15 August 1999

ELSEVIER

Optics Communications 167 (1999) 149–153

OPTICS COMMUNICATIONS

www.elsevier.com/locate/optcom

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

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Received 20 April 1999; received in revised form 7 June 1999; accepted 9 June 1999

Abstract

Tunable laser operation in Yb:YCOB from 1018 to 1087 nm pumped by 1.4 W from a Ti:Sapphire laser tuned to 900 nm is demonstrated. The combination of the ability to grow large crystals with high optical quality, broad infrared emission, diode pumpable absorption bands, and a significant non-linear coefficient makes this material very promising for use in tunable and ultrafast laser systems. © 1999 Published by Elsevier Science B.V. All rights reserved.

Keywords: YCOB; Yb^{3+}; Tunable IR laser

It has long been known that trivalent ytterbium doped into a suitable laser host offers the potential of tunable infrared laser action in the infrared region and has several advantages compared to neodymium-doped laser materials, including a longer excitation lifetime and smaller quantum defect. The key characteristics of the ytterbium ion stem from its simple quasi-three level energy level structure. There is only one excited 4f manifold located around 10,000 cm^{-1}, with the next highest being in the 5d configuration starting at about 100,000 cm^{-1} [1]. The lack of energy states within this range severely limits the efficiency of flash lamp pumping [1]. However, it eliminates the problems of concentration quenching of the excited state lifetime [2], upconversion losses and excited state absorption [1,2].

Recent advances in the growth of rare earth calcium oxyborate crystals have lead to the creation of a new class of materials which can be used as laser hosts and as nonlinear crystals [3,4]. $GdCa_4O(BO_3)_3$ {GdCOB} [5–7] and $YCa_4O(BO_3)_3$ {YCOB} [8,9] are attractive alternatives to LiB_3O_4 (LBO) and β-BaB_2O_4 (β-BBO) for use as second harmonic generation (SHG) crystals because of their good material properties, including fairly uniform positive thermal expansion and quartz-like hardness (Vicker's microhardness $H_v = 604$ kg/mm^2 [10]), and relatively high d_{eff}, 1.3 pm/V and 1.1 pm/V, respectively [9] (see Table 1).

It has also been demonstrated that laser action and second harmonic generation can be accomplished within a single crystal, a characteristic referred to as self-frequency doubling (SFD). The SFD output of

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0030-4018/99/$ - see front matter
PII: S0030-4018(99)00293-X

Table 1
Crystal properties

Material	Average thermal expansion coefficient α (10^{-6}/K)	Average thermal conductivity κ (W/mK)	Hygroscopicity (susceptibility to moisture)
QX Phosphate Glass [11]	790	0.85	None
$Y_3Al_5O_{12}$ (YAG) [12]	7.5	13 at 300 K	None
Al_2O_3 Sapphire [12]	5.3	34.05 at 298 K	None
$YCa_4O(BO_3)_3$ (YCOB) [10]	7.38	2.65 at 298 K, 2.40 at 373 K	None

Nd:GdCOB [13], Nd:YCOB [14], Yb:$BaCaBO_3F$ [15], and Yb:YCOB [16] is comparable to that of Nd:MgO:$LiNbO_3$ [17] or NYAB [18]. However, the oxyborates have shown no significant sign of photorefractive damage, as is the case with Nd:MgO:$LiNbO_3$ [17], and demonstrate much less self-absorption at 530 nm than is the case with NYAB [18]. 63 mW at 530 nm, with 1 W of absorbed pump power, has been obtained from a diode pumped Nd:YCOB SFD laser [19]. Finally, since YCOB can be grown via Czochralski pulling, large crystals (diameter 3 inch and length 8 inch) of good optical quality can be grown with no visible inhomogeneities, dislocations, or striations [16], unlike crystals made using the high temperature flux method.

