High-brightness fiber laser-pumped 68 fs-2.3 W Kerr-lens mode-locked Yb:CaF2 oscillator

Guillaume Machinet, P. Sevillano, F. Guichard, R. Dubrasquet, P. Camy, Jean-Louis Doualan, Richard Moncorgé, Patrick Georges, Frédéric Druon, D. Descamps, et al.

Guillaume Machinet, P. Sevillano, F. Guichard, R. Dubrasquet, P. Camy, et al.. High-brightness fiber laser-pumped 68 fs-2.3 W Kerr-lens mode-locked Yb:CaF2 oscillator. Optics Letters, 2013, 38 (20), pp.4008. 10.1364/OL.38.004008 . hal-00904508

HAL Id: hal-00904508
https://hal-iogs.archives-ouvertes.fr/hal-00904508v1

Submitted on 22 Apr 2016

High-brightness fiber laser-pumped 68 fs–2.3 W Kerr-lens mode-locked Yb:CaF$_2$ oscillator

G. Machinet,[1,*] P. Sevillano,[1] F. Guichard,[1] R. Dubrasquet,[1,2] P. Camy,[3] J.-L. Doualan,[3] R. Moncorgé,[3]
P. Georges,[4] F. Druon,[4] D. Descamps,[1] and E. Cormier[1]

[1]*Université Bordeaux-CNRS-CEA-UMR 5107, Centre Lasers Intenses et Applications, 351 Cours de la Libération, F-33405 Talence, France*

[2]*Azur light System, Cité de la Photonique-Meropa, 33600 Pessac, France*

[3]*Centre de recherche sur les Ions, les Matériaux et la Photonique (CIMAP), UMR 6252 CEA CNRS-ENSICaen, Université de Caen, 14050 Caen, France*

[4]*Laboratoire Charles Fabry, Institut d'Optique, CNRS, Université Paris Sud, 2 Av. A. Fresnel, 91127 Palaiseau, France*

**Corresponding author: machinet@celia.u-bordeaux1.fr*

By using a high-brightness fiber pump laser, we demonstrate a pure Kerr-lens mode-locked (ML) Yb:CaF$_2$ oscillator. The laser delivers 68 fs pulses with 2.3 W average power at 73 MHz repetition rate and an optical-to-optical efficiency of 33% is achieved. To the best of our knowledge, this is the first demonstration of Kerr-lens mode-locking in Yb:CaF$_2$. Incidentally, we report here the highest average power ever achieved for a sub-100-fs active Kerr-lens ML Yb-bulk oscillator.

During the past decade, laser development using Yb-doped materials and in particular when Yb^{3+} ions are embedded in crystal hosts has become a very active and competing field in laser research in the quest of high average power and ultrashort pulses. Many studies aim at identifying the optimal Yb-doped material for these purposes. Among them, Yb:CaF$_2$ has made an impacting revival, demonstrating very promising results for short [1], high average power [2], and energetic pulse generation [3]. Indeed, Yb:CaF$_2$ offers good thermal properties with a thermal conductivity of 5 $\mathrm{W\cdot m^{-1}\cdot K^{-1}}$ for a 2.5% Yb doping concentration [4] associated to a very broad emission bandwidth. Finally, the long fluorescence lifetime of 2.4 ms denotes a high-energy storage capacity. All these properties would allow the amplification of energetic femtosecond pulses [5].

Nevertheless, compared to its other Yb-doped counterparts, femtosecond oscillators using Yb:CaF$_2$ crystals seem far from having exploited all the potential of this broadband material, with demonstrated pulse duration of around 100 fs [1]. In order to extend the performance currently demonstrated in Yb:CaF$_2$ mode-locked (ML) oscillators using saturable absorbers semiconductor saturable absorber mirror (SESAM), we propose to explore here the potential of Kerr-lens mode-locking (KLM) with this crystal. Within the current state of the art and as far as pulse duration is concerned, KLM tends to provide better results than other passive mode-locking techniques such as saturable absorbers, because KLM mode-locking is not limited by the SESAM properties. With respect to Yb-doped bulk lasers, mode-locking oscillators by Kerr-lens effect have been achieved so far only in four crystals, namely Yb:KYW, Yb:YVO$_4$, Yb:Sc$_2$O$_3$, and Yb:YAG where the shortest pulse durations were respectively 71 fs [6], 61 fs [7], 92 fs [8], and 35 fs [9]. In these cases, KLM is associated to A Kerr-lens ML strong self-phase modulation (SPM) that tends to significantly broaden the laser spectra. KLM also offers additional advantages. Some Yb-doped crystals, such as Yb-doped fluorides, have a low emission cross-section (high saturation fluence of the gain) that makes their use critical in an oscillator including a SESAM as energetic pulses can be easily produced during transient regimes damaging the semiconductor component [10]. These Q-switched regimes (both CW or ML) often appear while minimizing the pulse duration, and making some "fragile" SESAMs difficult or even impossible to handle with Yb:CaF$_2$. In this context, KLM could also provide a solution to these problems.

