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To cite this version:

Gaëlle Lucas-Leclin, Frédérica Augé, Sophie Charlotte Auzanneau, François Balembois, Patrick Georges, et al.. Diode-pumped self-frequency doubling Nd:GdCa4O(BO3)3 lasers : towards green microchip lasers. Journal of the Optical Society of America B, 2000, 17 (9), pp.1526-1530. hal-00701633

HAL Id: hal-00701633
https://hal-iogs.archives-ouvertes.fr/hal-00701633

Submitted on 25 May 2012

Diode-pumped self-frequency-doubling $Nd:GdCa_4O(BO_3)_3$ lasers: toward green microchip lasers

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Received September 21, 1999; revised manuscript received May 15, 2000

An output power of 115 mW at 545 nm has been obtained from a diode-pumped self-frequency doubling $Nd:GdCa_4O(BO_3)_3$ laser in a stable cavity. The infrared emission of the laser was found to be 1091 nm, not the 1060 nm that was expected when the highest line of the fluorescence spectrum was considered. We have demonstrated that the emission at 1091 nm was caused by the temperature increase at the focus of the pump beam. We demonstrated also, for what we believe was the first time, lasing operation of Nd:GdCOB in a plano–plano cavity and obtained an output power of 22 mW at 545 nm. To our knowledge, this is the highest output power ever reported with a self-frequency-doubling crystal in a plano–plano cavity. [S0740-3224(00)00409-4]

OCIS codes: 140.3480, 140.3580, 140.7300, 190.2620.

1. INTRODUCTION

There is a great demand for low-cost, low-consumption lasers that emit a few milliwatts in the green portion of the spectrum. Many applications are possible, starting from the simple replacement of air-cooled ionized argon lasers, to alignment, pointing, and new applications in the medical domain. A simple way to produce these lasers would be to develop a diode-pumped self-frequency-doubling (SFD) microchip laser consisting of only one crystal directly coated with the appropriate dielectric mirrors. Of the SFD crystals, the one that showed the best performance was neodymium yttrium aluminum borate $[Nd:YAl_3(BO_3)_4]$.[1] However, this noncongruent melting crystal suffers from growing difficulties. By comparison, the SFD crystal $Nd:GdCa_4O(BO_3)_3$ (Nd:GdCOB) is much easier to grow, and $GdCa_4O(BO_3)_3$ (Gd:COB) pieces 5 cm in diameter and 12 cm in length have already been demonstrated.[2] Nd:GdCOB has already proved to be an efficient SFD material when it is either Ti:sapphire[3] or diode[4] pumped. The unique combination of good mechanical, nonlinear, and spectroscopic properties makes this crystal an excellent candidate for use in low-cost microchip lasers, in which mirrors are deposited upon the faces of the laser material for easier manufacturing and operation.

In this paper we report on diode-pumped Nd:GdCOB lasers in green microchip laser devices. First we investigate the laser emission of the crystal in a stable concave–concave cavity to determine the ultimate performance of the SFD crystal. We report lasing emission at 1091 nm and study the origin of this unexpected long-wavelength laser line, which should affect the phase-matching condition for efficient SFD. We describe the performance of this laser in the green portion of the spectrum. Finally we describe what is to our knowledge the first SFD operation of Nd:GdCOB in a short plano–plano cavity.

2. Nd:GdCOB IN A STABLE CONCAVE–CONCAVE LASER CAVITY

A. Description of the Experimental Setup

The main advantage of a stable laser cavity compared with a microchip laser with plane mirrors is that the waist is perfectly defined and does not change with pump power. We used a concave–concave cavity (as illustrated in Fig. 1) to place the crystal perfectly at the cavity waist

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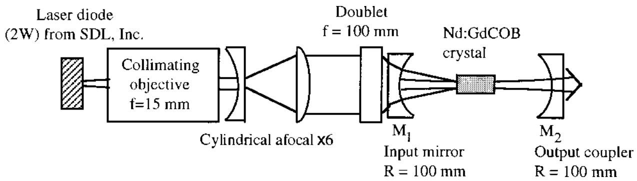

Fig. 1. Experimental setup; the afocal system is a 6× beam expander in the direction parallel to the diode junction.

position. In this way we could use the entire Rayleigh length for efficient frequency conversion, unlike with plano–concave cavities with which only half of the Rayleigh length can be used.

