Efficient, tunable, zero-line-diode-pumped, continuous-wave Yb3+:Ca4LnO(BO3)3 (Ln=Gd,Y) lasers at room temperature, application to miniature lasers

Frédéric Druon, Frederika Auge-Rochereau, François Balembois, Patrick Georges, Alain Brun, Astrid Aron, Frédéric Mougel, Gerard Aka, Daniel Vivien

Efficient, tunable, zero-line diode-pumped, continuous-wave Yb^{3+}:$Ca_4LnO(BO_3)_3$ ($Ln = $ Gd, Y) lasers at room temperature and application to miniature lasers

Frédéric Druon, Frédérika Augé, François Balembois, Patrick Georges, and Alain Brun

Laboratoire Charles Fabry de l'Institut d'Optique, Unité Mixte de Recherche Associée au Centre National de la Recherche Scientifique, UMR 8501, B.P. 147, 91403 Orsay, France

Astrid Aron, Frédéric Mougel, Gérard Aka, and Daniel Vivien

Laboratoire de Chimie Appliquée de l'État Solide, Unité Mixte de Recherche Associée au Centre National de la Recherche Scientifique, UMR 7574, École Nationale Supérieure de Chimie de Paris, 11 rue Pierre et Marie Curie, 75231 Paris Cedex, France

Received May 20, 1999; revised manuscript received July 12, 1999

We demonstrate an efficient cw 976-nm-diode-pumped Yb^{3+}:$Ca_4GdO(BO_3)_3$ laser. At room temperature we obtained 814 mW of power with a slope efficiency of 77% and a small-signal gain per round trip of 1.67. We also demonstrate that the Yb^{3+}:$Ca_4LnO(BO_3)_3$ ($Ln = $ Gd, Y) crystals are suitable for a plano–plano microchip-type cavity. With this microlaser we have obtained an average power of 300 mW, which corresponds to an optical–optical conversion efficiency of 27%. [S0740-3224(00)00101-1]

OCIS codes: 140.270, 140.390, 140.110, 140.460.

During the past few years the great potential of Yb-doped media has been demonstrated by very efficient and powerful diode-pumped lasers.[1–6] Owing to their simple quasi-three-level electronic structure,[7] based on two electronic manifolds, Yb-doped media allow a reduction of the thermal load and thus are highly suitable for high-power diode pumping. The quasi-three-level electronic structure of the Yb^{3+} ions allows a low quantum defect to be achieved. In addition, the absence of additional parasitic levels higher than the first excited state of this rare-earth element avoids undesired effects such as excited-state absorption and upconversion. The absence of concentration quenching is also an advantage to help reach high doping rates in Yb. Thus these properties, added to the development of high-power InGaAs laser diodes, make the Yb^{3+} ion very interesting for the doping of solid-state media.[3–5,8–14] Another advantage of Yb, compared with other dopants such as Nd, is its broadband nature, which is suitable for both tunable and ultrafast lasers.[6] However, the main problem with Yb as a dopant is its quasi-three-level nature. In fact, because of the thermal filling of the lower laser levels, the performance of the Yb laser strongly depends on the temperature.[9,15,16] Operating this laser at room temperature[1,2,17,18] thus often leads to a sacrifice in efficiency or in average output power. When the absorbed pump power is high and the thermal load is increased, the efficiency of the laser drastically decreases. This is why, from the point of view of reducing the thermal effects, the choice of the host matrices is very important for diode-pumped Yb lasers.

