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

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ABSTRACT

Progress in the growth of the rare earth calcium oxyborate crystals has now generated a new class of laser materials that can be used as both a laser host and a nonlinear frequency converter. Laser action and self-frequency doubling (SFD) has been observed with both 10% and 20% Yb^{3+}-doped YCOB crystals. Laser operation was obtained in a hemispherical linear cavity, end-pumped with a tunable cw Ti:Sapphire or a 980 nm laser diode pump source. Under Ti:Sapphire pumping at 900 nm, an output power of 230 mW and a slope efficiency of 29% was obtained using the 10% doped sample. Laser action was seen at 1050 nm. Laser operation of the 20% sample had a maximum output power of ~ 300 mW with a slope efficiency of 35.8% at 1088 nm. Laser action was not obtained at the peak of the fluorescence emission (~1030 nm) in this crystal as a consequence of self-absorption on the short-wavelength side of the emission band. Diode-pumped operation at the narrow absorption peak of 977 nm was achieved and early results show an improved slope efficiency of 34% in comparison to the 10% doped crystal under Ti:Sapphire pumping. We have also observed self-frequency doubling in Yb^{3+}:YCOB. The 20% Yb^{3+}:YCOB crystal used for this test was cut with a phase-matching angle of 36.22°. The self-frequency doubling efficiency was low due to the absence of any frequency selective elements in the cavity to narrow the linewidth of the fundamental emission. The SFD emission occurred at 543 nm.

Keywords: Ytterbium, $YCa_4O(BO_3)_3$, Diode-Pumping, Self-Frequency Doubling, Visible Laser Source

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), which is 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 preferable 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 both as 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^{3+}:GdCOB[14], Nd^{3+}:YCOB[17], and $Yb^{3+}:BaCaBO_3F$[18]. The self-

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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 suffering from self-absorption at 530 nm as with NYAB[20]. NYAB also has 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 experiments with Yb^{3+}-doped YCOB. Specifically, we report the 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^{3+}:YCOB (3" diameter by 8" 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 10% and 20% Yb in the melt was used. The orthogonal x, y and z optical indicatrix axes are defined relative to the crystalographic axes and planes, by adopting the traditional refractive index convention $n_x < n_y < n_z$ [17,24]. A Bomem DA8 Fourier-transform spectrometer with 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 photoluminescence excitation was accomplished using an 806 nm laser diode. An InGaAs detector operating at 77 K was used. Both spectra were measured at room temperature.

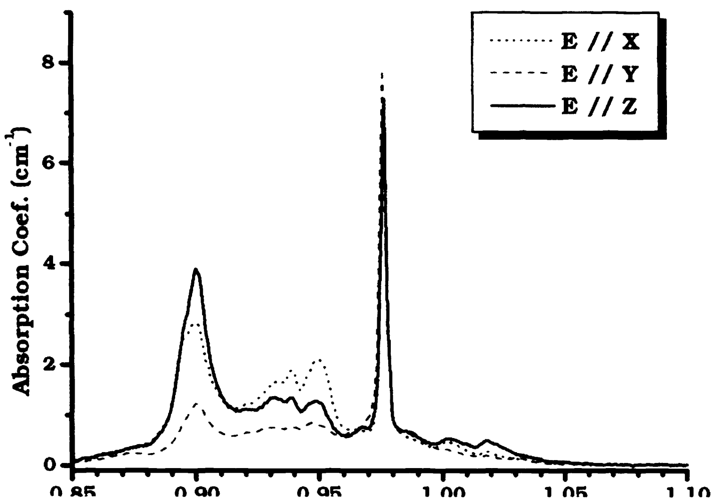

Figure 1. Polarized absorption spectra of 20% doped Yb^{3+}:YCOB.

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 singly 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 gives rise to a broad absorption feature at 900 nm and an additional absorption line at 977 nm. The absorption and emission spectra are shown in Fig. 1 and 2, 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 other oxide crystals.

