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Dimitris N. Papadopoulos, Frédéric Druon, Justine Boudeile, Igor Martial, Marc Hanna, Patrick Georges, Pierre-Olivier Petit, Philippe Goldner, Bruno Viana

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D. N. Papadopoulos,[1,*] F. Druon,[1] J. Boudeile,[1] I. Martial,[1] M. Hanna,[1] P. Georges,[1] P. O. Petit,[2] P. Goldner,[2] and B. Viana[2]

[1]*Laboratoire Charles Fabry de l'Institut d'Optique, CNRS, Université Paris Sud, RD 128, 91127 Palaiseau, France*
[2]*Laboratoire de Chimie de la matière condensée de Paris (UMR 7574), 11 Rue Pierre et Marie Curie 75231 Paris*
**Corresponding author: dimitris.papadopoulos@institutoptique.fr*

Received October 24, 2008; revised December 1, 2008; accepted December 1, 2008; posted December 10, 2008 (Doc. ID 103232); published January 14, 2009

We report on an extended-cavity mode-locked laser based on an Yb:CALGO crystal operating either at 27 MHz and 93 fs pulse duration or at 15 MHz and 170 fs duration single-pulse regime. To the best of our knowledge this is the first demonstration of an extended-cavity oscillator based on Yb-doped crystal producing sub-100 fs pulses. The pulse energy was 24 nJ directly at the output of the oscillator (and 17 nJ after compression). Based on a similar design, we also demonstrate an unprecedented double-pulse dual-wavelength femtosecond regime. An explanation of this atypical regime is proposed.

OCIS codes: 140.3615, 140.4050.

In the field of femtosecond lasers, an intense interest has been shown for ytterbium-doped laser crystals. These crystals are well known to be particularly suitable for very efficient, directly diode-pumped, solid-state femtosecond oscillators. However, it has been shown that the spectral properties of the Yb^{3+} dopant strongly depend on the matrix host, and a lot of work has been done to find the perfect matrix to allow the development of both ultrashort and high-power lasers. In fact, broadband emission spectrum and good thermal conductivity are often antagonistic for rare-earth-ion-doped materials [1–3]. One approach is based on relaxing the constraint of the broad spectrum by combining different crystals. This technique has already given very promising results [4]. Another possibility is the use of atypical crystals combining these two properties [5–8]. Among them, $Yb^{3+}:CaGdAlO_4$ has been recently proved to be very interesting for the development of diode-pumped short-pulse mode-locked lasers. In fact, this crystal combines two very promising properties. First, it has the broadest and the flattest emission band of all the Yb-doped materials. Second, the measured thermal conductivity of the 2 at. % Yb:CALGO crystal is as high as $\sim 6.5\ W\,K^{-1}\,m^{-1}$ [9], allowing high-power pumping. The generation of both very short pulse and high average power femtosecond oscillators has been demonstrated [8,10].

However, for some applications it is interesting to have lower repetition rate (RR) short-pulse oscillators. Actually, the first interest is related to the fact that reducing the RR allows the increase of the energy per pulse for the same average power. This method has been successfully used with Yb:YAG, resulting in the production of 13 μJ pulses directly at the output of a picosecond oscillator [11,12]. The main challenge, however, especially in the case of ultrafast oscillators, is to maintain the ultrafast duration of the produced pulses at the increased energy level of the low RR cavities. The careful adjustment of the intracavity dispersion is the key factor toward this effort. Additionally, the reduction of the RR is important for oscillators used in chirped-pulse-amplification systems. In fact, in these laser chains, the RR is reduced extracavity with acousto- or electro-optic modulators. Starting with a lower RR (therefore less constraint on the rise and fall times of the modulators) allows a lower loss of average power and a more energetic seeding for the amplifiers. Since for a mode-locked laser the RR is directly related to the cavity round trip, low RR requires a long cavity of typically 10–100 m. However, generation of short pulses by long cavity oscillators requires special care on the intracavity dispersion management [13] owing to the increased intracavity pulse energy as well as the increased number of beam reflections on the cavity mirrors. This explains the fact that no sub-100 fs pulses have ever been demonstrated for long cavity (>10 m) with Yb-doped crystals. We are presenting in this Letter the results obtained with Yb:CALGO in extended-cavity lasers. Our goal was the generation of shorter pulses (sub-100 fs) and the assessment of the limitations. During this exploration, we observed a very atypical double-pulse regime with bicolor femtosecond pulses. We also propose an explanation to this regime that, to the best of our knowledge, has never been observed in bulk-material laser oscillators.