In this paper we present the results obtained with Yb^{3+}-doped $Ca_4GdO(BO_3)_3$ (Yb:GdCOB) and Yb^{3+}-doped $Ca_4YO(BO_3)_3$ (Yb:YCOB) materials. These recently discovered crystals[13,19] belong to the Ca rare-earth oxoborate family. They can be Yb-doped by substitution of their Gd, Y rare-earth ions. The doping in Yb^{3+} can be very high because of the lanthanide site in the oxoborate structure and the absence of quenching concentration. In our case we used a 15%-doped Yb:GdCOB crystal and a 35%-doped Yb:YCOB crystal. The high concentration allows a short pump-absorption length in the crystal, which is an advantage when it is pumped with a non-diffraction-limited beam from a high-power laser diode. Moreover, Yb:*Ln*COB ($Ln = $ Gd, Y) crystals also exhibit more inherent properties that are interesting from the point of view of obtaining efficient, largely tunable laser sources. First, Yb:*Ln*COB crystals have a very broadband emission spectrum (43 nm FWHM) compared with that of other crystals, such as Yb:YAG (12 nm FWHM). Second, these crystals, in comparison with glasses, have a relatively good thermal conductivity ($k = 2.1\ W\,m^{-1}\,K^{-1}$ for GdCOB compared with $0.7\ W\,m^{-1}\,K^{-1}$ for glasses). The thermal conductivity is an important parameter for quasi-three-level media because it directly influences the temperature of the gain area and thus the thermal population in it. The Yb:*Ln*COB crystals then add the advantage of a broadband emission that is comparable with that of Yb-doped glasses to the relatively good thermal conductivity of crystal, as is shown in Table 1.

Another advantage of the Yb:*Ln*COB crystals is that they can be diode pumped to their zero-line peak wavelength. In fact, Yb doped crystals are usually pumped

Table 1. Comparison of Yb:LnCOB with Other Yb-Doped Matrixes

Characteristic	Yb:YAG	Yb:YAB	Yb:S-FAP	Yb:glass phosphate (QX/Yb)	Yb:YCOB	Yb:GdCOB
Emission bandwidth (nm)	10[a]	~20[b]	5.5[c]	62[d]	44	44
Thermal conductivity ($Wm^{-1}K^{-1}$)	14[d]	3[b]	2.1[e]	0.85[d]	2.1[f]	2.1[f]
Maximum obtained slope efficiency (%)	80[g]	71[b]	78[h]	49[i]	73[f]	77
Corresponding maximum output power (mW)	270	123	75	440	654	815

[a] Ref. 3.
[b] Ref. 14.
[c] Ref. 8.
[d] Ref. 20.
[e] Ref. 15.
[f] Ref. 12.
[g] Ref. 21.
[h] Ref. 5.
[i] Ref. 22.

far below their zero line. The pump wavelengths are, for example, 941 nm for Yb:YAG (Ref. 10) and 900 nm for $Yb:Sr_5(PO_4)F$ (Ref. 8). The zero-line peak is narrower than the other absorption peaks, a situation that is often incompatible with diode pumping because of the broadband emission spectrum of the laser diodes. In the case of Yb:GdCOB and Yb:YCOB the absorption bandwidth is 2.3 nm. To evaluate the importance of the broadness of the pump spectrum compared with the broadness of the absorption peak, we introduced the integrating absorption cross-section factor (f):

$$f = \frac{\int_\lambda \sigma_{\text{abs}}(\lambda) I_p(\lambda)\,\mathrm{d}\lambda}{\sigma_{\text{abs}}(\lambda_{\text{peak}}) \int_\lambda I_p(\lambda)\,\mathrm{d}\lambda}, \tag{1}$$

where σ_{abs} is the absorption cross section as a function of the wavelength (λ), $\sigma_{\text{abs}}(\lambda_{\text{peak}})$ is the maximum absorption cross section of the peak, and I_p is the intensity of the pump as a function of the wavelength. In our case, where the width of the diode spectrum is 2.5 nm, we calculated an integrating absorption cross-section factor of 0.7 (compared with 1 for an infinitely sharp pump spectrum). The high value of this factor is favorable for efficient diode pumping.