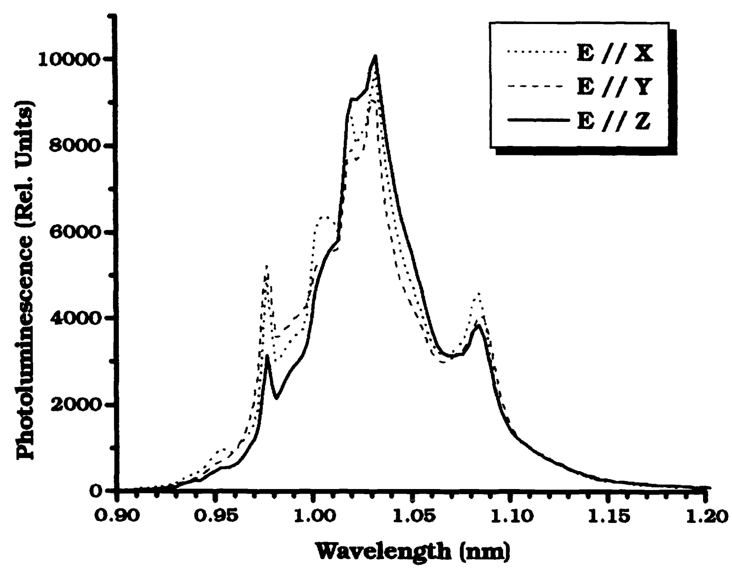

Figure 2 Polarized emission spectra of 20 % doped Yb^{3+}:YCOB.

3. TI:SAPPHIRE-PUMPED CONTINUOUS-WAVE LASER OPERATION

We have investigated Yb^{3+}:YCOB as a laser material in cw operation. The 10 % and 20% doped Yb^{3+}:YCOB laser rod, mounted on a thermoelectric cooler with a cross-section of 5 mm x 5 mm, a length of 13 mm, 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-meter radius of curvature (ROC) high reflector and a 10-cm ROC output coupler. The uncoated Yb^{3+}:YCOB crystal was placed next 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. Using a 1% transmitting output coupler, slope efficiencies of 29% and 36% were achieved for the 10% and 20% doped crystals, respectively.

The threshold of the absorbed pump power for lasing was high with 230 mW and 370 mW for the two samples. In both cases, the laser emission was weakly polarized. Unexpectedly, laser action was observed at longer wavelengths than the peak of the fluorescence emission (~ 1030 nm) for both the 10% and 20% doped media at 1050 nm and 1090 nm, respectively. 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 will allow laser action across the whole emission band, and the achievement of higher slope efficiencies.

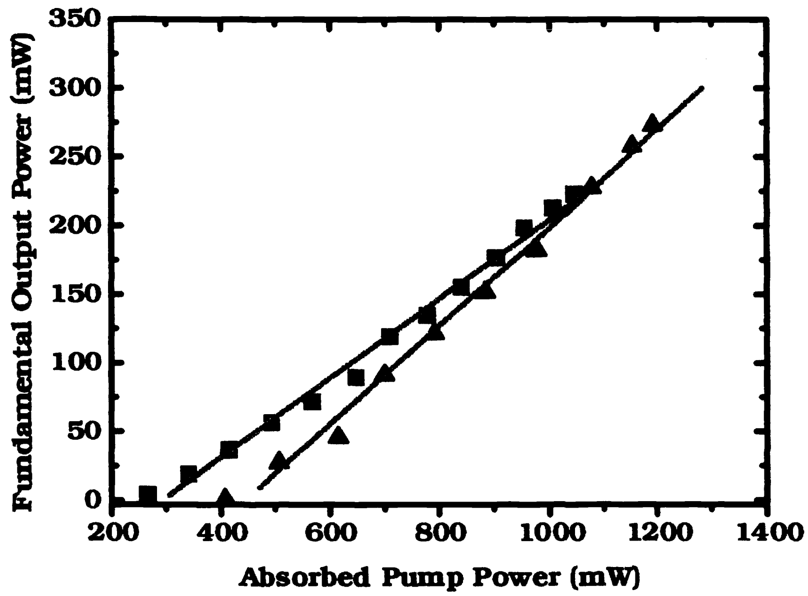

Figure. 3. Laser output power at 1050 nm for 10% doped Yb^{3+}:YCOB (Squares) and laser output power at 1085 nm for a 20% doped Yb^{3+}:YCOB (Triangles) as a function of absorbed 900 nm pump power

4. DIODE-PUMPED CONTINUOUS-WAVE LASER OPERATION

Diode-pumped experiments were performed with a simple laser resonator, similar to the Ti:Sapphire pumped Yb^{3+}:YCOB cavity. The high brightness, AlGaAs laser diode (Polaroid POL-5300 BW) had a maximum output power of 1.6 W from a 100 μm stripe and was centered at a wavelength of 980 nm. The diode was temperature-tuned to match the 977 nm absorption line by cooling the diode to ~15 °C. A 125 mm diameter microlens (anti-reflection coated aspheric lens) was utilized to collect the emission from the laser diode's fast axis and help equalize the divergence from the fast and slow axes. After the micro lens, a 50 mm focal length achromatic doublet lens was used to collect the diverging pump beam. Since the laser diode beam is essentially monochromatic, the achromatic doublet lens was utilized because of its ability to compensate for spherical aberration. After collimation, the pump beam is refocused with a 60 mm focal length Gradium™ plano /convex lens. The measured pump spot size at the crystal was measured to be ~65 μm ($1/e^2$). None of the lenses' antireflection coating was optimized for the 977 nm pump light. Figure 4 shows the setup for the diode-pumped laser experiments.

