3$ [19] or suffer from self-absorption at 530 nm as with NYAB [20]. NYAB has also suffered from poor optical quality and small size [20]. SFD action has also been demonstrated in several other crystalline hosts recently [21,22]. In this paper, we report the first experiments with Yb-doped YCOB. Specifically, we report the first laser action in Yb^{3+}:YCOB and the observation of self-frequency doubling.

2. Spectroscopy

The crystals used in this study were grown by the Czochralski technique. Large crystals of Yb:YCOB (3-in.

* Corresponding author. E-mail: mcr@creol.ucf.edu

0030-4018/98/$ - see front matter
PII: S0030-4018(98)00460-X

diameter by 8-in. long) have been grown with no visible inhomogeneities, dislocations or striations. The crystals have relatively high nonlinear coefficients [15,23], high damage thresholds (> 1 GW/cm^2), and good mechanical properties which allow ease in optical polishing. Furthermore these crystals are nonhygroscopic even in boiled water [15]. Since Yb and Y have similar ionic radii, high Yb doping is possible. However, we find that pure YbCOB does not melt congruently. Therefore, we currently limit the Yb doping to 50% or less in the melt. In this study, YCOB doped with 20% Yb in the melt was used. The orthogonal x, y and z optical indicatrix axes are defined relative to the crystallographic axes and planes as shown in Fig. 1, by adopting the traditional refractive index convention $n_x < n_y < n_z$ [17,24].

A Bomem DA8 Fourier-transform spectrometer with inherently-high frequency accuracy (0.004 cm^{-1} at 2000 cm^{-1}), collected polarized absorption and photoluminescence data at a resolution of 16 cm^{-1}. The detector was InGaAs operating at 77 K. Both spectra were measured at room temperature. The photoluminescence excitation was accomplished using a 806 nm laser diode.

The spectroscopic properties of Yb^{3+} in YCOB were measured for prospective laser operation. As with other Yb^{3+}-doped gain media, laser action is based on the one excited 4f manifold, approximately 10 000 cm^{-1} above the ground state [25]. The large vibronic components of the $^2F_{7/2}$–$^2F_{5/2}$ transition give rise to a broad absorption feature at 900 nm and an additional absorption line at 976 nm. The absorption and emission spectra are shown in Fig. 2a and 2b, respectively, for light polarized parallel to the X, Y, and Z axes. The samples were orientated such that each optical indicatrix axis was parallel to the pump beam polarization. The fluorescence spectrum shows multiple emission lines from 950 nm to 1090 nm with the strongest emission feature at 1030 nm. Using a tunable 10 mJ, 30 ns duration, Q-switched Cr:LiSAF$_6$ laser as a 900 nm pump source, the fluorescence decay time was measured to be approximately 3 ms, which is considerably longer than for other oxide crystals.

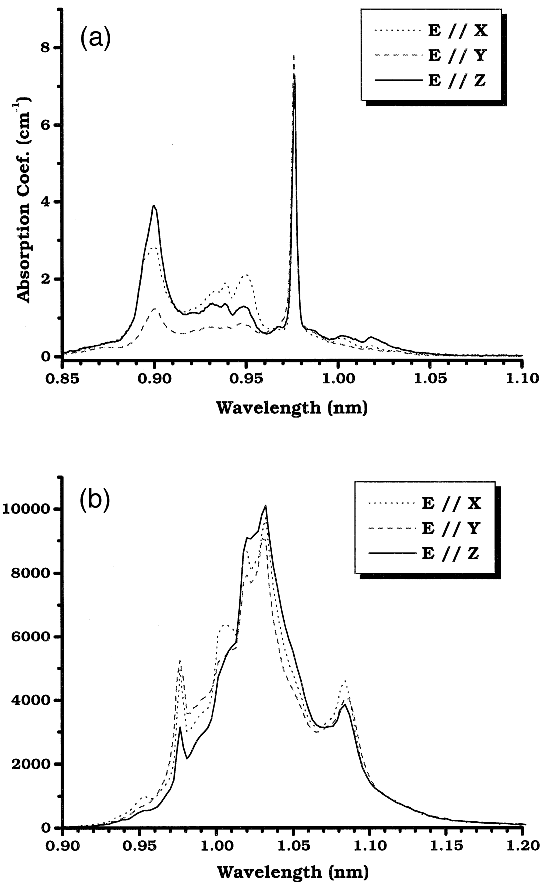

Fig. 2. (a) Polarized absorption spectra of 20% doped Yb^{3+}:YCOB; (b) Polarized emission spectra of 20% doped Yb^{3+}:YCOB.