The cavity consisted of two 100-mm radius-of-curvature mirrors, M_1 and M_2. The diverging pump beam was collected by a high-numerical-aperture objective (focal length, 15 mm; numerical aperture, 0.6), a cylindrical afocal expander in the direction parallel to the diode-active area reshaped the pump beam, and a spherical doublet with a focal length of 100 mm focused the pump beam inside the crystal through M_1. The pump laser diode (SDL, Inc., Model 2372) had a maximum output power of 2 W at 810 nm from a single 1 μm by 100 μm stripe. In this configuration the pump beam was measured to be 70 μm × 50 μm (half-width at $1/e^2$) at the focus point, and the cavity waist was approximately 70 μm. The pump polarization was parallel to the Z axis of the crystal.

Experiments were performed on two Nd:GdCOB crystals cut in type I phase matching in the XY plane ($\theta = 90°$ and $\phi = 46°$) for SFD operation at 530 nm. The first crystal was doped with 5-at. % Nd^{3+} (3.2×10^{20} ions cm^{-3}) and was 8 mm long. It absorbed 87% of the incident pump power. The second crystal was doped with 7-at. % Nd^{3+} (4.4×10^{20} ions cm^{-3}) and was 4 mm long. It absorbed 85% of the incident pump power. Both crystals were antireflection coated at 1060 and 530 nm.

B. Investigation of the Emitted Fundamental Wavelength

First we investigated the emitted wavelength in the infrared with the 7-at. %-doped crystal. For this purpose we recorded the output power on the leakage of mirror M_2. M_2 was highly reflective in the infrared from 1000 to 1100 nm for efficient intracavity doubling, and we intended to study the laser emission in a SFD operation. As shown in Fig. 2, we observed that the laser emitted at 1060 nm at low pump power. However, at the maximum pump power the predominant emission surprisingly was centered at 1091 nm. Similar behavior was obtained with output couplers of various transmissions.

In GdCOB, two transitions between Stark levels of the Nd^{3+}:${}^4F_{3/2} \rightarrow {}^4I_{11/2}$ band, one from the upper level of the ${}^4F_{3/2}$ manifold and the other from the lower level, which is the same emitting level as for the 1060-nm radiation (see Fig. 3), may correspond to the emission wavelength at 1091 nm. Laser radiation near 1091 nm was, however, unexpected because the highest emission cross-section line of the fluorescence spectrum was obtained at 1060 nm for emission light polarized along the Z axis.[3]

This switch of the laser wavelength needs to be carefully studied because it can crucially compromise the power stability of the laser. Moreover, the phase-matching angles for frequency doubling at 1060 and 1091 nm are different, and thus the SFD of dual wavelengths should be less efficient. Furthermore, this dual-wavelength emission is incompatible with the realization of a single-frequency microchip laser.

The influence of a thermal effect on the laser emission was suspected because of the slow growth of the 1091-nm radiation compared with the immediate emission of the 1060-nm line in the infrared spectrum. We verified this hypothesis by investigating the effect of crystal temperature on the laser radiation at both wavelengths. We mounted the crystal upon a copper support heated to 80 °C with two superposed thermoelectric devices. The output power of the diode was square-wave modulated between the maximum output laser power (1.2-W absorbed pump power) and zero with a very low duty cycle ($d \cong 1/9$) to prevent any local heating from being induced by the pump beam. The average pump power absorbed by the crystal was only 140 mW. The modulation frequency was ~100 Hz, which is low enough that any transient regimes either for the pump diode or for the laser itself can be neglected. Figure 4 shows that laser emis-

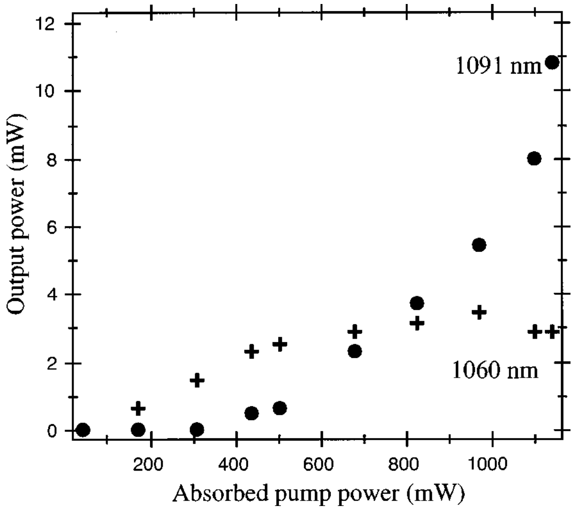

Fig. 2. Output power at 1060 and 1091 nm for the 7-at. % Nd^{3+} doped GdCOB crystal measured after mirror M_2 versus absorbed pump power for cw operation.