The experiment to obtain the high-energy single-pulse regime is performed with a 2%-doped $Yb^{3+}:CALGO$ crystal. The crystal is pumped by a 25 W fiber-coupled diode laser (LIMO) with a 100 μm

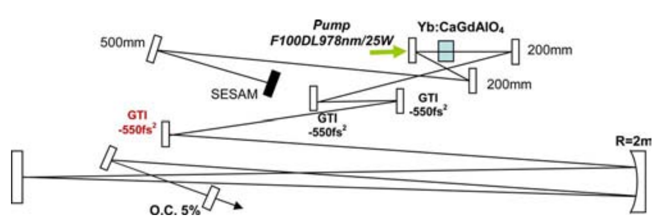

Fig. 1. (Color online) Experimental setup for low-repetition-rate single-pulse regime.

core diameter. By the addition of a q-preserving telescope, formed by a 2 m radius of curvature concave mirror and a plane one at a fixed distance of 1 m, we could easily vary the length of the cavity by properly choosing the number of beam bounces on the telescope mirrors [14,15]. Initially, the cavity round trip was set at 11 m, corresponding to two reflections on the concave telescope mirror. For the intracavity dispersion compensation we included 3 Gires–Tournois interferometer (GTI) mirrors with a group-velocity dispersion (GVD) $= -550\ \text{fs}^2$ (Fig. 1). This resulted in a negative net dispersion that can be estimated around $-2600\ \text{fs}^2$/round trip (assuming $\sim 50\ \text{fs}^2/\text{mm}$ for the CALGO crystal and $0\ \text{fs}^2$ for all unknown dispersion optics: semiconductor saturable absorber mirror (SESAM), output coupler, dichroic mirror). The output coupler transmission was 5%, which corresponds to an optimum of intracavity power for the chosen GVD compensation. The SESAM (from Amplitude Système) has a modulation depth of 1% and a saturation fluence $> 120\ \mu\text{J cm}^{-2}$.

In this configuration the mode-locked regime was observed for an intracavity pulse energy between 0.3 and 0.5 μJ. The highest average power produced from this mode-locked laser was 650 mW at 27 MHz, corresponding to an output pulse energy of 24 nJ, for 16 W of pump power. Further increase of the output power resulted in an unstable mode-locking regime leading to cw operation; no multiple-pulse operation was observed. The pulse duration in this case was measured both with an autocorrelator and a second-harmonic generation (SHG) frequency-resolved optical gating (FROG) setup at 145 fs. The spectrum was centered at 1043 nm and had a bandwidth of 15 nm. The time bandwidth product is 0.6, and the FROG retrieved spectral phase of the pulse clearly indicates positively chirped pulses with a parabolic phase [Figs. 2(a)–2(c), left side]. These pulses, however, could be still used as direct inputs for various fiber amplifier systems [16,17].

Further increase of the intracavity dispersion to reduce the pulse duration directly out of the cavity made the mode locking of the oscillator impossible. Nevertheless, to compensate this parabolic phase of about $3400\ \text{fs}^2$, an external compressor based on a standard SF10 prism pair has been used. The compressed pulse duration is 93 fs. The corresponding SHG FROG trace and retrieved pulse shape and spectrum are shown in Figs. 2(a)–2(c) (right side). The time bandwidth product is reduced down to $\Delta t \Delta \nu = 0.38$ while the main remaining spectral phase distortion is cubic. The values of the remaining phase is $-140 \pm 5\ \text{fs}^2$ for the quadratic term, $-6000 \pm 500\ \text{fs}^3$ for the cubic term and $-1.4 \times 10^6 \pm 4 \times 10^5\ \text{fs}^4$ for the fourth order. The energy per pulse after compression is 17 nJ, corresponding to only 70% compression efficiency as a result of the reduced quality prisms used.

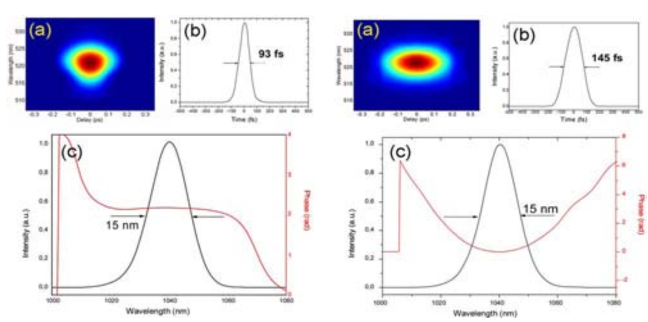

Fig. 2. (Color online) Pulse characterization at the output of the oscillator after (left) and before (right) compression. (a) Experimental SHG FROG trace, (b) retrieved pulse, (c) retrieved spectrum and spectral phase.

To further reduce the RR, we increased the cavity round trip to 20 m, adding two more round trips inside the telescope. For stable single-pulse mode locking the negative dispersion of the cavity had to be increased by adding two more GTI mirrors of -550 and $-250\ \text{fs}^2$ (about $-4200\ \text{fs}^2$ net cavity dispersion). With this setup, the highest average power produced in the single-pulse regime was 240 mW at 15 MHz, corresponding to an output pulse energy of 16 nJ, for 13 W of pump power. The optimum output coupling of the cavity was 3.8%, corresponding to maximum intracavity pulse energy of 0.42 μJ. Further increase of the energy resulted in multiple-pulse instabilities [17–19]. In Fig. 3 the dependence of the output pulse duration as a function of the average output power is shown. We can clearly observe the onset of double pulsing for output power greater than 250 mW ($\sim$16.5 nJ). The minimum pulse duration measured in this longer cavity with an autocorrelation and a SHG FROG setup [Figs. 4(a)–4(c)] was 170 fs. The spectrum was (for one or two pulses) centered at 1040 nm and had a bandwidth of 8 nm. The time bandwidth product for this spectrally narrower pulse is 0.37.