The present paper deals with the results[12,14] of the Yb:GdCOB and Yb:YCOB crystals diode pumped at their zero-line peak of 976 nm. As a result, the quantum defect is decreased to 7% from a quantum defect of 14% with a pump wavelength[11] of 902 nm. The thermal load, which arises mainly from the quantum defect, is then reduced by a factor of 2. Owing to the large splitting of $^2F_{7/2}$ Stark levels in the Yb:GdCOB crystal[11,12] (1003 cm^{-1} compared with 614 cm^{-1} in Yb:YAG), the effect of temperature on the thermal population is much less important in the Yb:*Ln*COB crystals than in the others.[23] All of these thermal and spectral properties thus motivated us to study the performance of Yb:GdCOB lasers at room temperature. First, we describe the performance, obtained with a high pumping power at room temperature. Then, we will discuss the results of our study still at room temperature, of the Yb-doped crystals in a plano–plano microchip geometry (which is to our knowledge the first ever demonstrated).

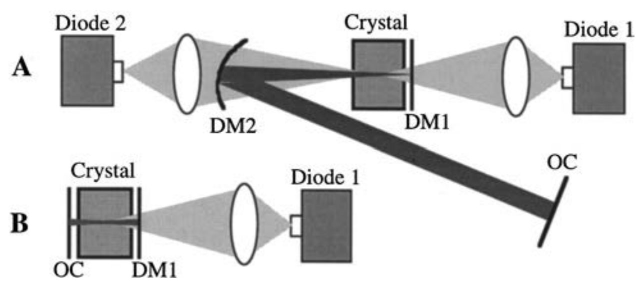

Fig. 1. Experimental setups. A, L cavity; B, Plano–plano cavity. DM, dichroic mirrors with high transmission at 976 nm, high reflection between 1000 and 1100 nm; DM1, plane mirror; DM2, 100-mm curvature radius mirror; OC, output coupler.

The first experiment consisted in optimizing the performance in a stable cavity with a longitudinally pumped Yb:GdCOB crystal (Fig. 1A). This experiment was performed with one 2-W, 1 μm × 100 μm junction laser diode emitting at 976 nm. This diode (diode 1), from Polaroid, was collimated by a 15-mm objective, then reshaped by an 8× cylindrical telescope in the slow direction, and finally focused by a 60-mm doublet. The pump power incident upon the crystal after the dichroic mirror (DM1) was 1.1 W. The crystal was a 3-mm-long, 15%-doped Yb:GdCOB crystal. It absorbed 653 mW of the incident pump power (59%). In this configuration, with a 4% output coupler, a cw output power of 300 mW was obtained with a slope efficiency of 77% and an absorbed-power threshold of 265 mW.

To estimated the tunability of this source, we inserted a prism into the collimated arm (DM2–OC in Fig. 1A) to tune the wavelength. As is shown in Fig. 2, the tunability was very broad: from 1017 to 1086 nm with a FWHM of 44 nm. Without the prism, the source naturally operates near 1040 nm, which corresponds to the maximum of the tuning curve.

To increase the performance of this laser, a second diode was used to pump the crystal on both sides. This diode (diode 2), from Opto Power Corporation, which included a collimating fiber lens, was recollimated by a 140-mm doublet and focused by a 100-mm doublet. The power incident upon the crystal after the dichroic mirror (DM2) was 0.9 W. To optimize the double-side pumping, a longer, 4-mm, 15%-doped Yb:GdCOB crystal was used. Under these conditions the total absorption pump power was 1.3 W, corresponding to 65% of the optical–optical conversion. Figure 3 shows the results obtained at room temperature with a 2% and a 4% transmission output coupler (OC). The maximum slope efficiency of 77% was obtained with a 2% OC mirror (see Table 1 for comparison with other crystals). Moreover, no diminution of the efficiency was observed even at high absorbed pump powers in the absence of cooling of the crystal. In fact, nothing was done to help cool the crystal: First, this 4 mm $\times$ 5 mm $\times$ 5 mm crystal was pumped in its center; second, only one side of the crystal was set on a metallic surface. Even under these unfavorable conditions, thanks to the good thermal behavior of the Yb:GdCOB crystal, the thermal load stayed weak enough to avoid a degradation of the efficiency. The maximum output power for 1.3 W of absorbed pump power was then as high as 814 mW, which corresponded to a 63% optical–optical conversion.