YCOB is a negative biaxial crystal belonging to monoclinic crystal system with the space group Cm (point group m) and the number of formulae in one unit cell is $Z = 2$ [20]. X-ray diffraction (XRD) measurements, from Mougel et al. [8], have determined the lattice constants to be $a = 8.0773$ Å, $b = 16.0194$ Å, $c = 3.5308$ Å, and $\beta = 101.167°$. Since the crystallographic axes a, b, and c are not mutually orthogonal, it has been necessary to impose X, Y, and Z optical indicatrix axes relative to the crystallographic axes according to the traditional refractive index convention $n_x < n_y < n_z$. This has proven difficult and has led to some confusion in the literature, and, in fact, the crystal structure and orientation of YCOB is still being refined. A detailed examination of the growth and orientation of YCOB has been done by our collaborators in the Crystal Growth Laboratory at CREOL. This research has determined the orientation of optical indicatrix axes relative to the crystallographic axes to be as shown in Fig. 1 [20]. Since ytterbium and yttrium have very similar ionic radii, up to approximately 50% ytterbium dopant concentration in the melt can be achieved, beyond which incongruent melting is observed [16,20]. Yb:YCOB is particularly promising as a nonlinear crystal. In addition to its high damage threshold (> 1 GW/cm^2) and the fact that these crystals are nonhygroscopic even in boiled water [9], it has been demonstrated that the replacement of yttrium with ytterbium induces a modification of the electric field in the lattice structure which causes a 10–15% increase in the second harmonic conversion efficiency (at 1064 nm) of 20% Yb:YCOB with respect to undoped YCOB [21].

The $^2F_{5/2} \rightarrow {}^2F_{7/2}$ transition [1,22] of trivalent ytterbium doped in YCOB was characterized by measuring the polarized room temperature absorption and photoluminescence spectra with a Bomem DA8 Fourier-transform spectrometer and an InGaAs detector operating at 77 K [16]. Fig. 2 shows the

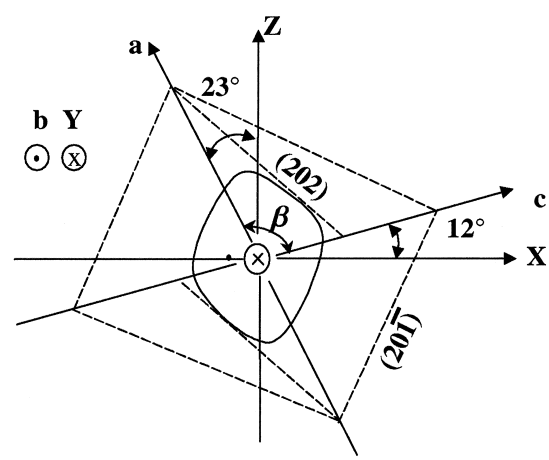

Fig. 1. Orientation of optical indicatrix axes (X, Y, Z) relative to the crystallographic axes (a, b, c) for YCOB crystal.

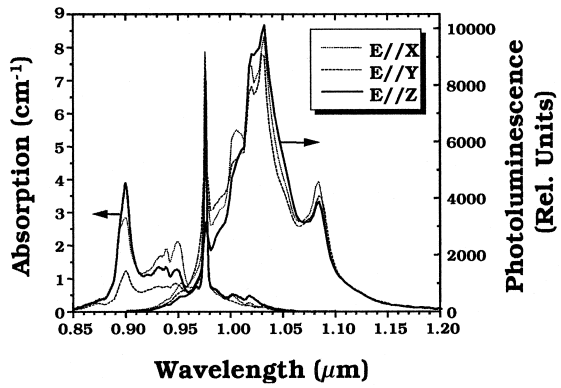

Fig. 2. Polarized absorption and fluorescence emission spectra of Yb:YCOB as a function of wavelength.

absorption and emission spectra for light polarized parallel to the X, Y, and Z optical indicatrix axes, respectively. The large vibronic components of the ytterbium transition are evident in the wide absorption feature at 900 nm, which is ideal for high power pumping with InGaAs laser diodes because there is no need to precisely control the temperature of the diode. There is another absorption feature at 976 nm, which is approximately twice as strong but which has a significantly narrower spectral width. The fluorescence emission spectrum ranges from 950 to 1090 nm with a maximum at 1030 nm. A fluorescence decay time of 3 ms was measured with a Q-switched Cr:LiSAF$_6$ laser tuned to 900 nm [16].

A 10 mm crystal with 10% ytterbium dopant concentration in the melt was used to demonstrate tunable laser action. The crystal was cut such that the pump and the fundamental propagate parallel to the Y axis, and the E-field of the pump was parallel to the Z axis. The crystal faces were cut at an angle of 60° to the Y axis, corresponding to the Brewster angle for the refractive index of 1.7. The pump source was a Ti:Sapphire laser tuned to 900 nm with a maximum power of approximately 1.4 W. The pump beam was focused into an x-cavity, as shown in Fig. 3. The focused spot was measured with a photon beam scanner and was found to have a diameter of approximately 70 μm FWHM. All the mirrors were coated for broadband reflectivity, limited by the high reflector and the 2% output coupler which had a bandwidth of approximately 100 nm centered at 1064 nm. The crystal was cooled on one side by a thermoelectric cooler set to 15°C.

