1-1-1999

Diode-pumped self-frequency doubling in a Nd3+: YCa4O(BO3)(3) laser

J. M. Eichenholz
University of Central Florida

D. A. Hammons
University of Central Florida

L. Shah
University of Central Florida

Q. Ye
University of Central Florida

R. E. Peale
University of Central Florida

See next page for additional authors

Recommended Citation

Eichenholz, J. M.; Hammons, D. A.; Shah, L.; Ye, Q.; Peale, R. E.; Richardson, M.; and Chai, B. H. T., "Diode-pumped self-frequency doubling in a Nd3+: YCa4O(BO3)(3) laser" (1999). *Faculty Bibliography 1990s*. 2614.
https://stars.library.ucf.edu/facultybib1990/2614

Authors

J. M. Eichenholz, D. A. Hammons, L. Shah, Q. Ye, R. E. Peale, M. Richardson, and B. H. T. Chai

Applied Physics Letters

Diode-pumped self-frequency doubling in a Nd^{3+}:YCa$_4$O(BO$_3$)$_3$ laser

Cite as: Appl. Phys. Lett. **74**, 1954 (1999); https://doi.org/10.1063/1.123739
Submitted: 13 November 1998 . Accepted: 10 February 1999 . Published Online: 01 April 1999

J. M. Eichenholz, D. A. Hammons, L. Shah, Q. Ye, R. E. Peale, M. Richardson, and B. H. T. Chai

ARTICLES YOU MAY BE INTERESTED IN

Highly efficient 2% Nd:yttrium aluminum garnet ceramic laser
Applied Physics Letters **77**, 3707 (2000); https://doi.org/10.1063/1.1331091

LASER OSCILLATIONS IN Nd-DOPED YTTRIUM ALUMINUM, YTTRIUM GALLIUM AND GADOLINIUM GARNETS
Applied Physics Letters **4**, 182 (1964); https://doi.org/10.1753928

Promising ceramic laser material: Highly transparent Nd^{3+}:Lu$_2O_3$ ceramic
Applied Physics Letters **81**, 4324 (2002); https://doi.org/10.1063/1.1527234

AIP Publishing

Appl. Phys. Lett. **74**, 1954 (1999); https://doi.org/10.1063/1.123739 **74**, 1954

APPLIED PHYSICS LETTERS VOLUME 74, NUMBER 14 5 APRIL 1999

Diode-pumped self-frequency doubling in a Nd^{3+}:$YCa_4O(BO_3)_3$ laser

J. M. Eichenholz,[a] D. A. Hammons, L. Shah, Q. Ye, R. E. Peale, M. Richardson,[b]
and B. H. T. Chai[c]
School of Optics/Center for Research and Education in Optics and Lasers, University of Central Florida,
4000 Central Florida Blvd., Orlando, Florida 32816-2700

(Received 13 November 1998; accepted for publication 10 February 1999)

We report efficient, diode-pumped, self-frequency doubling (SFD) in the newly developed laser crystal Nd^{3+}:$YCa_4O(BO_3)_3$. More than 350 mW of fundamental output power at 1060 nm was achieved with a slope efficiency of 51%. With one watt of absorbed pump power, 62 mW of green cw laser emission at 530 nm was observed with proper phase matching. This initial performance, and the good optical properties of the crystalline host, are encouraging for the development of a high power diode-pumped SFD visible light laser source. © *1999 American Institute of Physics.* [S0003-6951(99)01614-9]

There is much interest in the development of Nd^{3+} doped laser crystals which possess nonlinear optical properties.[1–6] These crystals have the advantage of combining the active laser medium and the nonlinear frequency conversion medium into a single element. Self-frequency doubled (SFD) lasers are an attractive alternative to conventional intra-cavity frequency doubling with a separate nonlinear crystal such as KTP. A SFD laser incorporates lower reflection, absorption and scattering losses and leads to a simpler and more robust resonator design. With the addition of diode pumping, SFD lasers provide a type of compact high-power visible laser light source.