KLM Yb:CaF$_2$ implies solving serious issues. In fact, Yb:CaF$_2$ has a very low nonlinear refraction index ($n_2 \sim 1.9 \times 10^{-20}\ \mathrm{m^2/W}$) [11] as compared to other crystals, such as Yb:YAG ($6.2 \times 10^{-20}\ \mathrm{m^2/W}$) [12], Yb:Sc$_2O_3$ ($11 \times 10^{-20}\ \mathrm{m^2/W}$) [13], or Yb:YVO$_4$ ($40 \times 10^{-20}\ \mathrm{m^2/W}$) [14]. A Kerr-lens ML oscillator with Yb:CaF$_2$ requires very large intensities to induce a noticeable modification of the spatial mode cavity through the nonlinear refractive index variation. A straightforward solution would consist in increasing significantly the intensity inside the cavity. It could be achieved by either increasing the doping concentration, at the cost of deleterious thermal issues [15], or by simply using longer crystals where the thermal load is spread over a longer distance. However, maintaining a tight focusing in long crystal requires a high brightness pump source incompatible with high power laser diodes.

In this Letter, we report, to the best of our knowledge, on the first demonstration of a pure KLM in Yb:CaF$_2$ crystal in a configuration implementing high-brightness optical pumping with a single-mode fiber laser source [16]. After describing the experimental setup, we present the performance of the KLM Yb:CaF$_2$ oscillator and discuss the robustness of the mode-locking with regard to the pumping parameters.

A sketch of the laser cavity and pumping geometry is presented in Fig. 1. We use a 6-mm-long, 4 mm × 4 mm Brewster-angle cut 4.5 at. % Yb:CaF$_2$ crystal mounted

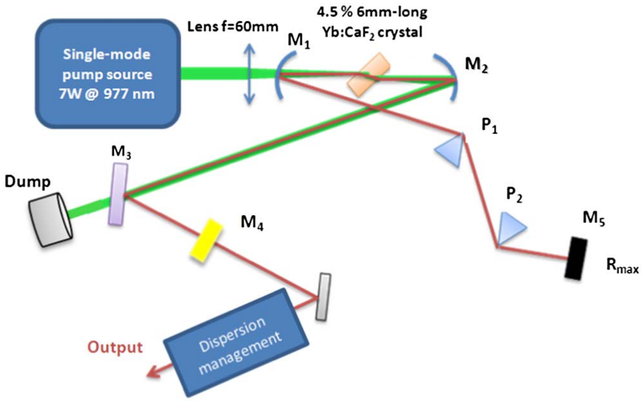

Fig. 1. Experimental setup of the KLM Yb:CaF$_2$ oscillator.

in a water-cooled copper holder. The Yb:CaF$_2$ crystal is positioned between two $R = 100$ mm spherical mirrors (M$_1$, M$_2$) in a standard X-fold cavity configuration. To compensate the astigmatism due to the Brewster-angle incidence, these mirrors are tilted with an angle of 8°. On one side, the cavity is delimited by a high reflection (HR) mirror (M$_5$) where a pair of SF10 60° prisms (P$_1$, P$_2$) (separated by a distance of 325 mm) is inserted as an intracavity dispersion control. The cavity is closed on the other side by a 10% output-coupler (M$_4$). The mirrors of the cavity are specified to introduce a low group-velocity dispersion. The cavity is nearly symmetric and its length of 2.05 m corresponds to a repetition frequency close to 73 MHz.

