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# Diode-pumped Nd:YVO<sub>4</sub>/Yb:S-FAP laser emitting at 985 and 492.5 nm

Marc Castaing,<sup>1,2,\*</sup> François Balembois,<sup>1</sup> Patrick Georges,<sup>1</sup> Thierry Georges,<sup>2</sup> Kathleen Schaffers,<sup>3</sup> and John Tassano<sup>3</sup>

<sup>1</sup>Laboratoire Charles Fabry de l'Institut d'Optique, CNRS, Université Paris-Sud, Campus Polytechnique, RD128, 91127 Palaiseau CEDEX, France

<sup>2</sup>Oxxius S.A., 4 Rue Louis de Broglie, F-22300 Lannion, France

<sup>3</sup>Lawrence Livermore National Laboratory, 7000 East Avenue, L-470, Livermore, California 94551, USA

\*Corresponding author: marc.castaing@institutoptique.fr

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For the first time, to the best of our knowledge, Yb:S-FAP crystals have been intracavity pumped by a Nd:YVO<sub>4</sub> laser at 914 nm. This original pumping scheme allows efficient laser action on the three-level transition at 985 nm with 1.4 W output power. Second-harmonic generation is also presented with a total output power of 120 mW at 492.5 nm. © 2008 Optical Society of America  
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Laser sources at approximately 980 nm have been developed for many years owing to their wide range of applications, particularly for second-harmonic generation experiments. Indeed, the blue range at approximately 490 nm, which is close to the Ar laser line at 488 nm, is then reachable. As problems with Ar lasers (size, low efficiency, and maintenance) are well-known, solid-state lasers represent a good alternative thanks to their compactness and efficiency. Several architectures based on optically pumped semiconductor lasers [1,2], on sum-frequency mixing of two Nd lines [3,4], or on frequency doubling of laser diodes [5,6] are already commercially available.

Despite the very broad emission cross section at ~980 nm, Yb lasers are rarely used for this kind of application. This is due to the three-level nature of the transition line leading to strong reabsorption losses and to severe requirements on the pump intensity. To be far above the pump transparency of this three-level system, the pump power has to be confined as it is in fibers [7,8].

A direct diode pumping could be considered since high-brightness laser diodes are now commercially available with large wavelength panels and narrow spectral widths. However, the spatial beam quality remains relatively low, with an  $M^2$  factor of ~80 for 100  $\mu\text{m}$  core diameter fiber coupled laser diode, leading to a strong pump divergence and so to a quick decrease of the pump intensity along the crystal.

A high finesse cavity at the pump wavelength represents another way to reach pump density far above the pump transparency. This is the "intracavity pumping concept" that has already been implemented in the mid IR, both in bulk for Ho:YAG lasers [9] and in Er-doped fibers [10], but never for laser emission at ~980 nm.

We have investigated, for the first time to our knowledge, the intracavity pumping concept with an Yb:S-FAP crystal chosen for its very high emission cross section at 985 nm [11]. Moreover, as opposed to many other Yb-doped materials, Yb:S-FAP has an emission spectrum composed of narrow lines at 985

and 1047 nm [Fig. 1(a)]. Hence the spectral selectivity will be easy even if the quasi-four-level transition at 1047 nm presents much more gain. Laser emission at 985 nm in Yb:S-FAP has already been demonstrated in pulsed operation (LiSAF pumping [12] or diode pumping [13]) and in cw operation under Ti:sapphire pumping [14] with only 250 mW of output power.

In this Letter we will demonstrate that the intracavity pumping concept based on Yb:S-FAP is a promising scheme to achieve an efficient diode-pumped system at 985 and 492.5 nm by second-harmonic generation. The choice of the pump laser (in which Yb:S-FAP will be inserted into the cavity) depends on the absorption spectrum of the Yb:S-FAP that peaks at 899 nm [Fig. 1(b)]. This wavelength has recently been achieved in a diode-pumped Nd:YAG crystal [15], but the laser efficiency and the gain are relatively low. We prefer to use a diode-pumped Nd:YVO<sub>4</sub> laser operating at 914 nm for its better performance [16]. This wavelength is at the edge of the Yb:S-FAP absorption; however, in intracavity pumping an absorption of only a few percent is needed for efficient laser action [9]. The Nd:YVO<sub>4</sub> laser is pumped by a laser diode at 808 nm, and its emission at 914 nm is used for pumping the Yb:S-FAP. The energy diagram of the experimental combination Nd:YVO<sub>4</sub>/Yb:S-FAP is then presented in Fig. 2.