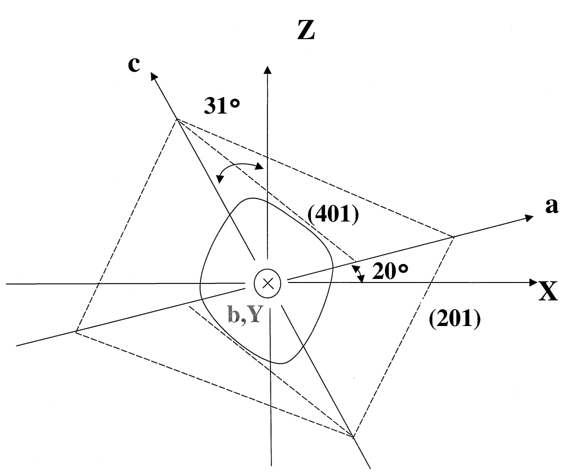

Fig. 1. Orientation of X, Y, Z optical indicatrix axes relative to the crystal axes of Yb:YCOB.

3. Continuous-wave laser operation

We have investigated Yb:YCOB as a laser material in cw operation. The 20% doped Yb YCOB laser rod, mounted on a thermoelectric cooler had a cross-section of 5 mm × 5 mm, a length of 13 mm, and was cut with the x-axis collinear with the laser axis. The pump source consisted of a tunable cw Ti:sapphire capable of 1.5 W of power at 900 nm. The pump source was used to end-pump a hemispherical linear cavity consisting of a 5-m radius of curvature (ROC) high reflector and a 10-cm ROC output coupler. The uncoated Yb:YCOB crystal was placed next

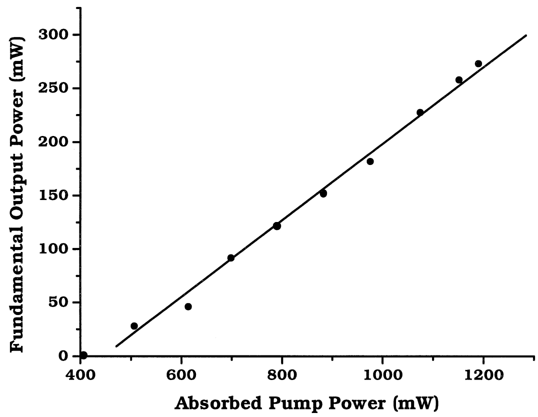

Fig. 3. Laser output power at 1085 nm as a function of absorbed 900 nm pump power in 20% doped Yb^{3+}:YCOB.

to the high reflector. The crystal absorbed more than 90% of the incident pump light. The pump laser polarization was parallel to the Z-axis and focused into the crystal through the rear mirror, which was 95% transparent at 900 nm. The pump beam was focused with a 8.8-cm focal length plano/convex lens to a ~70 μm (FWHM) spot size as measured with a scanning slit beam profiler (Photon Inc.). The cavity waist was approximately 50 μm (FWHM). Fig. 3 shows the observed cw oscillator output power as a function of absorbed pump power. The highest laser slope efficiency of 35.8% was achieved with a 1% transmitting output coupler. The threshold of the absorbed pump power for lasing was 370 mW. The laser emission was weakly polarized. Unexpectedly, laser action was observed at a wavelength of 1090 nm (Fig. 4), instead of at the peak of the fluorescence emission (~1030 nm). We attribute this to a consequence of self-absorption on the short-wavelength side of the emission band. Most probably careful selection of crystal dopant concentration and length

