Ultra-short-pulsed and highly-efficient diode-pumped Yb:SYS mode-locked oscillators

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Laboratoire Charles Fabry de l'Institut d'Optique du CNRS et de l'Université Paris-Sud, Centre Universitaire, Bat 503, 91403 Orsay Cedex, France Phone: (33) 1 69 35 88 52, Fax: (33) 1 69 35 88 07,
frederic.druon@iota.u-psud.fr

http://www.elsa-laser.com

Abstract: We report the shortest pulses ever produced with an $Yb^{3+}:SrY_4(SiO_4)_3O$ {Yb:SYS} laser. 70 fs has been demonstrated for an average power of 156 mW at 1066 nm. Moreover, tunability in the 100-fs range has been obtained between 1055 nm and 1072 nm. Finally, an average power of 420 mW has been obtained at 1068 nm with 110-fs pulses.

OCIS codes: (140.5680) Rare earth, solid state laser, (140.3480) Laser, diode-pumped, (140.4050) Mode-locked lasers, (999.9999) Laser, Ytterbium, (140.3070) Infrared and far-infrared lasers.

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1. Introduction

Ytterbium-doped crystals are now well-known to be particularly suitable for directly diode pumped, solid state femtosecond oscillators. In fact, thanks to their absorption band accessible by efficient InGaAs diode lasers and their good spectral properties, very efficient lasers have been demonstrated in the sub-picosecond regime [1-16]. Another interesting advantage of Yb-doped crystals concerns their simple electronic level structure, composed of only two manifolds ($\Delta E \approx 10000$ cm^{-1}), that avoids most of the parasitic effects such as up-conversion, excited-state absorption or concentration quenching and that leads to a very low quantum defect. This is why numerous efficient, simple, compact and robust ultrashort-pulsed solid-state lasers using such materials have been studied and developed for the last decade. Nevertheless, among the dozen of Yb-doped crystals already demonstrated in mode-locked oscillators, only five of them had allowed the efficient production (>100 mW) of sub-200 fs pulses: Yb:BOYS [11], Yb:SYS [12], Yb:KGW [5,8,9], Yb:KYW [6-9] and Yb:CaF_2 [16] (Fig. 1).

On the first hand, the undoubtedly most developed Yb-doped crystals for the production of high power oscillators emitting pulses within this duration range are the Yb-doped tungstates: Yb:KY$(WO_4)_2$ {Yb:KYW} and Yb:KGd$(WO_4)_2$ {Yb:KGW}. Indeed, their exceptionally high cross sections (in particular the emission cross sections of $\approx 4\ 10^{-20}$cm^2) made the Yb-doped tungstates very attractive. The laser developments with these crystals have then led to a multitude of remarkable femtosecond systems including modelocked oscillators using SESAM [5,8,9] (which is up to now the most common and most reliable process in terms of stability for modelocking [17] with the Yb-doped crystals), Kerr-lens-modelocked (KLM) oscillators [6], very-high-power thin-disk oscillators [7], femtosecond amplifiers [18,19]. In the actual state of the art, the shortest pulse durations obtained with tungstate-based oscillators modelocked with SESAM are limited to 100 fs for the Yb:KYW, demonstrated by Klopp *et al*.[8], and, more recently, to 101 fs for Yb:KGW, demonstrated by Paunescu *et al*.[9].