For the experimental setup presented in Fig. 3, the pump source is a laser diode emitting at 808 nm coupled into a 100  $\mu\text{m}$  core diameter fiber with a numerical aperture of 0.22. This diode provides up to 25 W of unpolarized emission. The fiber output is imaged with two identical doublets (60 mm focal length) into the Nd:YVO<sub>4</sub> crystal with a waist radius of 50  $\mu\text{m}$ . The 5 mm long, 0.1%-doped Nd:YVO<sub>4</sub> crystal is antireflection (AR) coated at 914 and 985 nm to reduce the intrinsic losses of the cavity, and at 1064 nm to prevent laser oscillation between the two faces of the crystal. The first three mirrors of the cavity ( $M_1$ ,  $M_2$ , and  $M_3$ ) are highly reflective at 914 and 985 nm

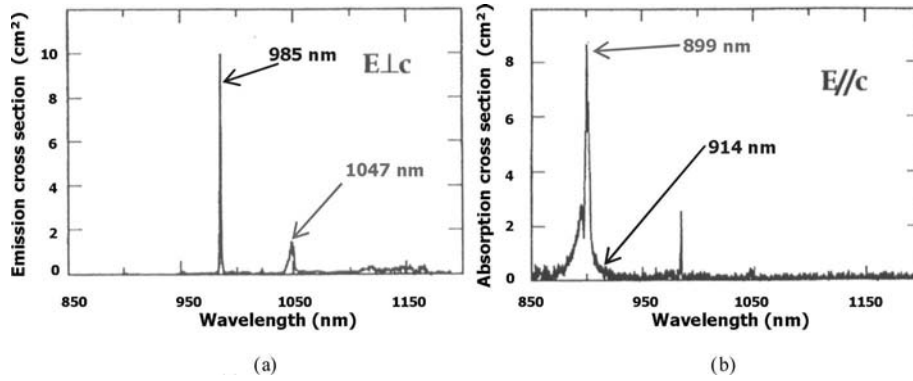


Fig. 1. (a) Emission and (b) absorption spectra of Yb:S-FAP crystals.

and highly transmissive at 1047 and 1064 nm once again to prevent the parasitic oscillation of the high gain transition lines in Nd:YVO<sub>4</sub> (1064 nm) and Yb:S-FAP (1047 nm). Different output couplers have been tested for the last mirror, M<sub>4</sub>, but the best results were obtained with one having a transmission of 33% at 985 nm, but which was still highly reflective at 914 nm. In the second waist of the cavity (between M<sub>3</sub> and M<sub>4</sub>), we introduced an AR-coated (at 985 and 914 nm) Yb:S-FAP crystal. As the Yb:S-FAP absorption is an important parameter for the overall efficiency, we experimentally investigated the laser performance with different Yb:S-FAP samples whose lengths and doping concentrations varied. The results obtained are presented in Fig. 4. We can notice an optimum for a small signal absorption at ~3.4%. For a smaller absorption the intracavity power at 914 nm is very high, but the amount of the absorbed power at 914 nm is limited. On the contrary, for a higher absorption the induced losses are too important, which decreases the intracavity power at 914 nm and, therefore, absorbed power at 914 nm is lower. Thus, similar to the optimal output coupler for a laser cavity, the absorption of the Yb:S-FAP crystal has to be correctly chosen to achieve the best performance.

For the optimal crystal we obtained a power of 1.4 W at 985 nm for 20 W incident pump power at 808 nm [Fig. 5(a)] corresponding to a circulating power of 4.2 W with a 33% output coupler. The threshold was ~3.2 W of incident pump power at 808 nm, and the slope efficiency was ~8%. The laser emission was TEM<sub>0,0</sub>, fully polarized, and no other higher wavelength (1047 nm) has been observed. The measured line width was ~70 pm at half-maximum, limited by the resolution of the spectrum analyzer. Moreover, even with a high transmission output coupler (*T*=70% at 985 nm) laser oscillation has been obtained, leading to 500 mW at 985 nm. This demonstrates the very high gain at 985 nm with this pump configuration.

To achieve second-harmonic generation we inserted a 5 mm long KNbO<sub>3</sub> crystal (type 1 phase matching, *b* cut), inside the cavity close to the Yb:S-FAP crystal. As the two crystals have to share the same waist, we slightly shifted the Yb:S-FAP crystal from the waist plane so that the nonlinear

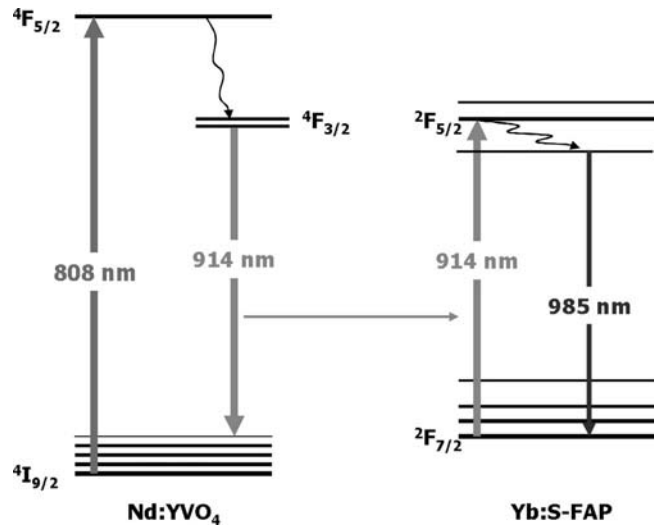


Fig. 2. Experimental energy level diagram for the Nd:YVO<sub>4</sub>/Yb:S-FAP system.