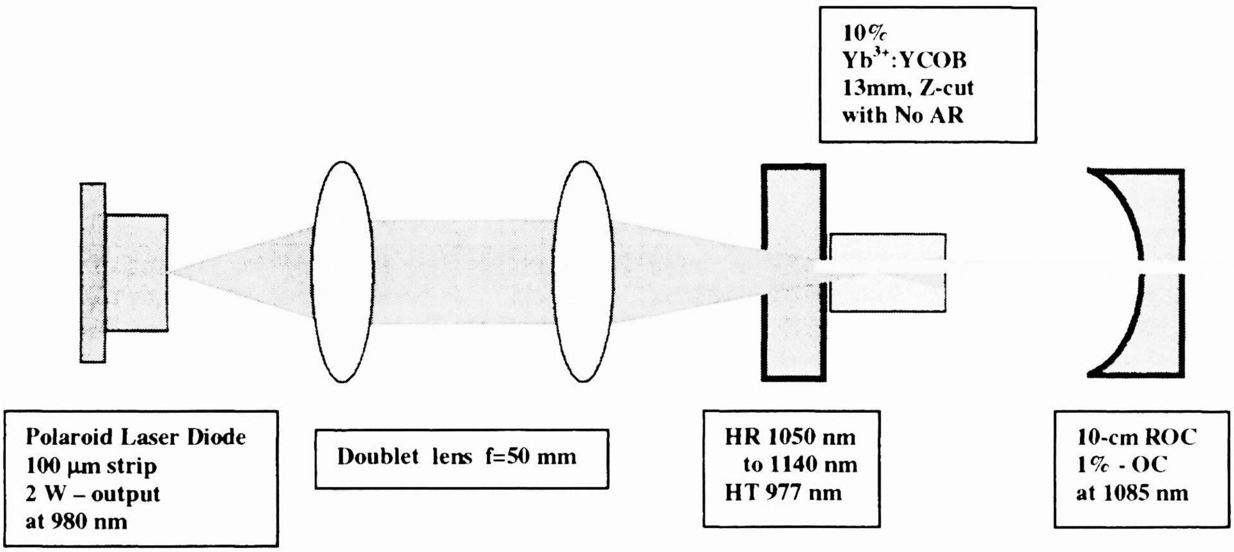

Figure 4. Experimental setup for diode-pumped Yb^{3+}:YCOB laser using a 980 nm diode

The hemispherical laser resonator consisted of a flat, highly reflective rear mirror and a 10-cm radius of curvature output coupler (OC). The 10% Yb^{3+}:YCOB laser rod, mounted on a thermoelectric cooler had a cross-section of 5 mm x 5 mm, a length of 13 mm, and was cut with the x-axis collinear with the laser axis. The uncoated Yb^{3+}:YCOB crystal was placed next to the high reflector. The crystal absorbed approximately 70% of the pump light. The temperature of the crystal was maintained at room temperature (23 °C) with the TE cooler. The pump laser polarization was parallel to the Z-axis and was focused into the crystal through the rear mirror. The rear mirror developed, by Quality Thin Films, was highly reflecting from 1050 - 1150 nm and over 95% transparent at 977 nm. The diode-pumped output power versus the absorbed pump power with 1% OC is shown in Fig. 5. The polarization of the laser output was parallel to the Z-axis. Output powers exceeding 100 mW for 1000 mW of absorbed pump power were obtained with 1% output coupling. The laser wavelength was measured to be 1085 nm, similar to that of the Ti:Sapphire pumped 20% doped Yb^{3+}:YCOB laser which had a center wavelength of 1090 nm. In this case, the lack of reflectivity at wavelengths below 1050 nm caused the laser to operate at longer wavelengths.