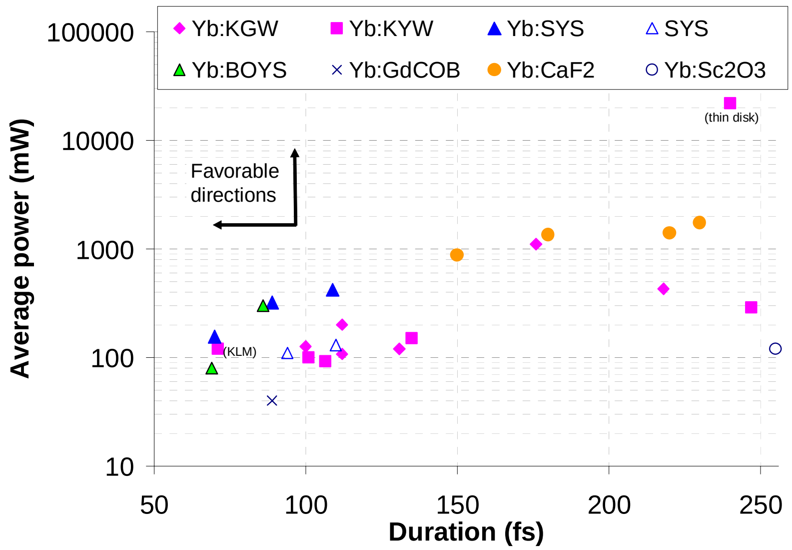

Fig. 1. Performances (average power vs. pulse duration) for mode-locked lasers based on Yb-doped crystals[5-13,16] (N.B. The modelocking process use SESAM if not mentioned).

On the other hand, Yb:BOYS and Yb:SYS crystals are very interesting crystals for the production of sub-100 fs thanks to very broad and smooth emission spectra. Moreover, the Yb:SYS crystal, thanks to better spectroscopic properties (higher emission cross section and broader emission band) [20-22], its better thermal conductivity [23] and its recent demonstration in a regenerative amplifier [24], seems *a priori* more interesting than the Yb:BOYS. Nevertheless, up to now the potential of this crystal was not truly exploited: the shortest pulses obtained with the crystal were only 94 fs [12] and the maximum output power was only 130 mW. Yb:SYS is then a very interesting crystal; but, up to now, no veritable breakthrough have been demonstrated using this crystal. In this paper, we demonstrate that Yb:SYS crystal is also convenient for the production of shorter pulse and higher average powers.

2. Spectral properties of Yb:SYS

Yb^{3+} ion spectroscopy is well known to be very dependant on the matrix host. In particular the broadness of the emission and absorption bands strongly depends on the disorder of the crystal and subsequently on the variance of the local crystalline electric field seen by Yb^{3+} ions. Yb:$SrY_4(SiO_4)_3O$ crystal thus presents a broad emission band due to a high disorder in its lattice. Firstly, a cationic disorder: there is an equally random distribution of strontium and yttrium on a same Wyckoff site 4f [20-22, 24]. Secondly, a multisite occupancy of the dopant: there are two different sites for the substitution of Yb^{3+}. Actually, owing to compatibility of charge and ionic radii, the ytterbium ions tend to substitute yttrium ions; and, because Y^{3+} ions occupy two different Wyckoff sites (4f and 6h), Yb^{3+} can be then located in these sites. The ratio of Yb occupancy is 3 to 1 at the advantage of the 6h sites. The two sources of disorder lead to broad optical spectra. However, one can notice little differences between the optical properties for the two crystallographic axes of this biaxial crystal. In fact, although, the absorption spectra are very similar whatever the direction (Fig. 2), the emission spectrum is smoother along the π axis (polarization $// \vec{c}$) than along the σ axis (polarization $\perp \vec{c}$).

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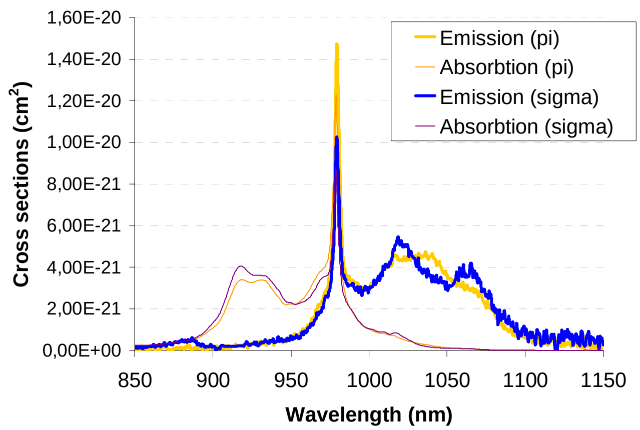

Fig. 2. Absorption and emission spectra of the Yb:SYS along the σ and π axes.