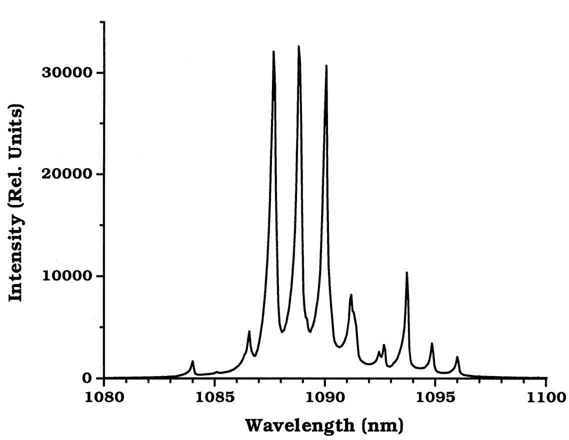

Fig. 4. Spectral lasing emission from a 20% Yb^{3+}:YCOB crystal.

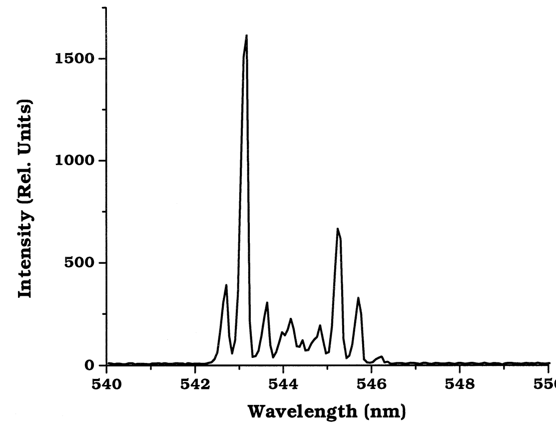

Fig. 5. Laser emission at 540 nm by SFD in Yb^{3+}:YCOB.

will allow laser action across the whole emission band, and the achievement of higher slope efficiencies.

4. Self-frequency doubling

We have also observed self-frequency doubling in Yb:YCOB. The 20% Yb:YCOB crystal used for this test was cut based on the Sellmeir equations of Iwai et al., with the crystal's X-axis at 36.22° to the laser axis, appropriate for phase matching at 1090 nm. The resonator design was identical to that descried above. In order to obtain SFD, the intracavity power density was increased by changing the output coupler to a 10-cm ROC mirror with high reflectivity at 1090 nm ($R > 99.7\%$) and high transmission ($T > 96\%$) at 540 nm. Optimization of the SFD output was attempted by adjusting the angle and hence phase matching the crystal, and by varying the mode size in the crystal by changing the cavity length. Less than 1 mW of 540 nm laser light was obtained with 900 nm of pump power absorbed in the crystal. The SFD emission spectrum in Yb^{3+}:YCOB is shown in Fig. 5. The SFD efficiency was low due to the laser bandwidth being larger than the angular acceptance bandwidth (1.3 mrad cm) [15]. It would improve significantly with the use of a frequency selective element in the cavity to narrow the linewidth of the fundamental emission. We have found Yb:YCOB to be an excellent frequency converter for Nd:YAG laser emission at 1064 nm with conversion efficiencies approaching 40% and an effective nonlinear coefficient of 1.3 pm/V [23].

5. Conclusions

In summary, we report the initial growth, laser action, and self-frequency doubling of Yb^{3+}:YCOB single crystals. Fundamental laser action occurred at 1090 nm with a slope efficiency of 35.8%. Low powered SFD occurred when a high reflector for the fundamental lasing was used. The broadband absorption spectra near 900 nm makes diode pumping a viable and economical option to generating a compact high powered tunable green laser source. Compared to Nd:YCOB, the Yb laser has the advantage of broadband emission which can be used for tunable IR laser systems and short pulse operation in the femtosecond regime.

Acknowledgements

The authors would like to thank G.M. Luntz, W.K. Jang, and Neil Vanasse for their invaluable support. This work was in part supported by the State of Florida.

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