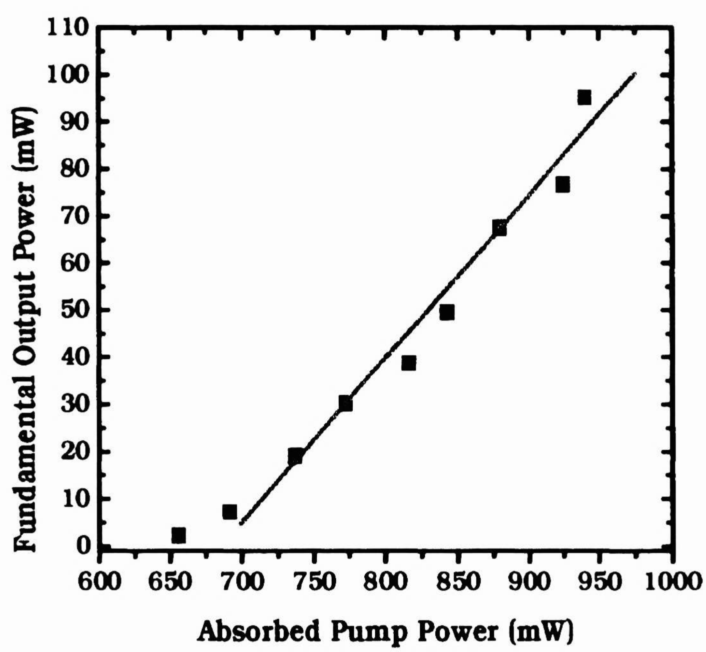

Figure 5. Laser output power at 1085 nm for a 10% doped Yb^{3+}:YCOB as a function of absorbed 977 nm pump power

5. SELF-FREQUENCY DOUBLING

We have also observed self-frequency doubling in Yb^{3+}:YCOB under cw Ti:Sapphire pumping. The 20% Yb^{3+}:YCOB crystal used for this test was cut based on the Sellmeir equations of Iwai et al [15], 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 described 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 of 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. 6. 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^{3+}:YCOB to be an excellent frequency converter for Nd^{3+}:YAG laser emission at 1064 nm with conversion efficiencies approaching 40% and an effective nonlinear coefficient of 1.3 pm/V [23].

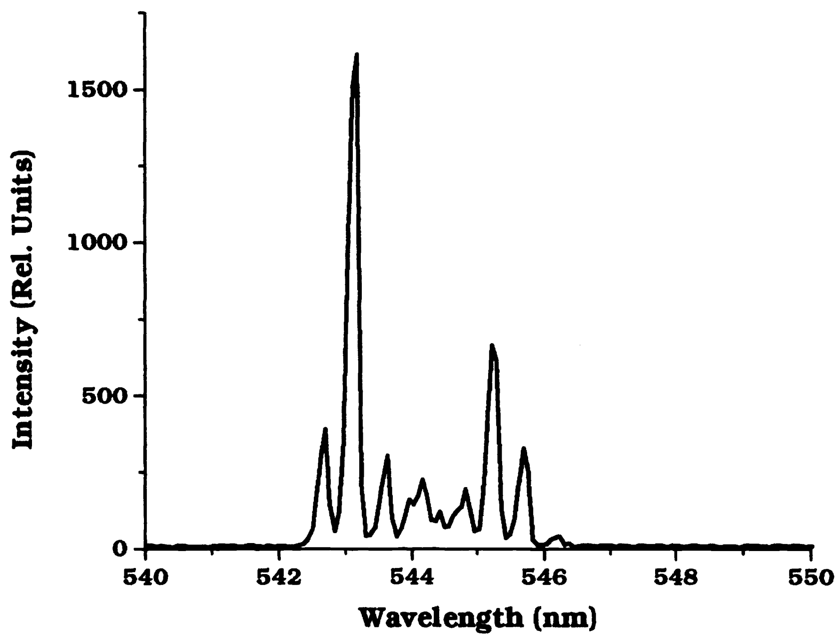

Figure 6. Laser emission at 540 nm by SFD in Yb^{3+}:YCOB

6. CONCLUSIONS

In summary, we report the growth, laser action, and self-frequency doubling of Yb^{3+}:YCOB single crystals. Fundamental laser action occurred at 1050 nm and 1090 nm with slope efficiencies of 29% and 36% for 10% and 20% doped YCOB under cw Ti:Sapphire pumping. Initial diode-pumped operation was also achieved with a slope efficiency of 34% using a 10% doped crystal. The 977 nm diode-pumped results shows a significant improvement of slope efficiency over Ti:Sapphire pumping, which may be a result of the reduced quantum defect. In addition, low-power 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 economic option for building a compact high powered tunable green laser source. Compared to Nd^{3+}:YCOB, the Yb^{3+} laser has the advantage of broadband emission, which can be used for tunable IR laser systems and short pulse operation in the femtosecond regime.

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