High-power diode-pumped cryogenically cooled Yb:CaF2 laser with extremely low quantum defect

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High-power diode-pumped laser operation at 992-993 nm under a pumping wavelength 981 nm or 986 nm is demonstrated with $Yb:CaF_2$ operating at cryogenic temperature (77 K) leading to extremely low quantum defects of 1.2 % and 0.7 %, respectively. An average output power of 33W has been produced with an optical efficiency of 35 %. This represents the best laser performance ever obtained at such low quantum defects on intense laser lines.

OCIS Codes: 140.3615, 140.3380, 140.3480, 140.3580

Doped fluoride crystals have been known and identified as attractive laser media since the very beginning of the lasers [1]. In the field of ultrahigh-peak power laser with high repetition rate, very interesting laser development at cryogenic temperature has been done with Yb:YLF[2,3] and $Yb:CaF_2$ [4,5]. In the case of $Yb:CaF_2$, crystallographic and luminescence properties were already known a long time ago [6]. However, the characteristics of these materials have not been fully exploited, especially at high dopant concentration [7-10]: a broad emission band, a long emission lifetime of 2.3 ms, with moreover a good thermal conductivity [11,12] and at last, but not least, a well-mastered growing process for high-quality and large single crystals. Thus, Yb doping now allows calcium fluoride to strike back for high power laser applications; they indeed become in few years among the most promising laser materials for high-energy/high-power diode-pumped laser systems [13-16].

In this letter we present another typical property of $Yb:CaF_2$, which allows for efficient laser emission in a "quasi-two-level" laser scheme without any ultra wavelength-selective or narrow-linewidth intracavity element. This could represent a breakthrough for ultra-high-power lasers since it could lead both to efficient diode-pumped laser operation and to a minimal thermal load [5,17-19]. Moreover, as this quasi-two-level laser system operates at cryogenic temperature, it brings another positive advantage for high power laser devices, which consists in improving the thermal properties of the laser element such as its thermal conductivity.

Yb^{3+} has a simple electronic-level structure based on only two manifolds ($^2F_{7/2}$ and $^2F_{5/2}$) which splits into different crystal-field Stark sublevels whose number and energy separation depend on the symmetry and the strength of the local crystal-field environment. Due to charge compensation and minimum-energy arrangements of the ions in this system [6], the case of heavily doped $Yb:CaF_2$ is very particular. Indeed, the luminescent centers, responsible for the laser properties of the material, give rise to a typical relatively weak crystal-field and reduce crystal-field splittings of the Yb^{3+} energy levels (see in Fig. 1a).

Consequently, in addition to the broad-band vibronic structure, which extends from about 1000 to 1060 nm, and to the zero-phonon lines (corresponding to the so-called "zero-line" around 981 nm), there is another set of clear lines at 985.2 and 991.5 nm with substantial emission/absorption cross sections. They correspond to zero-phonon transitions from the lowest $^2F_{5/2}$ (emitting level at about 10200 cm^{-1}) to the second and third energy levels of the $^2F_{7/2}$ ground multiplet (around 50 and 110 cm^{-1}), respectively.

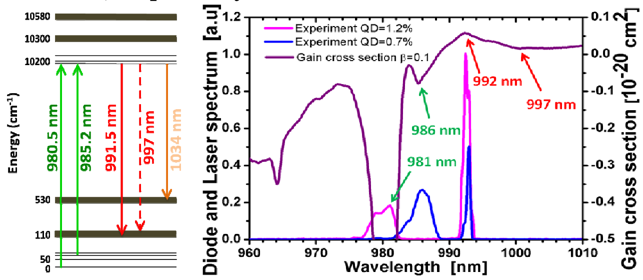

Fig. 1a Spectroscopic lines of Yb :CaF_2 at 77 K, (b) Experimental measurements of pump and laser wavelengths for pumping at 981 nm (blue curve) or 986 nm (red curve); and gain cross section of the Yb :CaF_2 at 77 K and for β=0.1 (purple curve).

Thus, laser operation at short-wavelength and "ultra-low quantum-defect" is possible by cooling the laser crystal down to Liquid Nitrogen (LN_2) temperature, as presented in the letter.

The experiments were performed with a 2.2-%-Yb-doped, 5-mm-long fluorite crystal. The experimental set-up is displayed in Fig. 2. In order to pump the crystal longitudinally and to allow simultaneously an extremely short wavelength separation between pump and laser, a broadband HR mirror of 2-mm-diameter glued on a 25-mm-diameter AR plate is implemented. This pump-beam-occulting mirror uses the advantage of the large diameter pump beam (collimated fiber-coupled laser diode with NA = 0.22) compared to the laser beam inside the $Yb:CaF_2$ laser resonator, forming as a so-called modal multiplexer. The corresponding losses observed on the pump beam do not exceed 4%. Moreover, the laser is free from any spectral selection and operates very efficiently at its maximum spectral gain without additional losses.