Modifying slightly the 27 MHz setup, it was also possible to observe double-pulse operation. In fact, increasing the intracavity energy and modifying the dispersion (replacing the left-most $-550\ \text{fs}^2$ GTI in Fig. 1 with another one of GVD $= -250\ \text{fs}^2$, reducing the net dispersion to about $-2000\ \text{fs}^2$), the soliton naturally splits in multiple pulses. Multiple-pulse operation is not unusual in femtosecond lasers [18–20], but in our case, owing to the very atypical dispersion curve of the cavity added to the very broad emission spectrum of the Yb:CALGO, it is possible to generate linearly polarized double pulses with different wavelengths, which we believe is the first demonstration of bicolor femtosecond double-pulse operation. Usually the multiple pulses are separated in time but not in the spectral domain. A very broad spectrum has been obtained with a bandwidth greater than 30 nm [Fig. 5(a)]. The spectrum can be almost perfectly fit with two Gaussian curves: one centered at 1040 nm

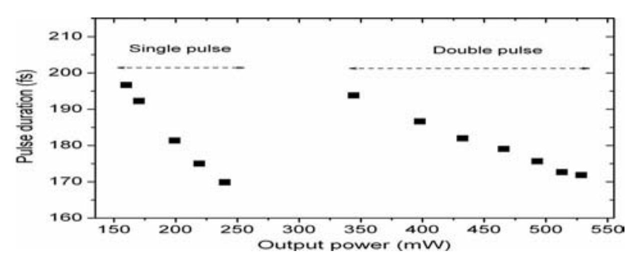

Fig. 3. Pulse duration as a function of the average output power for the 15 MHz laser cavity.

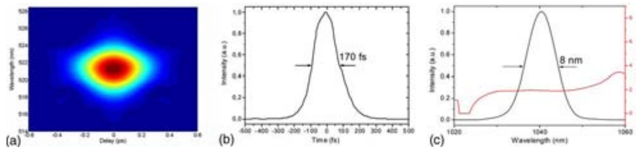

Fig. 4. (Color online) Pulse characterization at the output of the 15 MHz oscillator. (a) Experimental SHG FROG trace, (b) retrieved pulse, (c) retrieved spectrum and spectral phase.

with a bandwidth of 21 nm and one centered at 1057 nm with a bandwidth of 10 nm with lower amplitude (~60%). This double pulse is clearly corroborated by the FROG exhibiting four spots forming a diamond shape [Fig. 5(b)]. Although the convergence of the retrieving algorithm from the FROG is low, we can evaluate the pulse durations to be respectively 80 and 130 fs with a pulse separation of 200 fs [Fig. 5(c)]. This bicolor double-pulse regime might be explained on the basis of the combination of two factors: first, the very broad and constant gain that, in the case of Yb:CALGO, is inhomogeneous owing to the contribution of its two different crystallographic sites Gd^{III} and Al^{III}, which allows one to reduce cross talk between the two pulses; second, and probably the most important effect, the specific intracavity dispersion distribution resulting in two spectrally distinguished regions of almost constant GVD, overlapping the two Gaussian contributions of the double pulse [inset of Fig 5(a)].

In this Letter we demonstrated that it is possible to obtain sub-100 fs pulse at 27 MHz with a pulse energy of 17 nJ from an Yb-doped CALGO crystal. Further reduction of the RR down to 15 MHz has been also achieved, resulting in the generation of 170 fs pulses of 16 nJ energy directly out of the cavity. We also demonstrated an unprecedented bicolor double-pulse regime within a bulk oscillator generating ultrabroad bandwidth of about 30 nm. Two ~100 fs pulses have been produced temporally separated by 200 fs and spectrally by 17 nm. This bicolor double regime is to our best knowledge an original observation. This regime is possible due to a very specific dispersion curve of the cavity with multiple inflexions, and this regime is probably helped by the broad and partly inhomogeneous gain of the Yb:CALGO, which tends to reduce cross-talk influence between the bicolor pulses.

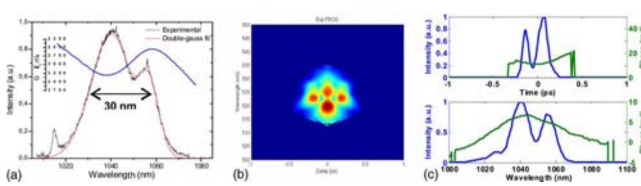

Fig. 5. (Color online) Dual-wavelength double-pulse operation regime. (a) Experimental spectrum and double Gaussian fit (intracavity GTI GVD as inset), (b) SHG FROG trace, (c) SHG FROG retrieved pulse temporal–spectral intensity and phase.

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