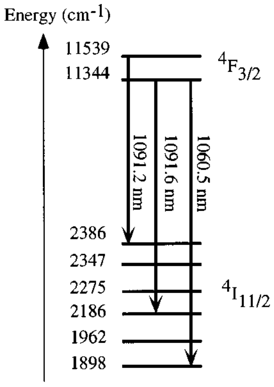

Fig. 3. Energy-level diagram of Nd^{3+} ions in GdCOB at 77 K.

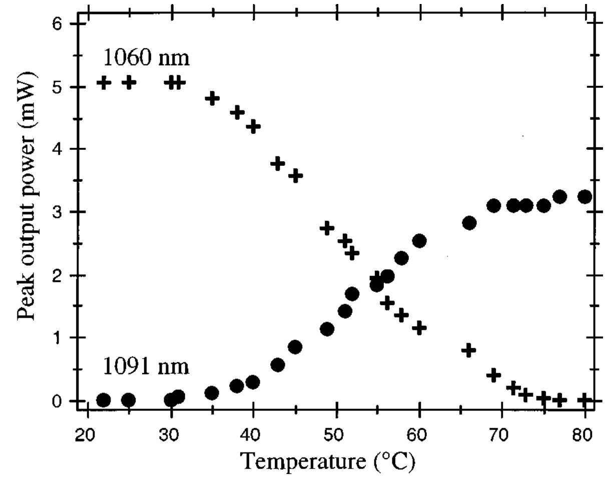

Fig. 4. Peak output power at 1060 and 1091 nm for the 7-at. % doped Nd:GdCOB crystal versus crystal temperature in square-wave modulated operation; the average absorbed pump power was 140 mW, and the peak absorbed pump power was 1200 mW.

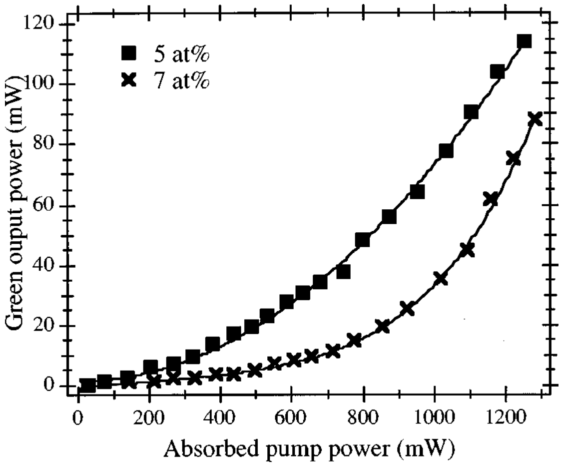

Fig. 5. Self-frequency-doubled output power in the green for 5-at. % doped and 7-at. % doped Nd:GdCOB crystals in concave–concave cavities; solid curves are quadratic fits of the experimental results.

sion occurred at 1060 nm at room temperature but switched to 1091 nm above 55 °C.

By comparison, in cw pumping the local temperature rise induced by the pump beam focused in the crystal can be estimated by solution of the heat equation for an axially heated cylinder with a thermally conductive boundary at the periphery.[5] Assuming a pump beam radius of 60 μm, a thermal conductivity of 2.1 W m^{-1} K^{-1} for Nd:GdCOB,[6] and an absorbed pump power of 1.2 W, we expect the temperature to rise above 100 °C at the center of the crystal. This temperature level corresponds to a laser emission at 1091 nm in our experiments (Fig. 4), in accordance with our first observations in cw operation (Fig. 2).

From these experiments we have concluded that the change in the emitted wavelength observed in cw operation as the pump power was increased (Fig. 2) is the consequence of local heating of the crystal induced by the pump power absorbed by the Nd:GdCOB.