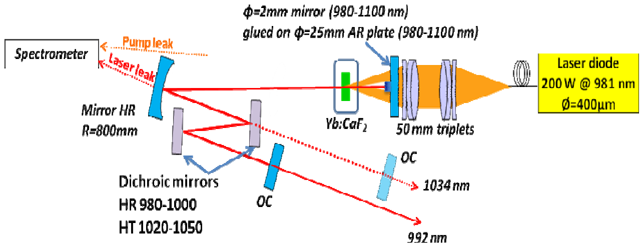

Fig.2: Experimental setup.

According to the emission and absorption spectra of $Yb:CaF_2$ registered at low temperature [5], the laser should have naturally operated, without extra wavelength selector, at 992 nm for an inversion population (β) higher than 10%. However, it is not the case, since laser operation remains fixed at 1034 nm, even for an average inversion population higher than 40%. This is probably due to uncertainty on the temperature elevation in the crystal. In order to favor the short wavelengths emission with a minimum of losses, we insert in the cavity (Fig. 2) a wavelength selector consisting of two high-pass dichroic mirrors highly reflective between 980 and 1000 nm with losses per bounce <0.1% at 992 nm, <1% at 997 nm and a high transmission (>95%) around 1030 nm. Consequently, the impact of this selector is acceptable and allows efficient laser at low wavelengths. In these conditions, laser operation occurs between around 992 nm and 997 nm.

Figure 3a displays the output power obtained for different output couplers. Thereby, we determine the spectral gain of the crystal at varying population inversion levels, estimated using the following equation:

$$\left(1 - T_{oc} - L\right)\exp\left(\left(\beta\sigma_{em} + (1-\beta)\sigma_{abs}\right)N\ell\right) = 1 \qquad \text{Eq. 1}$$

where N is the Yb-dopant concentration, σ_{em}, σ_{abs} are the emission and absorption cross sections at the laser wavelength (λ_L), ℓ is the length of the crystal, T_{OC} is the output coupler transmission and L the losses (vs λ_L).

At low inversion (β<0.05, e.g. T_{oc}=5%), only 997 nm is observed, whereas at intermediate levels (0.05<β<0.08) the gain is flat between 993-997 nm, e.g. for a 10% output coupler (β=0.065), the laser operates simultaneously at 997.1, 994.2 and 993.0 nm. At higher inversion levels (β>0.08) the laser operates around 992 nm: for an output coupler of 15% (β=0.09) or higher the laser wavelength lies between 992.7 and 992.0 nm.

The best CW laser performance at 992 nm has been obtained with the 15% OC (β=0.11) with a laser emission of 33 W for 93 W absorbed pump power (under laser operation). The laser efficiency is then 35 % (Fig. 3b). The measured small signal gain is found to be equal to 2.7.

The laser and pump emission wavelengths were measured simultaneously. Figure 1b reports these pump and laser wavelengths at the maximum output power. On the same graph the gain cross section is also plotted for the value β=0.1 corresponding to the optimal power. The predominance of the gain at 992.0 nm clearly appears, corroborating the experimental results. The mean emission wavelength is 992.7 nm and the mean pump wavelength is 980.7 nm, which corresponds to a very low laser quantum defect $\eta_{QD\ laser}=1-\lambda_p/\lambda_L=1.2\%$. Those results clearly indicate the strong potential of $Yb:CaF_2$ used at cryogenic temperature for high power laser developments where efficiency and heat load are an issue.

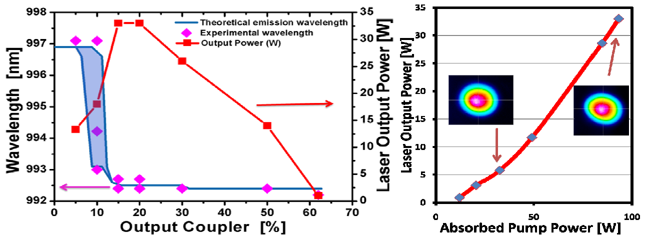

Fig. 3a : Experimental and theoretical emission wavelengths and laser power obtained for different output couplers. 3b: Corresponding laser power (at optimum) vs absorbed pump power at 981 nm obtained with a 15 % OC and associated beam profiles at low and high powers.

It is interesting to note that for broadband amplification (992-997 nm), the optimal operation should be obtained at low inversion levels.