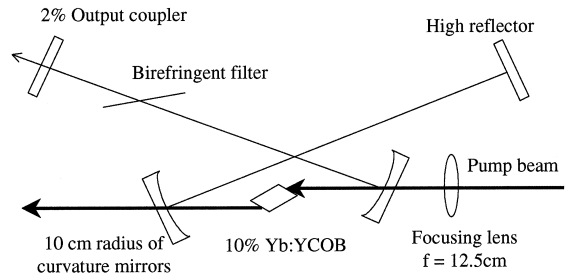

Fig. 3. X-cavity schematic.

The cavity was optimized for a minimum threshold of 184 mW pump power absorbed, with 330 mW pump power incident upon the focusing lens. Due to the reflection losses caused by the focusing lens and the first curved mirror, only about 1.1 W of pump light reached the crystal of which 73.5% was absorbed. The slope efficiency of this cavity was 24% with a maximum output power of 150 mW at 1050 nm, as shown in Fig. 4. This relatively low slope efficiency was at least partially the result of the parasitic effects caused by the lower laser level population, which act as a saturable loss in such quasi-three level laser systems. This additional loss tends to decrease overall slope efficiency, η, which is proportional to $T/(\delta + \delta_s)$, where T is the output coupling, δ are the round-trip cavity losses, and δ_s is the saturable loss term (in a four-level laser $\delta_s = 0$) [23].

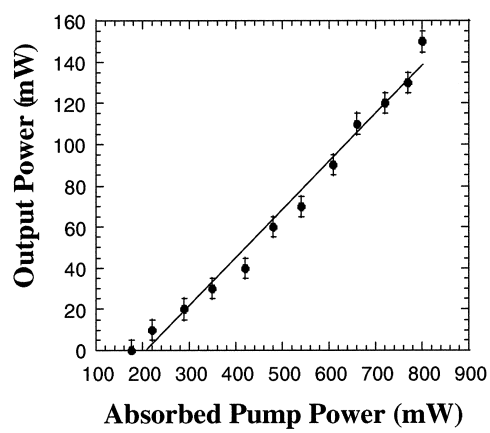

Fig. 4. Output power at 1050 nm versus absorbed Ti:Sapphire pump power at 900 nm. Slope efficiency is 24% with a 2% output coupler.

Tuning was accomplished by inserting a single plate birefringent filter (BRF) into the cavity. This introduced an additional loss into the cavity, which reduced the maximum output power to 120 mW. Laser tunability was achieved over a range of 70 nm centered at 1050 nm, as shown in Fig. 5.

A Spiricon beam analyzer was used to measure the near and far field beam profiles. In the near field, the beam was asymmetrical with a beam diameter of 1.313 mm along the horizontal axis and 0.975 mm along the vertical axis (Fig. 6(a)). The far field beam profile was obtained by measuring the beam diameter at the focus of a 40 cm focal length lens. From the measured diameter of 8.71×10^{-4} m (Fig. 6(b)), the M^2 of the beam was calculated to be 1.415. Using this M^2 value, the beam waist in the cavity was calculated to be approximately 150 μm FWHM. Since the pump spot is about half the diameter, slope efficiency and tunability should improve given better cavity mode matching.

By comparing the demonstrated laser tunability (Fig. 5) and the emission and absorption spectra (Fig. 2), it is clear that the emission spectra falls off at longer wavelengths and thus limits laser tunability. Furthermore, the reduction in output power at 1070 nm reflects the dip in the fluorescence emission spectrum between 1060 nm and 1070 nm. Finally, the tunability at shorter wavelengths is limited by

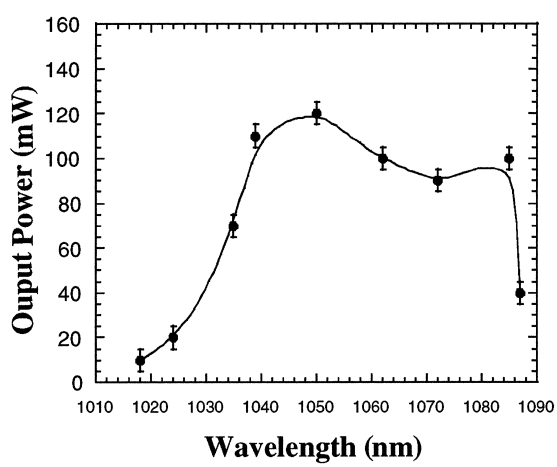

Fig. 5. Yb:YCOB laser output power as a function of laser wavelength with ~1.1 W of pump light incident on the crystal. Tunability observed from 1018 to 1087 nm using a single plate birefringent filter.