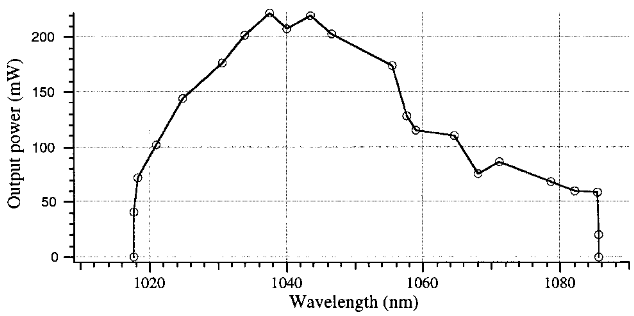

Fig. 2. Tunability of the Yb:GdCOB laser diode pumped at 976 nm. The sharp edges at 1018 and 1086 nm are due to the cutoff of the mirrors.

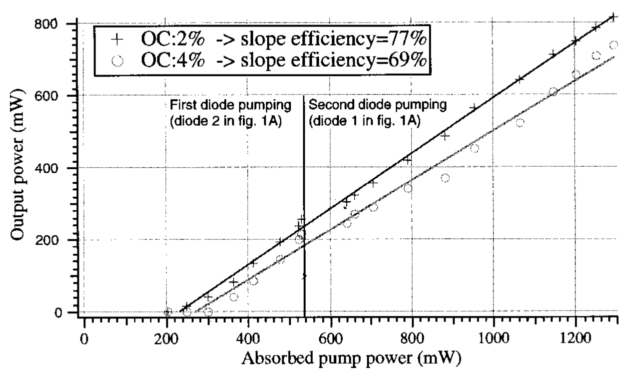

Fig. 3. Output power of the laser versus absorbed pump power for the double-side pumped 15%-doped Yb:GdCOB laser emitting at 1050 nm.

These results are very promising for the use of Yb:GdCOB as a gain medium in a femtosecond oscillator or regenerative amplifier, considering its broadband tunability and its high pump-to-signal power conversion. However, the pump-to-signal power conversion is not the best parameter for estimating the efficiency of an amplifier. Actually, the crucial parameter for an efficient amplifier is the small-signal gain. To measure the double-pass small-signal gain, we inserted a glass plate whose angle was varied continuously to adjust the losses.[24] A small-signal gain of 1.67 was then obtained. According to this result, it appears, in the actual state of the art, that the Yb:GdCOB crystal is one of the best candidate for the realization of near-1-μm femtosecond pulsed sources.

But amplifiers are not the only application for high-gain media. Another advantage of having a very high gain is for greater flexibility in the microchip cavity type in the cw regime. In fact, it is very interesting in terms of simplicity, compactness, and low price, to be able to use a plano–plano cavity. These cavities are usually stabilized by thermal lensing and gain guiding. In the case of Yb:*Ln*COB crystals, for which a slightly negative thermal lens (approximately -10 m of focal lens) was measured, an efficient gain medium is necessary to stabilize the cavity.

The second series of experiments was then performed in the plano–plano microchip cavity geometry (Fig. 1B). In this configuration the crystal was pumped on only one