The spectral properties of the Yb:SYS are interesting for several reasons: firstly, its absorption spectra allows the possibility of pumping on very broad bands around 930 or 980 nm without concern regarding the polarization. Secondly, Yb:SYS, which belongs to the apatite family (silicate oxyapatite), exhibits a relatively high emission cross section (around $0.5\text{x}10^{-20}$ cm^2 at 1040 nm) compared to the other materials with similar broad and smooth spectra such as Yb:glass and Yb:BOYS [11]. Thirdly, the large emission bands of Yb:SYS can extend laser operation to the longer wavelengths (especially compared to tungstates), which may lead to interesting laser emission in the 1050-1070 nm range overlapping the Nd-doped-material spectra (e.g., compatibility with Yb:glass femtosecond terawatt chains, compatibility with very standard optical components). This last point can be clearly observed in Fig. 3 representing the gain cross sections versus the wavelength. One can notice, along the π axis, an almost flat gain between 1040 and 1070 nm for $\beta \in [0.06, 0.1]$ and along the σ axis, a broad peak appearing at 1064 nm. Finally another advantage of the Yb:SYS material is its large ground-state crystal-field total splitting of 810 cm^{-1} [20] (compared to ≈550 cm^{-1} for the tungstates). This splitting is very important to reduce the effect of thermal population in this quasi-3-level laser material.

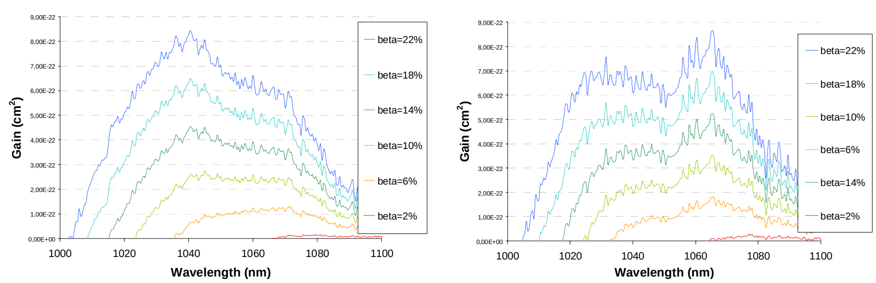

Fig. 3. Gain cross section (σ_g) along the π (left figure) and σ (right figure) axes for different values of population inversion rate β. σ_g is given by $\sigma_g = \beta\sigma_e - (1-\beta)\sigma_a$ where σ_e and σ_a are the emission and absorption cross sections.

The disadvantages of the Yb:SYS, especially compared to the tungstates, involve, of course, the emission cross section that is one order of magnitude lower for the SYS, but also the thermal properties which are better in the tungstates whose thermal conductivity (for undoped crystals) is 3.8 $Wm^{-1}K^{-1}$ compared to 2.85 $Wm^{-1}K^{-1}$ ($// \vec{c}$) and 1.5 $Wm^{-1}K^{-1}$ ($\perp \vec{c}$) for the SYS. Nevertheless, in the case laser oscillators (for which the laser extraction efficiency is important), these disadvantages do not necessary lead to a degradation of laser performance, and the laser efficiency in watt-range pump-power can be equivalent for Yb:SYS and Yb-doped tungstates.