Self-frequency doubling was first demonstrated in Tm:$LiNbO_3$[7] and then later in Nd:MgO:$LiNbO_3$.[1] The latter met limited success because of its poor optical quality and the occurrence of photorefractive damage in the crystal.[2] SFD has also been observed in Nd:$YAl_3(BO_3)_4$, (NYAB) but this material suffers from self-absorption at 530 nm[3,6] and is grown by a high-temperature flux method that often gives rise to crystals with poor optical quality and of small size.[3]

Our interest in SFD lasers is driven by developments in a class of laser host materials, the oxyborates.[8,9] These materials appear to have ideal properties for SFD action. Initial development of the oxyborates with SFD operation under Ti:sapphire and diode pumping was recently reported in both GdCOB[10,11] and $YCa_4O(BO_3)_3$ (YCOB).[12]

We now report efficient self-frequency generation in Nd^{3+}:YCOB under diode pumping. Nd:YCOB is an attractive material for SFD because it has demonstrated high optical gain at 1060 nm, a high nonlinear coefficient (~ 1 pm/V),[13] a high damage threshold (~ 1 GW/cm^2),[13] and the ability to fabricate large laser crystals possessing good optical quality. Moreover, its principal absorption bands overlap well with the emission of high-power, near infrared-red, laser diodes. The oxyborates also offer advantages for harmonic generation[13,14] in that they are nonhygroscopic and can be grown with large apertures. In a separate study, we have found that both Yb and Nd doped YCOB can be used as an efficient second harmonic generation crystal.[15]

We have successfully developed the Czochralski growth process to produce large (3 in. diam×8 in. long) high quality, single Nd:YCOB crystals. YCOB has a monoclinic crystal structure belonging to the space group Cm (point group m)[9] and therefore the crystallographic axes are nonorthogonal. The lattice parameters of the unit cell are $a = 8.046$ Å, $b = 15.959$ Å and $c = 3.517$ Å with the angle $\beta = 101.19°$.[13] We have previously defined the *X, Y*, and *Z*, optical indicatrix axes relative to the crystallographic axes and planes by adopting the traditional refractive index convention $n_x < n_y < n_z$.[16,17] The polarized absorption and emission spectra of 5% Nd:YCOB for light polarized parallel to the *X, Y*, and *Z* optical axes are shown in Figs. 1 and 2, respectively. These figures show that the strongest absorption and emission occurs for light polarized parallel to the *Z* axis.

Diode-pumped experiments were performed with a simple laser resonator, similar to the Ti:sapphire pumped cavity described elsewhere.[12] The high brightness, AlGaAs laser diode (Polaroid POL-5100BW) had a maximum output power of 1.85 W from a 100 μm stripe and was centered at a wavelength of 812 nm. A 125 μm diam fiber lens was utilized to collect the emission from the laser diode's fast

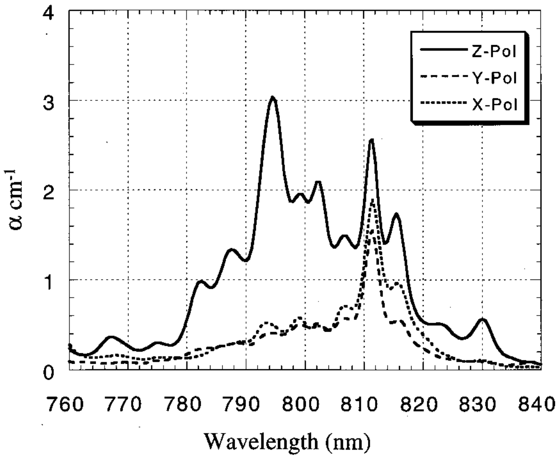

FIG. 1. Absorption spectrum for 5% Nd:YCOB for light polarized parallel to the *X, Y, Z* axes.

---

[a] Now with Laser Energerics Inc., 100 Alexandria Blvd., Suite 6, Oviedo, FL 32765.

[b] Also with Laser Energetics Inc., 100 Alexandria Blvd., Suite 6, Oviedo, FL 32765. Electronic mail: mcr@creol.ucf.edu

[c] Also with Crystal Photonics, Inc., 3403 Technological Ave., Suite 14, Orlando, FL 32817.