The Yb:CaF$_2$ crystal is longitudinally pumped by the high-brightness fiber pump source through the M$_1$ dichroic mirror (HT for wavelength below 980 nm and HR above 1020 nm). The pump source consists in an Yb-doped fiber laser emitting up to 7 W of linearly polarized amplified spontaneous emission radiation at 977 nm with a spectral bandwidth of 3 nm and is characterized by a high spatial quality with a M$_2$ of 1.5. The pump radiation is focused into the Yb:CaF$_2$ crystal by a 60 mm focal-length lens. The high spatial quality of the pump beam allows us to obtain a spot radius at the focal plane of 32 μm (at $1/e^2$) leading to a confocal parameter equal to 4.4 mm and a maximum pump intensity of 435 kW/cm^2. Hence, the absorption of the Yb:CaF$_2$ is saturated when the pump focus is positioned in the middle of the crystal leading to an unabsorbed power of 4.2 W. Under this pump intensity and without lasing effect, the inverted population on-axis is estimated to be 48% [17].

Because of the very high brightness of our pump source and the significant unabsorbed pump power, a back reflection of the pump from the output coupler is observed. In this situation, the gain channel in the Yb:CaF$_2$ crystal is laterally extended and can additionally affect the power stability of the single-mode pump source. Both effects depend on the M$_2$ position. To avoid these troubles inherent to the high brightness pump, we insert a dichroic mirror M$_3$ (HT at 980 nm and HR above 1020 nm for an incident angle of 22.5°) before the output coupler.

At first, we characterize the CW performance of the high-brightness fiber-pumped Yb:CaF$_2$ oscillator. At 7 W of incident pump power, a maximum output power of 3 W is obtained at the central wavelength of 1049 nm. In this configuration, the unabsorbed pump power measured after the dichroïc mirror M$_3$ is 1 W leading to an optical-to-optical efficiency of 43%. Since optical losses in the cavity are weak and no thermal birefringence in Yb:CaF$_2$ crystal is observed (Prisms losses ~100 mW and Brewster Yb:CaF$_2$ losses ~20 mW), the laser threshold has been measured to be 800 mW with a 10% output coupler. From the Brewster-angle reflection of the Yb:CaF$_2$ crystal, the laser beam waist in the sub-cavity has been measured to be $38\ \mu m \times 32\ \mu m$ (radius at $1/e^2$) in good agreement with the ABCD matrix formalism. Since the pump source used in this setup is characterized by a low M^2 value, a very good spatial overlap between the laser beam waist and the gain channel is achieved over the 6 mm crystal length and leads to a high optical-to-optical efficiency [17].

In order to discriminate the CW and ML regimes in the oscillator, we adjust the M$_2$ curved mirror position (+400 μm), a configuration where the CW regime is less stable. The CW output power drops down to 2 W and the output spatial beam becomes elliptical [cf. Fig. 2(c)].

Then a stable KLM is initiated by simply translating the prism P$_2$. In a daily operation, when the KLM starts, a small fraction of the power remains in the CW regime, however suppressed with a small displacement of the prism P$_1$. In an optimal configuration (3 mm of P$_2$ is inserted in the beam path), the oscillator delivers 75 fs (FWHM autocorrelator value assuming a sech pulse shape) at the 73 MHz repetition rate with an average power of 2.32 W. We estimate the GDD introduced by the prisms to be -2600 fs^2. Stable femtosecond pulse trains have been always observed without *Q*-switching and an ML shot-to-shot energy stability of 1.35% RMS over 30 min has been measured. The spectrum of the femtosecond pulses is centered at 1049 nm with a 19 nm bandwidth [see Fig. 2(a)] and corresponds to a Fourier transform-limited duration of 67 fs (FWHM). Indeed, the temporal pulse profile from the oscillator has been characterized through a SHG-FROG device and a quadratic phase has been measured and compensated by an external compressor requiring 8 bounces on -100 fs^2 chirped mirror (global transmission of 99.2%). Figure 3 shows the FROG traces as well as the retrieved pulse characteristics at the external compressor output. A 68 fs pulse duration (FWHM) has been achieved in close agreement with the independently measured autocorrelation width of 105 fs (68.2 fs deconvoluted