3. Experimental setup

The experiment was performed with a 5.5-%-doped (8.4×10^{20} Yb^{3+} at/cm^3), 3-mm-long, AR-coated Yb:SYS crystal put in a standard cavity designed for the production of femtosecond pulses as described in Fig. 4. The crystal was cut to have the propagation axis perpendicular to $\vec{c}$, which allowed to have the laser polarized $// \vec{c}$ or $\perp \vec{c}$. The crystal was located between two dichoïc mirrors whose radius of curvature (RoC) was 100 mm; the laser beam waist in the cavity was 27 µm. In one of the collimated arms of the cavity a pair of SF10 prisms, separated by 40 cm, was used to compensate the group velocity dispersion, and a slit to tune the central wavelength was placed between these two prisms. The output coupler was placed behind the second prism; its transmission was typically 2 % or 4 %. On the other arm, we used a 300-mm, 400-mm or 500-mm RoC mirrors (M_1) to focus the laser beam onto the SESAM [25] in order to optimized the incident fluence on the saturable absorber. The SESAM was designed by High Q lasers for lasers emitting around 1.06 µm and has a saturable absorption around 2 %.

The pump beam was emitted by a 4-W single-stripe 1x100-µm^2 laser diode linearly polarized parallel to the polarization of the laser. The laser-diode emission wavelength was 979 nm. The pump beam was collimated a by 16 mm aspherical lens, then extended along its slow axis by cylindrical lens x8-expander. The beam was then reshaped in order to increase the brightness in its slow direction using a Porro prism design (Fig. 4). After the focalization by an 80-mm-focal-length doublet, the pump spot in the crystal was about 60x40µm^2.

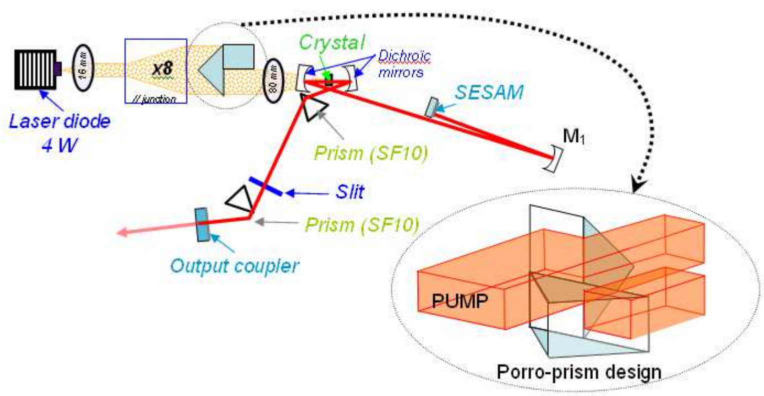

Fig. 4. Experimental setup.

The use of the Porro-prism system increased the brightness of the diode along its slow-axis and uniformized the pump beam in the crystal and allowed to avoid the appearance of TEM_{10} spatial profile which counteracted the mode-locking process especially when using the tuning slit. Compared to the design described in reference [12], we could then extend the tunability, use broader-band SESAM, increase the gain and finally reduce the pulse duration.

4. Experimental results

First, we design a cavity in the purpose of obtaining the shortest pulse duration. The crystal was oriented to have the laser polarized $// \vec{c}$ e.g. to access the broadest gain bandwidth. The output coupler transmission was 2 %, the RoC of M_1 was 300 mm. Adjusting the prisms and slit position, we could reach the production of 70 fs pulses as shown in the Fig. 5 representing the autocorrelation trace of these pulses.

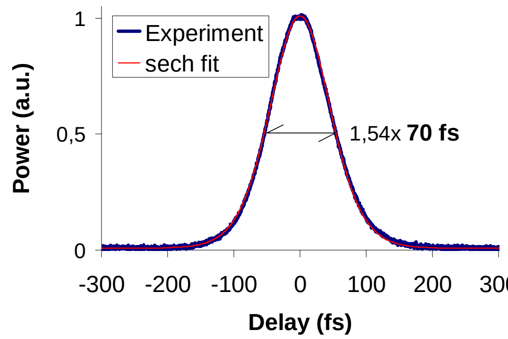

Fig. 5. Autocorrelation trace of 70-fs pulses.

The central wavelength of the 70-fs pulses was 1066 nm and the FWHM bandwidth of the spectrum was 17.3 nm (Fig. 6), which leads to time-bandwidth product of 0.32.