Exploiting such small quantum defect configuration might be challenging and it is worth considering a number of points. It is important to identify that thermal loads in ytterbium-doped laser materials come from three types of non-radiative relaxations: the laser quantum defect ($\eta_{QD\ laser}$=1.2%) between pump and laser photons, the fluorescence quantum defect ($\eta_{QD\ fluo}=1-\lambda_p/\lambda_F=3.1\%$) between the pump and fluorescence photons and non radiative desexcitations from $^2F_{5/2}$ to $^2F_{7/2}$ levels, evaluated in our case to 0.7 % of the absorbed pump photons [12]. Then, 1.2%×35% (35%=laser efficiency) of these absorbed pump photons heats the crystal by laser quantum defect and 3.1%×64% by fluorescence quantum defect. Consequently, for a total absorbed pump power of 93W, this leads respectively to 0.65 W, 0.39 W and 1.85 W (total of 2.9 W).

This clearly indicates that in a small quantum defect laser the thermal loads due to the fluorescence quantum defect cannot be neglected. Therefore, the laser efficiency directly impacts on the thermal loads. In our experiement, the efficiency is limited by the losses providing from the not fully-ideally-coupled cavities of the uncoated facet of the crystal and/or to residual pollution due to our non-perfect cryostat vacuum.

The second issue to be considered, especially at high pump power, is the thermal conductivity of the laser material. From this point of view, $Yb:CaF_2$ is particularly interesting since its thermal conductivity at LN_2 temperature rises up to 68 W/m/K for an undoped material[11] and to 23 W/m/K[5] for a 2.2%Yb-doped one.

This means that the thermal loads can be efficiently evacuated and that the thermal lensing effects should be greatly reduced. This is clearly what we noticed in our experiments since no thermal lensing effect was observed even at full pump power (Fig. 3b).

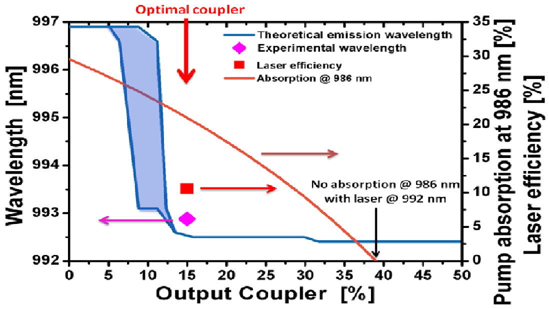

Fig. 4 : Theoretical emission wavelength and theoretical percentage of absorbed pump power at 986 nm versus β. Experimental laser wavelength and laser efficiency have been plotted for the optimal value β=0.09 (15 % OC).

A last point which can be noticed by examining the gain cross section for β=0.1 reported in the figure 1 is the absorption line at 986 nm in order to decrease further the laser quantum defect. As plotted in the figure 4, the theoretical absorption of our crystal at 986 nm (for a single pump pass) is only 30 % at maximum (and without saturation) and becomes null for β=0.21 (or equivalently for a laser at 992 nm and with T_{oc}=39 %). On the other hand, we have to remember that there is also a constraint for β to emit at 992 nm. As a matter of fact, the optimal inversion population was found around 0.09 which corresponds in our case to an output coupler of 15 %. The experiment was performed and we obtained a laser output power of 4 W for an absorbed pump power of 35 W (efficiency of 11 %). The laser wavelength (Fig. 1b and Fig. 4) was 992.9 nm, leading to a low quantum defect of 0.7 %.

In conclusion, we have demonstrated, simultaneously for the first time, a low quantum defect, highly efficient and high-power laser operation of an Yb:CaF_2 laser crystal at cryogenic temperature. This represents an important step towards practical lasers based on Yb:CaF_2 operating at very high power levels. As a matter of fact, by using the simple figure of merit given by the ratio (thermal conductivity)/(quantum defect), we find record values of 5700 W/m/K for pumping around 981 nm and 9700 W/m/K around 986 nm[14]. Moreover, Yb:CaF_2 really appears as a favorable material for such a kind of low quantum-defect laser operation (more than any other material) because of the existence of this sharp emission peak around 992 nm with a substantially high emission cross section. Such a peak does not exist in a system like Yb:CALGO [15], Yb:KGdLu(WO_4) [17], materials which also gave rise to a very low-quantum defect laser operation, but with a much lower laser efficiency. Such a peak exists in the case of Yb:YLF [18]. However, the lowest quantum defect which could be (theoretically) obtained would be around 2% and the one achieved so far, by pumping around 960nm (which is not a common diode wavelength) was around 3.5%. Yb:CaF_2 has then this rare property of having clear peaks very close to the zero-phonon-line, which is very auspicious to efficient ultra-low-quantum-defect diode-pumped laser. Moreover concerning absorption improvement, this can be done using pump-recycling such as in thin disks.

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