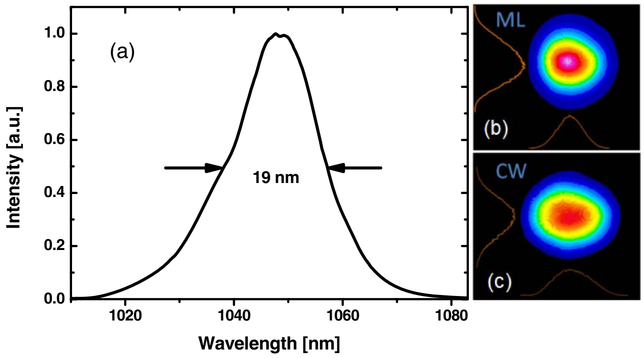

Fig. 2. (a) Spectrum measurement. Far-field spatial beam in (b) ML and (c) CW regime.

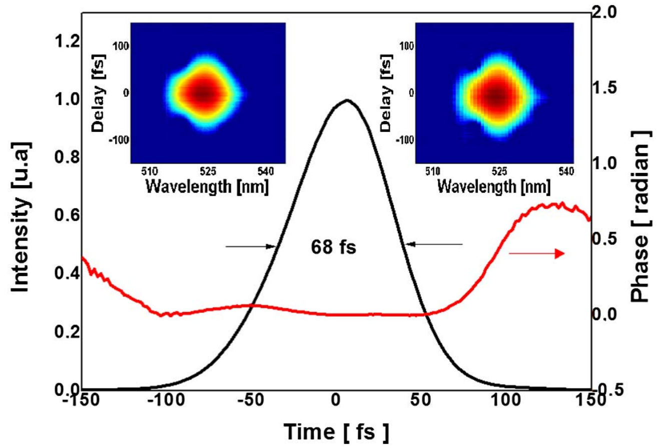

Fig. 3. SHG-FROG. Retrieved intensity profile and temporal phase of the output pulses (inset measured and retrieved SHG-FROG traces).

duration assuming sech pulse shape). At the external compressor output, the time-bandwidth product of the pulses reaches then 0.35.

The sensitivity of the gain channel in Yb:CaF_2 to obtain stable ML has been investigated by longitudinally moving the 60 mm lens of the pump source. At 7 W of pump power, we can move the pump focal point over 1 mm either side of the optimum point (pump focus at 2 mm after the first crystal face) without any significant change in the oscillator performance. Away from this focus position range, a CW peak is superposed on the ML spectrum. This observation confirms the importance of the spatial overlap quality between the gain channel and the laser beam waist to obtain pure KLM.

In addition, we have investigated the influence of the pump power level on the stability of the KLM regime. We have recorded the output power and the compressed pulse duration at different pump powers. Results are displayed in Fig. 4. The best performance (pulse duration and output power) is obtained for the maximal pump power of 7 W but the KLM regime persists with a pump power down to 4 W. As pump power decreases, the spectral broadening from SPM in Yb:CaF_2 becomes less efficient and leads to longer pulse durations. However the Kerr-lens effect is efficient enough to discriminate ML and CW until 4 W of pump power. In this pumping condition, the oscillator delivers at least 1 W of average power with 79 fs pulse duration. Below 4 W of pump power, a continuous peak appears in the spectrum of the output pulses.

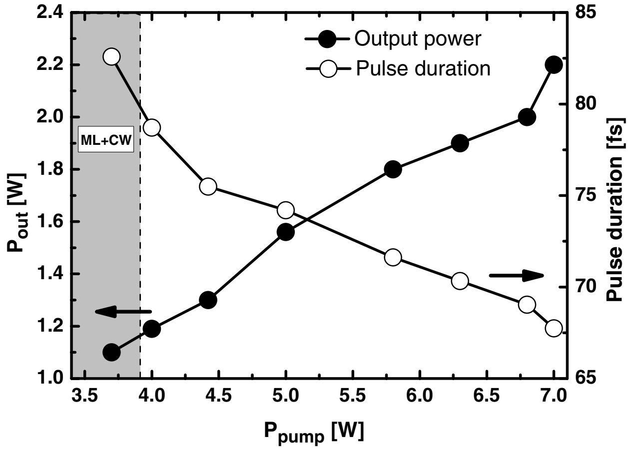

Fig. 4. Output power and pulse duration of the ML Yb:CaF_2 oscillator as a function of the pump power.