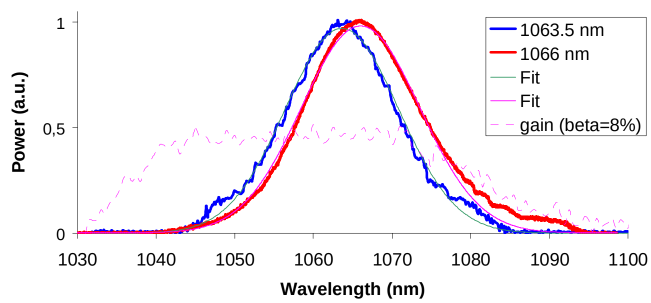

Fig. 6. Spectra of 70-fs pulses at 1066 nm and 75-fs pulses at 1063.5 nm. The gain cross section for $\beta = 8\%$ is also represented (in arbitrary units).

The average power was 156 mW and the repetition rate 98 MHz, corresponding to an energy per pulse of 1.6 nJ and a peak power of 20 kW. Translating the slit, one achieved to tune the laser of only 2.5 nm (Fig.6) for pulse durations below 75 fs and power above 142 mW as shown in Fig. 7. Out of this tunability region the laser switches to multi-pulse operation. This small tunability can be partially explained by the gain spectral broadness of Yb:SYS crystal. In order to have a simple visualization of the estimated gain bandwidth, we also represents in Fig. 6 the gain cross section (in arbitrary units) corresponding to a population inversion rate around 8 % which is compatible with this crystal under such diode pumping [26]. But, one can also observed that gain bandwidth (especially in the shorter wavelengths) is not fully covered by the pulse spectra, meaning that the Yb:SYS crystal is not fully exploited.

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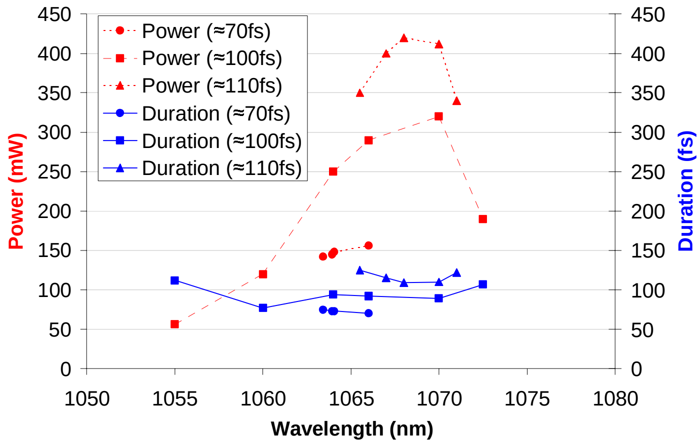

Fig 7. Tunability of the femtosecond oscillator: the laser average power and the pulse duration are plotted versus the central wavelength.

Secondly, in the purpose of increasing the power, the output coupler transmission is increased to 4 %. Average power up to 320 mW was obtained for pulse durations around 90 fs. Moreover, we demonstrated a continuous tunability from 1055 nm to 1072.5 nm (Fig. 7) which is still coherent with the estimated gain bandwidth (represented by the gain cross section for a population inversion rate around 8 %). At the maximum power (320 mW), the pulse duration was 89 fs and the central wavelength was 1070 nm. The corresponding energy per pulse was 3.3 nJ and the peak power 32 kW. The pulse durations were between 77 fs at 1060 nm and 112 fs at 1055nm (see Fig. 7).