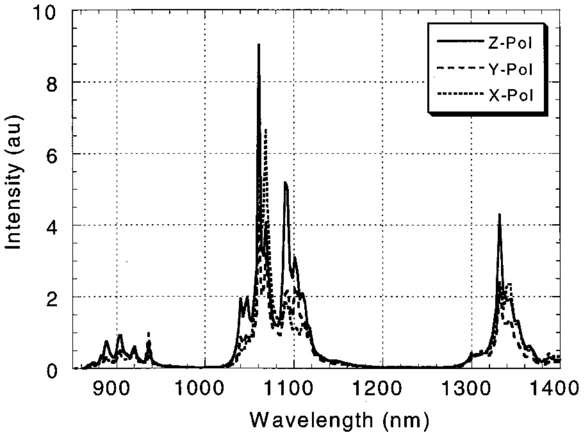

FIG. 2. Emission spectrum for 5% Nd:YCOB as a function of polarization relative to *X*, *Y*, and *Z* axes.

axis and help equalize the divergence from the fast and slow axis. After the micro lens, a 50 mm focal length achromatic doublet lens was used to collect the diverging pump beam. After collimation, the pump beam is refocused with a 60 mm focal length Gradium™ plano/convex lens to a ~50 $\times 70\,\mu$m full width at half maximum (FWHM) spot size, as measured with a scanning slit beam profiler (Photon Inc.).

The hemispherical laser resonator consisted of a highly reflective rear mirror and a 10 cm radius of curvature output coupler. The $3\times3\times5$ mm long, 5% Nd:YCOB crystal was placed next to the high reflector. The crystal was cut with the polished faces aligned at an angle of 33.95° to the *X* axis. Both surfaces were coated with a triple band anti-reflection coating which had less than 1% reflectivity at 1060, 530 and 812 nm.[18] The crystal absorbed approximately 75% of the incident pump light at full current to the diode. The pump laser polarization was parallel to the *Z* axis and was focused into the crystal through the rear mirror, which was 95% transparent at 812 nm. The fundamental (1060 nm) output power versus the absorbed pump power is shown in Fig. 3 for 2% transmission output coupling. The polarization of the laser output was parallel to the *Z* axis. Output powers exceeding 340 mW for 900 mW of absorbed pump power were obtained with a slope efficiency of 51%.

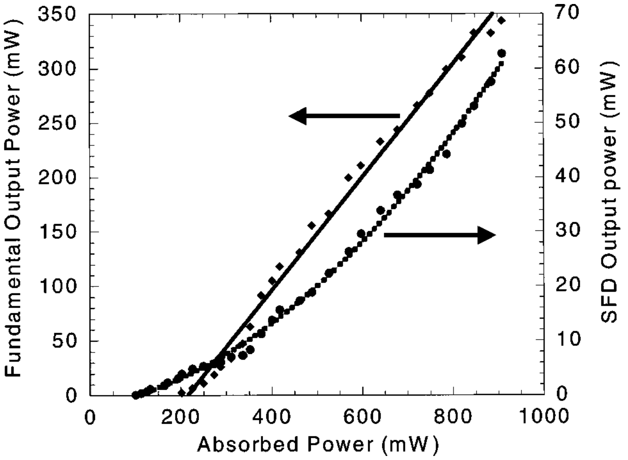

FIG. 3. Fundamental and self-frequency-doubled diode pumped output power vs absorbed pump power.

Efficient diode-pumped self-frequency doubling was demonstrated utilizing the same crystal. The resonator design was identical to that described above. To maximize the SFD output, the output coupler was a 10 cm receiver operating characteristic (ROC) mirror, highly reflective at 1060 nm ($R=99.82\%$) and highly transmissive ($T>96\%$) at 530 nm. The SFD output was optimized 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. The SFD power as a function of absorbed pump power is also shown in Fig. 3. Over 62 mW of 530 nm laser light was obtained with 900 mW of pump power absorbed in the crystal. At this power, the spatial mode profile of the SFD laser output as measured by a Spiricon LBA-100A was multimode. The onset of SFD output occurred for only 100 mW of diode power absorbed in the crystal. The spectrum of the SFD output consisted of a single, narrow (<0.6 nm) line at 530.3 nm.

The intracavity fundamental (IR) power was estimated to be approximately 4.2 W by measuring the fundamental power leaking through the 10 cm ROC highly reflective mirror. The intracavity conversion efficiency is estimated to be over 1.5%. On the assumption that the intracavity mode cross section is similar to the pump beam area (3.5×10^{-5} cm^2), the intracavity power density was estimated to be approximately 120 kW/cm^2.