In conclusion, we have presented the first experimental demonstration of a high-average power pure KLM femtosecond oscillator based on an Yb:CaF_2 crystal optically pumped by a very high-brightness fiber pump laser. The oscillator delivers, at 73 MHz repetition rate, pulses of 68 fs duration, which is the shortest pulse duration ever obtained in Yb-doped material at 2.3 W average power level.

We acknowledge the support from the Direction Générale de l'Armement et de la Recherche, the European Community through the I3 LASERLAB II JRA2 Happie, the Conseil Régional d'Aquitaine with the "Lougre Brillant" program, Aquitaine Valorisation, the CNRS national networks FEMTO and CMDO+ through the entitled HABRY program, and the Agence Nationale de la Recherche (ANR) through the FEMTOCRYBLE (ANR 2010 BLANC 0421) and PAMPERO (ANR-12-B509-0033) projects.

References

1. F. Friebel, F. Druon, J. Boudeile, D. Papadopoulos, M. Hanna, P. Georges, P. Camy, J.-L. Doualan, A. Benayad, R. Moncorgé, C. Cassagne, and G. Boudebs, Opt. Lett. **34**, 1474 (2009).
2. S. Ricaud, D. Papadopoulos, P. Camy, J. Doualan, R. Moncorgé, A. Courjaud, E. Mottay, P. Georges, and F. Druon, Opt. Lett. **35**, 3757 (2010).
3. M. Siebold, M. Hornung, R. Boedefeld, S. Podleska, S. Klingebiel, C. Wandt, F. Krausz, S. Karsch, R. Uecker, A. Jochmann, J. Hein, and M. Kaluea, Opt. Lett. **33**, 2770 (2008).
4. P. Popov, P. Fedorov, S. Kuznetsov, V. Konyushkin, V. Osiko, and T. Basiev, Dokl. Phys. **53**, 198 (2008).
5. F. Druon, S. Ricaud, D. N. Papadopoulos, A. Pellegrina, P. Camy, J.-L. Doualan, R. Moncorgé, A. Courjaud, E. Mottay, and P. Georges, Opt. Mater. Express **1**, 489 (2011).
6. H. Liu, J. Nees, and G. Mourou, Opt. Lett. **26**, 1723 (2001).
7. A. Lagatsky, A. Sarmani, C. Brown, W. Sibbett, V. Kisel, A. Selivanov, I. Denisov, A. Troshin, K. Yumashev, N. Kuleshov, V. Matrosov, T. Matrosova, and M. Kupchenko, Opt. Lett. **30**, 3234 (2005).
8. M. Tokurakawa, A. Shirakawa, K. Ueda, T. Yanagitani, and A. Kaminiskii, Opt. Lett. **32**, 3382 (2007).
9. S. Uemura and K. Torizuka, Jpn. J. Appl. Phys. **50**, 010201 (2011).
10. C. Hönninger, R. Paschotta, F. Morier-Genoud, M. Moser, and U. Keller, J. Opt. Soc. Am. B **16**, 46 (1999).
11. D. Milan, M. Weber, and A. Glass, Appl. Phys. Lett. **31**, 822 (1977).
12. R. Adair, L. Chase, and S. Payne, Phys. Rev. B **39**, 3337 (1989).
13. Y. Senatsky, A. Shirakawa, Y. Sato, J. Hagiwara, J. Lu, K. Ueda, H. Yagi, and T. Yanagitani, Laser Phys. Lett. **1**, 500 (2004).
14. A. Selivanov, I. Denisov, N. Kuleshov, and K. Yumahsev, Appl. Phys. B **83**, 61 (2006).
15. J. Boudeile, J. Didierjean, P. Camy, J. Doualan, A. Benayad, V. Ménard, R. Moncorgé, F. Druon, F. Balembois, and P. Georges, Opt. Express **16**, 10098 (2008).
16. J. Boullet, Y. Zaouter, R. Desmarchelier, M. Cazaux, F. Salin, J. Saby, R. Bello-Doua, and E. Cormier, Opt. Express **16**, 17891 (2008).
17. G. Machinet, G. Andriukaitis, P. Sévillano, J. Lhermite, D. Descamps, A. Pugžlys, A. Baltuška, and E. Cormier, Appl. Phys. B **111**, 495 (2013).