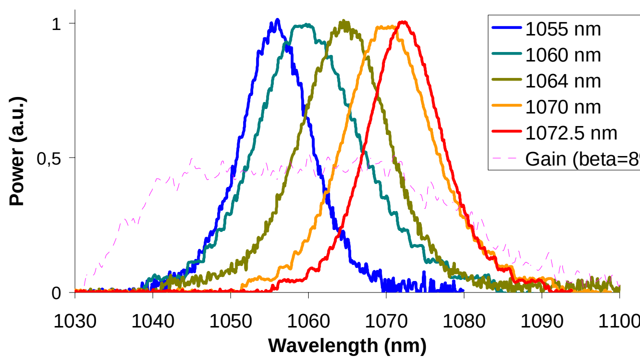

Fig. 8. Spectra presenting the tunability in the 100-fs range from 1055 to 1072.5 nm. The gain cross section for $\beta = 8\%$ is also represented (in arbitrary units).

Thirdly, in the purpose of maximizing the average power, we have modified the cavity. The crystal was oriented with laser polarized perpendicular to c axis, e.g., to access the highest emission cross section despite a more uneven gain bandwidth (Fig. 2). The maximum output power was obtained with an output coupler transmission of 4 %, and for a M_1 RoC of 500 mm. We then demonstrated up to 420 mW of average output power for 110 fs pulses (Fig. 7). The repetition rate was 93 MHz, the energy per pulse was 4.5 nJ and the peak power was 36 kW.

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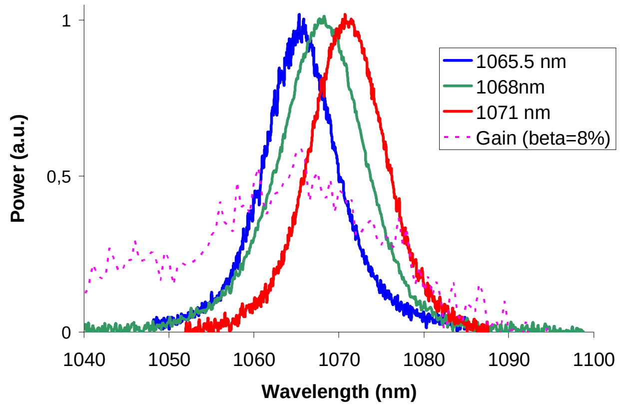

Fig. 9. Spectra representing the tunability in the 110-fs range from 1065.5 to 1071 nm. The gain cross section for $\beta = 8\%$ is also represented (in arbitrary units).

Tunability from 1065.5 nm to 1071 nm (Fig. 9) was also demonstrated for average powers higher than 340 mW and with pulse durations below 125 fs. Again, this tunability was in a relatively good agreement with the gain cross section considering laser emission polarized $\perp \vec{c}$ and also presented in Fig. 9.

6. Conclusion

In conclusion, we demonstrated that Yb:SYS is a suitable crystal for the efficient production of 70-fs pulses at 1066 nm. This pulse duration is very similar to the shortest durations obtained with the Yb:BOYS (69 fs) or Yb:KYW (71 fs) (Fig. 1). Nevertheless, the Yb:SYS becomes an interesting challenger in the 70 fs range. Actually, first, the experiment has been carried out with an oscillator modelocked by SESAM which is much more stable than the KLM modelocking used in the case of Yb:KYW. Second, the average output power was almost twice higher in the case of Yb:SYS than in the case of Yb:BOYS. A broad tunability between 1055 nm and 1072.5 nm has also been demonstrated. This tunability range is indeed interesting because it is shifted compared to the typical wavelengths emitted by Yb-doped tungstate and it is close to the ones of Nd-doped materials. Finally, an optical-optical efficiency larger than 10 % had also been demonstrated with production of 110-fs pulses with an average power of 420 mW at 1068 nm. This oscillator thanks to its high stability and its wavelength very closed to 1064 nm (wavelength where plethora of components are available) could have been used in a pulse-compression experiment using a photonic crystal fiber with zero-dispersion, and pulse down to 20 fs had been produced [27]. Up to now the only drawback of the Yb:SYS concerns its thermal properties which limits the pump power in the 5 W range (with classical longitudinal pumping design). Nonetheless, the solution of using undoped/doped composite crystals [28] (in particular using Yb:SYS bonded with YAG) seems to be interesting and is under investigation…

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