The reason why the 1091-nm radiation is preferentially emitted as the internal temperature of the crystal increases is not completely understood, but we suspect that it is probably thermal populating of the upper $^4F_{3/2}$ manifold sublevel (Fig. 3). Consequently, a decrease in the population of the lower sublevel occurs and is responsible for the laser emission at 1060 nm (Fig. 4). The 195-cm^{-1} split between the two $^4F_{3/2}$ manifold sublevels seems quite likely to lead to such a phenomenon.

C. Laser Performance in the Infrared

The maximum infrared output power that we obtained from the 7-at. % doped crystal, including both 1060- and 1091-nm lines, was 385 mW at 1.3-W pump absorbed power in the concave–concave cavity; the laser threshold was 95 mW and the slope efficiency was ~32% for an output coupling of 2.4% in the infrared (mirror M_2). However, our best result in the infrared was attained with the 5-at. %-doped crystal, for which we observed a similar emitted spectrum with two lines of various weights, depending on the absorbed pump power. Optical coupler M_2 transmitted 3.2% at 1060 nm, and mirror M_1 was highly reflective in the infrared. In these conditions we measured an output power of 434 mW in the infrared (1060 and 1091 nm) for an absorbed pump power of 1.25 W. The laser threshold was 140 mW of absorbed pump power, and the slope efficiency was 40%.

D. Laser Performance in the Green

Both the 5-at. % and the 7-at. % Nd^{3+} doped GdCOB crystals were cut for type I phase matching between the fundamental infrared wave at 1060 nm and the second-harmonic wave at 530 nm ($\theta = 90°$ and $\phi = 46°$). In fact, the phase-matching angle of the frequency doubling of the 1091-nm radiation is very close ($\theta = 90°$ and $\phi = 44°$) to that at 1060 nm. Therefore it is experimentally possible to obtain SFD operation at 545 nm with these crystals by slight adjustment of the crystal orientation in the cavity. To retain only one output for green emission, we chose mirror M_1 highly reflective in the green and M_2 highly transmissive in the green (Fig. 1).

Figure 5 gives the green laser performance relative to absorbed pump power for the two crystals. For each measurement the crystal was carefully oriented to maximize the green output power. As expected, the green emission was 530 nm at low pump power and became 545 nm at maximum pump power. The best performance, 115 mW of output power, was obtained with the 5 at. % doped crystal. We believe that this is the highest output power ever obtained in the green with a crystal of the oxoborate family under diode pumping.

3. Nd:GdCOB IN A PLANO–PLANO CAVITY

Whereas a large number of SFD crystals were tested in stable cavities, only a few papers have reported the use of SFD crystals in plano–plano cavities. A test was made with $Nd:YAl_3(BO_3)_4$ with a 500-mW laser diode as pump source, and 1.5 mW of output power in the green was reported.[7,8] We report here operation of Nd:GdCOB lasers in a 8-mm-long plano–plano cavity, which represents an important step toward achieving microchip lasers for which the mirrors are directly deposited onto the crystal faces.

We modified the previous pumping optics to obtain maximum infrared and green output powers (Fig. 6). Two cylindrical afocal systems were chosen to reshape the pump beam in the two transverse directions, and the pump beam was focused inside the crystal with an $f = 60$-mm doublet. The pump beam waist was then 66 μm × 32 μm (full width at $1/e^2$) at the focus point.

First we tested a plano–plano cavity for infrared laser emission. Mirror M_1 was highly reflective in the infrared, and the distance between the two cavity mirrors was 8 mm. The best result (150-mW cw output power, including both the 1060-nm and the 1091-nm lines for an absorbed pump power of 1 W; see Fig. 7) was obtained with an output coupler whose transmission was 4.7% at 1060 nm, and the 7-at. % doped crystal. The laser threshold was 550 mW of absorbed pump power, and the slope efficiency was 32%. In these conditions the infrared beam was slightly elliptical, ~110 μm × 70 μm (half-width at $1/e^2$).

Second, we investigated SFD performance in a plano–plano cavity. The input mirror was highly reflective at both 1064 and 532 nm, and the output mirror was highly reflective at 1064 nm and highly transmissive at 532 nm. The pumping optics were the same as for the previous infrared experiments (Fig. 6). 22 mW of green output power at 545 nm was obtained with the 7-at. % doped crystal. Figure 9 shows the output power versus absorbed pump power for the two crystals. Unlike for the concave–concave cavity, we obtained slightly better results with the 7-at. % doped crystal. The output beam was measured to be nearly diffraction limited ($M^2 < 1.2$) and perfectly circular, with a waist of 50 μm. The reduction of the doubling efficiency in the plano–plano cavity compared with that achieved in the concave–concave cavity is due to the larger infrared beam waist of the plano–plano cavity.