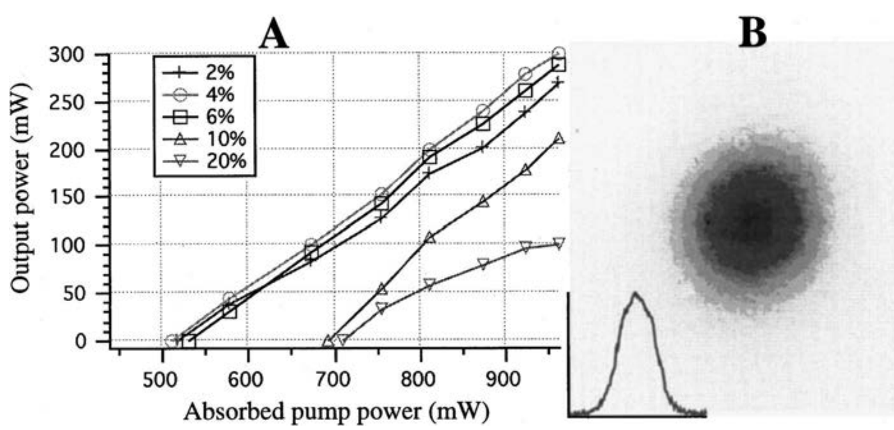

Fig. 4. A, Output power of the laser versus absorbed pump power for the plano–plano 35%-doped Yb:YCOB laser emitting at 1050 nm. B, Corresponding beam profile.

side, the other side being the output of the laser. A maximum output power of 270 mW was obtained with a 4% OC. The corresponding slope efficiency was then 79%. The slope was steeper in this configuration than in the stable configuration because the microchip cavity's stability increased with the gain and thus with the pump power. The threshold was also higher in this configuration. The optical–optical conversion efficiency was thus 25%.

To optimize the microchip laser, the idea was to increase the Yb-ion doping of the crystal and to reduce its size. But the GdCOB crystal cannot be doped with Yb^{3+} ions to more than 27%, because the solid solution no longer shows congruent melting behavior above that level. To obtain a higher doping ratio, we decided to use the Ca_4YCOB crystal. The experiment was performed with a 3-mm-long 35% doped Yb:YCOB crystal. The output power versus the absorbed pump power is plotted in Fig. 4A. An average output of 300 mW at 1050 nm was obtained, corresponding to an optical–optical conversion efficiency of 27%. Another important characteristic of the plano–plano cavity is the laser beam profile. In our case the beam profile (plotted in Fig. 4B) was circular and nearly Gaussian. Its M^2 factor was measured to be equal to 1.25.

In conclusion, we have demonstrated the possibility of efficient diode pumping at 976 nm for Yb:GdCOB. This 976-nm diode pumping allowed a low quantum defect and led to a reduced thermal load, which is often critical for a quasi-three-level Yb laser, especially at room temperature. The use of Yb:GdCOB and Yb:YCOB is, for the actual state of the art, the most suitable for highly efficient, tunable, diode-pumped Yb lasers at room temperature. A cw output power of 814 mW was obtained with a constant slope efficiency of 77% and a 65-nm tunability. Moreover, the high gain in these gain media was shown to be appropriate for plano–plano microchip cavities. Actually, both the 15%-doped, 4-mm-long Yb:GdCOB and the 35%-doped, 3-mm-long Yb:YCOB showed a very good optical–optical conversion efficiency (up to 27%) in this plano–plano geometry. Finally, these Yb:*Ln*COB crystals could be very interesting for ultrafast lasers. These large emission spectra are suitable for an oscillator to produce sub-100-fs pulses. Moreover, the high gain of Yb:*Ln*COB crystals seems to be very promising for the development of an ultrafast diode-pump amplifier. So the future step we are anticipating now is to apply the Yb:GdCOB and the Yb:YCOB results to femtosecond laser technology.