As with most intracavity frequency doubled lasers with many oscillating longitudinal modes, the SFD process in Nd:YCOB has large amplitude fluctuations due to longitudinal mode coupling through the sum-frequency generation process which strongly modulates the second harmonic light.[19] Other SFD crystals have seen between 3% and 6% peak-to-peak[20] amplitude fluctuations. The measured rms noise in the present laser within a bandwidth of 5 Hz-1 MHz was approximately 5%. This rms noise fluctuation is a consequence not only of multi-longitudinal mode oscillations but also of coupled polarization modes[21] and feedback instabilities on the diode due to the absence of anti-reflection coatings on the pump optics. In these initial experiments no attempts were made to reduce the rms noise of the SFD output.

In summary, by generating over 62 mW of diode-pumped, green SFD laser light, we have shown that Nd:YCOB is a good candidate for a compact, diode-pumped, visible laser system. Detailed measurements of the thermomechanical properties of the YCOB crystalline host are essential to help determine the factors which could limit the scaling of the SFD output to higher powers.

The authors acknowledge the experimental support of Neil Vannesse, Gary Luntz and Jesse Tawney. The State of Florida in part supported this work.

[1] V. G. Dmitriev, E. V. Raevskii, N. M. Rubina, L. N. Rashkovich, O. O Silichev, and A. A. Fomichev, Sov. Tech. Phys. Lett. **4**, 590 (1979).
[2] T. Y. Fan, A. Cordova-Plaza, M. J. F. Digonnet, R. L. Byer, and H. J. Shaw, J. Opt. Soc. Am. B **3**, 140 (1986).
[3] B. Lu, J. Wang, H. Pan, M. Jiang, E. Liu, and X. Hou, J. Appl. Phys. **66**, 6052 (1989).
[4] J. Bartschke, R. Knappe, K.-J. Boller, and R. Wallenstein, IEEE J. Quantum Electron. **33**, 2296 (1997).
[5] V. Ostroumov, K. Petermann, G. Huber, A. A. Ageev, S. Kutovoj, O.

Kuzmin, V. Panyutin, E. Pfeifer, and A. Hinz, J. Lumin. **72–74**, 826 (1997).

[6] J. Capmany and J. García Solé, Appl. Phys. Lett. **70**, 2517 (1997).

[7] L. F. Johnson and A. A. Ballman, J. Appl. Phys. **40**, 297 (1969).

[8] T. N. Khamaganova, V. K. Trunov, and B. F. Dzhurinshii, Russ. J. Inorg. Chem. **36**, 484 (1991).

[9] R. Norrestam, M. Nygen, and J. O. Bovin, Chem. Mater. **4**, 737 (1992).

[10] F. Mougel, G. Aka, A. Kahn-Harari, H. Hubert, J. M. Benitez, and D. Vivien, Opt. Mater. **8**, 161 (1997).

[11] Augé, F. Mougel, G. Aka, A. Kahn-Harari, D. Vivien, F. Balembois, P. Georges, and A. Brun, OSA Trends in Optics and Photonics on Advanced Solid-State Lasers, **19**, 53 (1998).

[12] B. H. T. Chai, J. M. Eichenholz, Q. Ye, D. A. Hammons, W. K. Jang, L. Shah, G. M. Luntz, and M. Richardson, OSA Trends in Optics and Photonics on Advanced Solid-State Lasers, **19**, 56 (1998).

[13] M. Iwai, T. Kobayashi, H. Furuya, Y. Mori, and T. Sasaki, Jpn. J. Appl. Phys., Part 2 **36**, 276 (1997).

[14] G. Aka, A. Kahn-Harari, F. Mougel, D. Vivien, F. Salin, P. Coquelin, P. Colin, D. Pelenc, and J. P. Damelet, J. Opt. Soc. Am. B **14**, 2238 (1997).

[15] W. Jang, Q. Ye, J. Eichenholz, B. H. T. Chai, and M. Richardson, OSA, CLEO Paper CFG4 (1998).

[16] Q. Ye and B. H. T. Chai, J. Cryst. Growth **197**, 228 (1999).

[17] V. G. Dmitriev, G. G. Garzadyan, and D. N. Nikogosyan, *Handbook of Nonlinear Optical Crystals*, 2nd ed. (Springer, Berlin, 1997).

[18] TBAR coating, Quality Thin Films Inc., Oldsmar, Florida.

[19] T. Baer, J. Opt. Soc. Am. B **3**, 1175 (1986).

[20] H. Hemmati, IEEE J. Quantum Electron. **28**, 1169 (1992).

[21] M. Oka and S. Kubota, Opt. Lett. **13**, 805 (1988).