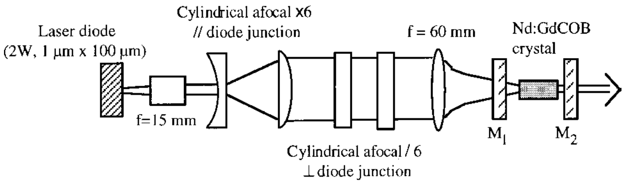

Fig. 6. Experimental setup for laser experiments in a plano–plano cavity; two telescopes in two perpendicular directions are used to reshape the pump beam.

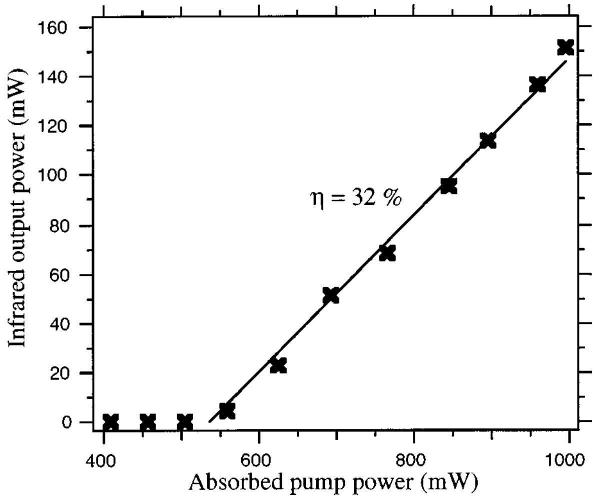

Fig. 7. Infrared output power versus absorbed pump power with the plano–plano cavity and the 7-at. % Nd^{3+} doped GdCOB crystal. The input mirror was highly reflective in the infrared, the transmission of the output coupler was $T = 4.7\%$ at 1060 nm, the slope efficiency was 32%, and the laser threshold was ~550 mW.

4. GUIDELINES FOR THE CONCEPTION OF MONOLITHIC GREEN MICROCHIP LASERS

From these experiments in concave–concave and plano–plano cavities we can now determine with some precision the conditions for realization of an efficient monolithic green Nd:GdCOB microchip laser. Such a device would be a simple and low-cost visible laser.

One important purpose of a so-called microchip laser is to produce infrared single-frequency emission to prevent competition between laser modes and ensure a high degree of power stability in the green. Thus the cavity length must be short enough to permit only one longitudinal mode in the emission spectrum. If a single line is selected in the infrared spectrum (say, 1060 nm) by temperature regulation or spectral filtering, the free spectral range of the laser cavity should be higher than the infrared spectrum width (~0.2 nm), i.e., a cavity length shorter than 1.5 mm.

The main drawback of such a short laser is the subsequent reduction of the absorption of the crystal at the pump wavelength, which results in a decrease of the power emitted in the infrared and in the green ranges. This constraint can be eliminated if the end mirror of the laser cavity is high-reflection coated for the pump wavelength. As a consequence the absorption length of the crystal is doubled. Let us consider, for example, a 7% doped, 1.5-mm-long Nd:GdCOB microchip laser: Its absorption at the pump wavelength is evaluated to be 76% from the characterization of the 7% doped, 4-mm-long crystal used in the reported experiments (see Subsection 2 A). At the maximum incident pump power, the output of the microchip laser should be ~7 mW in the green, according to the results of Fig. 8.

We evaluated the precision with which the crystal faces must be cut with respect to the phase-matching direction in the plano–plano configuration by rotating the crystal between the two plane mirrors. The output powers in the infrared and in the green were measured simultaneously (Fig. 9). The infrared emission was not so sensitive to crystal orientation as the green emission was, indicating that the decrease in the green output power was due only to phase mismatching. We determined experimentally that the misalignment acceptance is $\Delta\theta = 5$ mrad (FWHM) for a rotation around the Z axis and $\Delta\Phi = 6$ mrad (FWHM) in the other direction with the 4-mm-long microchip. Thus the faces need to be cut perpendicular to the phase-matching direction with a precision of ~1 mrad for a 1.5-mm-long microchip to yield the highest conversion efficiency.