F. Druon's e-mail address is frederic.druon@iota.u-psud.fr.

REFERENCES

1. P. Lacovara, H. K. Choi, C. A. Wang, R. L. Aggarwal, and T. Y. Fan, "Room-temperature diode-pumped Yb:YAG laser," Opt. Lett. **16**, 1089–1091 (1991).
2. D. S. Sumida and T. Y. Fan, "Room-temperature 50-mJ/pulse side-diode-pumped Yb:YAG laser," Opt. Lett. **20**, 2384–2386 (1995).
3. U. Brauch, A. Giesen, M. Karszewski, Chr. Stewen, and A. Voss, "Multiwatt diode-pumped Yb:YAG thin disk laser continuously tunable between 1018 and 1053 nm," Opt. Lett. **20**, 713–715 (1995).
4. T. Taira, J. Saikawa, E. Yamaguchi, T. Kobayashi, and R. L. Byer, "Single longitudinal mode oscillation in frequency doubled Yb:YAG miniature laser," in *Advanced Solid State Lasers*, W. R. Bosenberg and M. M. Fejer, eds., Vol. 19 of OSA Trends in Optics and Photonics Series (Optical Society of America, Washington, D.C., 1998), pp. 119–121.
5. M. R. Dickinson, L. A. W. Gloster, N. W. Hopps, and T. A. King, "Continuous-wave diode-pumped Yb^{3+}:S-FAP laser," Opt. Commun. **132**, 275–278 (1996).
6. C. Hönninger, F. Morier-Genoud, M. Moser, U. Keller, L. R. Brovelli, and C. Harder, "Efficient and tunable diode-pumped femtosecond Yb:glass lasers," Opt. Lett. **23**, 126–128 (1998).
7. T. Y. Fan, "Optimizing the efficiency and stored energy in quasi-three-level lasers," IEEE J. Quantum Electron. **28**, 2692–2697 (1992).
8. K. I. Schaffers, A. J. Bayramian, C. D. Marshall, J. B. Tassano, and S. A. Payne, "Analysis of $Sr_{5x}Ba_x(PO_4)_3F$:Yb^{3+} crystals for improved laser performance with diode-pumping," in *Advanced Solid State Lasers*, C. R. Pollock and W. R. Bosenberg, eds., Vol. 10 of OSA Trends in Optics and Photonics Series (Optical Society of America, Washington, D.C., 1997), pp. 420–424.
9. D. C. Brown, "Ultrahigh-average-power diode-pumped Nd:YAG and Yb:YAG lasers," IEEE J. Quantum Electron. **33**, 861–873 (1997).
10. C. D. Marshall, S. A. Payne, L. K. Smith, R. J. Beach, M. A. Emanuel, J. A. Skidmore, H. T. Powell, W. F. Krupke, and B. H. T. Chai, "Diode-pumped Yb:$Sr_5(PO_4)_3F$ laser performance," in *Advanced Solid-State Lasers*, B. Chai and S. Payne, eds., Vol. 24 of OSA Proceedings Series (Optical Society of America, Washington, D.C., 1995), pp. 333–338.
11. F. Augé, F. Balembois, P. Georges, A. Brun, F. Mougel, G. Aka, A. Khan-Harari, and D. Vivien, "Efficient and tunable continuous-wave diode-pumped Yb^{3+}:$CaGdO(BO)_3)_3$ laser," Appl. Opt. **38**, 976–979 (1999).
12. H. Zhang, X. Meng, P. Wang, L. Liu, R. Cheng, J. Dawes, P. Dekker, S. Zhang, and L. Sun, "Slope efficiency of up to 73% for Yb:$Ca_4YO(BO_3)_3$ crystal laser pumped by a laser diode," Appl. Phys. B **68**, 1147–1149 (1999).
13. F. Mougel, K. Dardenne, G. Aka, A. Khan-Harari, and D. Vivien, "Ytterbium-doped $Ca_4GdO(BO_3)_3$: an efficient infrared laser and self-frequency doubling crystal," J. Opt. Soc. Am. B **16**, 164–172 (1999).
14. P. Wang, J. M. Dawes, P. Dekker, and J. A. Piper, "Highly efficient diode-pumped ytterbium doped yttrium aluminum borate laser," in *Digest of Conference on Advanced Solid-State Lasers* (Optical Society of America, Washington, D.C., 1999), postdeadline paper 15.
15. S. A. Payne, L. K. Smith, L. D. DeLoach, W. L. Kway, J. B. Tassano, and W. F. Krupke, "Laser, optical, and thermomechanical properties of Yb-doped fluorapatite," IEEE J. Quantum Electron. **30**, 170–179 (1994).
16. S. Erhard, K. Contag, A. Giesen, I. Johannsen, M. Karszewski, T. Rupp, and C. Stewen, "Novel pump design of Yb:YAG thin disc laser for operation at room temperature with improved efficiency," in *Digest of Conference on Advanced Solid-State Lasers* (Optical Society of America, Washington, D.C., 1999), paper MC3.
17. E. Mix, L. Fornasiero, A. Diening, K. Petermann, and G. Huber, "Diode-pumped laser-operation of Yb:Sc_2O_3 at room-temperature," in *Advanced Solid State Lasers*, W. R. Bosenberg and M. M. Fejer, eds., Vol. 19 of OSA Trends in Optics and Photonics Series (Optical Society of America, Washington, D.C., 1998), pp. 122–124.
18. E. Mix, E. Heumann, G. Huber, D. Ehrt, and W. Seeber, "Efficient cw-laser of Yb-doped fluoride phosphate glass at room temperature," in *Advanced Solid-State Lasers*, B. Chai and S. Payne, eds., Vol. 24 of OSA Proceedings Series (Optical Society of America, Washington, D.C., 1995), pp. 339–347.
19. G. Aka, A. Khan-Harari, F. Mougel, D. Vivien, F. Salin, P. Coquelin, P. Colin, D. Pelenc, and J. P. Damelet, "Linear-