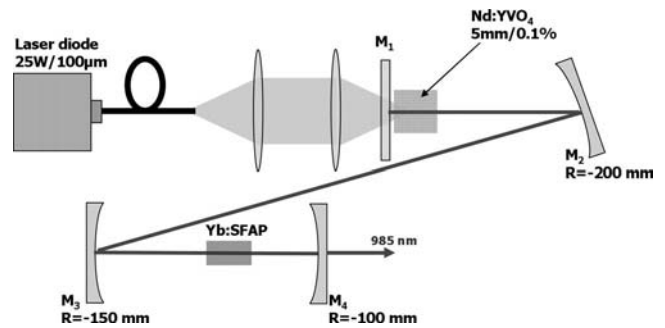


Fig. 3. Experimental setup.

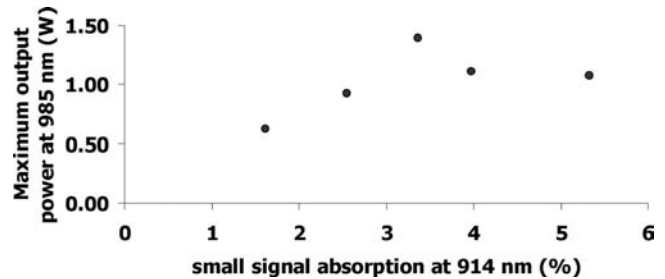


Fig. 4. Maximum output power at 985 nm versus Yb:S-FAP small signal absorption at 914 nm (20 W of incident pump power at 808 nm with a 35% output coupler at 985 nm).

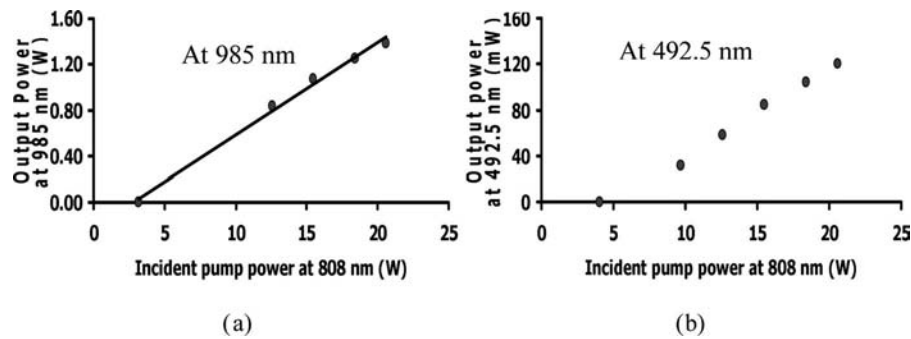


Fig. 5. (a) Output power at 985 nm versus incident pump power at 808 nm. (b) Output power at 492.5 nm versus incident pump power at 808 nm.

crystal could be closer to the waist position. Finally, we replaced the output coupler with a highly reflecting mirror at 914 and 985 nm.

The choice of a  $\text{KNbO}_3$  crystal is motivated by its nonlinear coefficient  $d_{\text{eff}}$ , which is 10 times higher than  $\text{LiB}_3\text{O}_5$ . With this configuration up to 120 mW (sum of the two output beams through the high-transmission mirror  $M_3$  and  $M_4$  in the blue) has been obtained at 492.5 nm, and the threshold was  $\sim 4$  W of incident pump power at 808 nm [Fig. 5(b)]. The threshold is slightly higher than in the previous configuration (with the output coupler of 35% at 985 nm) despite the use of a highly reflective mirror such as  $M_4$ . This is because the gain in the 985 nm cavity is lower, mainly owing to the shift from the waist position of the Yb:S-FAP crystal.

In conclusion, we have demonstrated the first, to our knowledge, indirectly diode-pumped Yb:S-FAP laser emitting at 985 nm with a maximum cw output power of 1.4 W for 20 W of incident pump power at 808 nm. This result is five times higher than previous results using Ti:sapphire pumping [14]. Hence, it represents what we believe to be the highest cw output power ever obtained with an Yb:S-FAP crystal operating on the three-level transition, and for the first time (to our knowledge) cw intracavity second-harmonic generation has been demonstrated, providing promising results with a total of 120 mW at 492.5 nm.

The laser efficiency at 985 nm can be improved because experiments and preliminary calculations show us that the optimal output coupler at 985 nm is not 33% but approximately 50%–60%. Indeed, the high output couplers used at  $\sim 70\%$  introduced passive losses of  $\sim 1\%$  at 914 nm. Thus, reducing the passive losses at this wavelength will increase the absorbed power and gain in the Yb:S-FAP and rep-

resents another way to enhance the output power at 985 nm. Finally, the microchip configuration will be investigated to develop a more compact and robust architecture.

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