Finally, the spatial beam quality (waist and divergence) will depend strongly on the focus of the pump

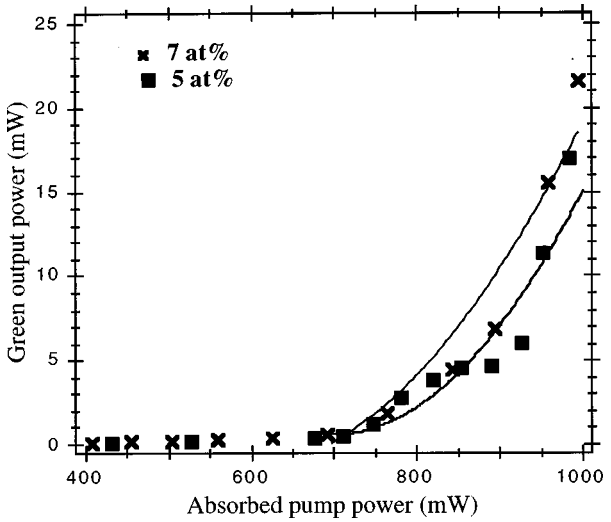

Fig. 8. Self-frequency-doubled output power in the green for the 5-at. % doped and the 7-at. % doped Nd:GdCOB crystal with the plano–plano cavity; solid curves, quadratic fits of the experimental results.

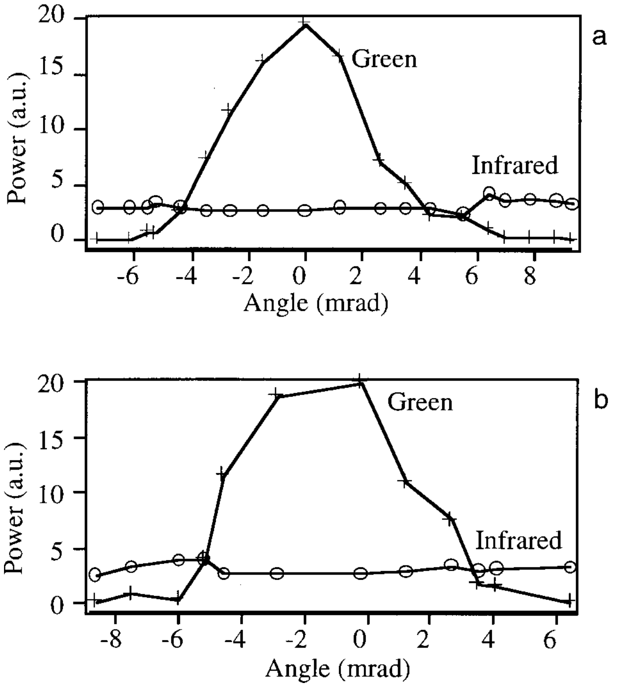

Fig. 9. Green and infrared output power versus orientation of a 4-mm-long Nd:GdCOB crystal for a rotation around (a) the *Z* axis and (b) an axis perpendicular to *Z* and the light propagation in the plano–plano cavity.

beam inside the crystal. The pump beam's dimensions must be thus carefully adjusted to optimize the green output power.

5. CONCLUSION

We have observed that the infrared laser emission of Nd:GdCOB exhibits a surprising behavior: The main laser wavelength switches from 1060 nm at low pump powers to 1091 nm at high pump powers. We have demonstrated experimentally that the 1091-nm line is favored by the heating of the crystal. We believe that the thermal population of the higher sublevel of the Nd^{3+} $^4F_{3/2}$ manifold induced by the pump power absorbed by the crystal is partially responsible for that. More experiments and theoretical studies are now in progress to explain precisely the physical origin of this effect.

Moreover, efficient self-frequency doubling has been performed in a diode-pumped microchip configuration. As much as 22 mW of green output power has been obtained, which we believe is the highest power ever obtained with a SFD crystal in a plano–plano cavity. Such a good result is promising for the realization of low-cost diode-pumped monolithic devices with mirrors deposited upon both faces of the Nd:GdCOB crystal, and guidelines for the conception of such a laser have been suggested.

ACKNOWLEDGMENTS

This research was supported by the Ministère de l'Éducation Nationale de la Recherche et de l'Enseignement (France) as part of the MICROCOB program and by the Centre National de la Recherche Scientifique as part of the program Matériaux.

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