nonlinear-optical properties of new gadolinium calcium oxoborate crystal, $Ca_4GdO(BO_3)_3$," J. Opt. Soc. Am. B **14**, 2238–2247 (1997).

20. C. Hönninger, *Ultrafast Ytterbium-Doped Bulk Lasers and Laser Amplifiers*, Vol. 9 of Series in Quantum Electronics (Hartung-Gorre Verlag, Kontanz, 1999), pp. 59, 65.
21. I. Chartier, C. Wyon, D. Pelenc, B. Ferrand, D. P. Shepherd, and D. C. Hanna, "High slope efficiency and low threshold in a diode pumped epitaxially grown Yb:YAG waveguide laser," in *New Materials for Advanced Solid State Lasers*, B. H. T. Chai, S. A. Payne, T. Y. Fan, A. Cassanho, and T. H. Allik, eds. (Materials Research Society, Pittsburgh, Pa. 1994), pp. 179–184.
22. X. Griebner, R. Koch, H. Schönnagel, S. Jiang M. J. Myer, D. Rhonehouse, S. J. Hamlin, W. A. Clarkson, and D. C. Hanna, "Laser performance of a new ytterbium doped phosphate laser glass," in *Advanced Solid-State Lasers*, S. A. Payne and C. R. Pollock, eds., Vol. 1 of OSA Trends in Optics and Photonics Series (Optical Society of America, Washington, D.C., 1996), pp. 26–29.
23. B. H. T. Chai, D. A. Hammons, J. M. Eichenholz, Q. Ye, W. K. Jang, L. Shah, G. M. Luntz, M. Richardson, and H. Qiu, "Lasing, second harmonic conversion and self-frequency doubling of Yb:YCOB ($Yb:YCa_4B_3O_{10}$)," in *Advanced Solid State Lasers*, W. R. Bosenberg and M. M. Fejer, eds., Vol. 19 of OSA Trends in Optics and Photonics Series (Optical Society of America, Washington, D.C., 1998), pp. 59–61.
24. F. Balembois, F. Kerboull, F. Druon, F. Falcoz, P. Georges, A. Brun, "Theoretical and experimental investigations of small-signal gain for a diode-pumped *Q*-switched Cr:LiSAF laser," IEEE J. Quantum Electron. **33**, 269–278 (1997).