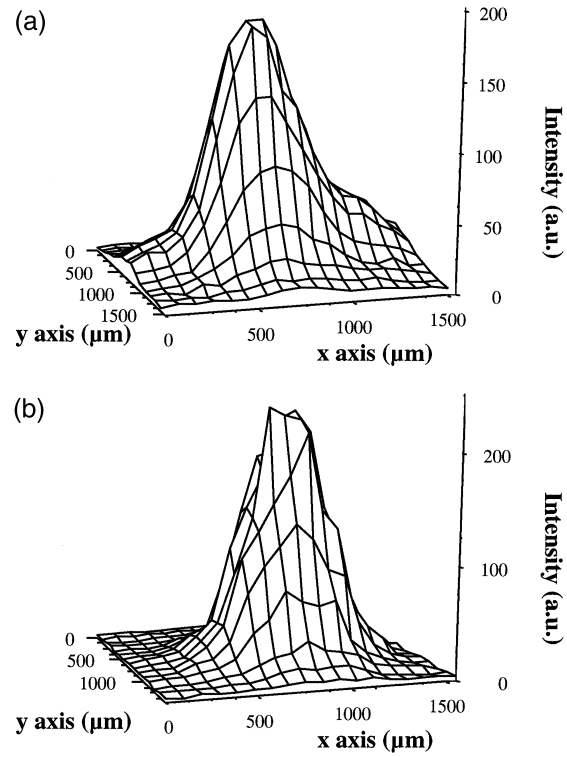

Fig. 6. The beam profile measured by a Spiricon Beam Analyzer: (a) the full-width $1/e^2$ maximum beam diameter is 1.313 mm and 0.975 mm, along the x and y axes, respectively; (b) the far field beam profile was generated by measuring the beam waist at the focus of a 40 cm focal length lens. The beam has a full width $1/e^2$ maximum beam diameter of 0.871 mm, corresponding to an M^2 of 1.415.

self-absorption from un-excited ytterbium ions in the crystal, as has been seen in other ytterbium-doped materials such as Yb:YAG [24]. By definition, in a quasi-three-level laser the thermal distribution of the ground state level overlaps with the lower laser level. As mentioned previously, this constant population in the lower laser level acts as a saturable loss. In Yb doped materials, this effect is greater for shorter wavelength emission because these transitions involve unexcited states that lie very close to the ground state. This effect shifts the peak gain of the media from the stimulated emission peak at 1030 nm further into the infrared. This effect has also been observed in a 13 mm long 20% Yb:YCOB crystal, in which the laser wavelength was shifted to 1090 nm [16]. Thus, further optimization of dopant concentra-

tion and absorption length should improve slope efficiency and output power.

In summary, these initial results on laser tunability in Yb:YCOB compare favorably with other ytterbium-doped host materials. The fact that Yb:YCOB has a broader fluorescence spectrum implies that an optimized linear cavity should yield broader laser tunability than in Yb:YAG [24]. Furthermore, the yttrium replacement and thermal/mechanical/optical properties of YCOB offer clear advantages over glass and over other crystalline hosts. Yb:YCOB should also be capable of generating ultrashort (sub 100 femtosecond) pulses, as in Yb:YAG [25], Yb:Glasses [26], and Yb:Silica Fiber [27], and could be a candidate for use in a compact and inexpensive diode-pumped, high repetition rate, high intensity laser system. Furthermore, self-frequency doubling has been achieved in Yb:YCOB [16], and Yb:YCOB's unique nonlinear properties [21] offer promise for applications in the visible as well as in the infrared range.

Acknowledgements

The authors gratefully acknowledge Dr. W.K. Jang for many helpful discussions and the technical support of G. Luntz and J. Tawney. This work is supported in part by the state of Florida.

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