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Femtosecond Yb:CaGdAlO$_4$ thin-disk oscillator

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A mode-locked thin-disk laser based on Yb:CALGO is demonstrated for the first time. At an average output power of 28 W we obtained pulses with a duration of 300 fs and a pulse energy of 1.3 μJ. 197 fs pulses with 0.9 μJ of energy were achieved at an average output power of 20 W. The shortest pulse duration measured in our experiments was 135 fs with a spectrum centered at 1043 nm. The experiments also revealed a very broad tunability from 1032 to 1046 nm with sub-200 fs pulses. © 2012 Optical Society of America

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The thin-disk (TD) laser technology marked a major breakthrough for both high-power continuous wave (CW) and ultrafast laser oscillators [1]. The thermal control of the gain medium permits the generation of femtosecond pulses with high average power and high energy directly from oscillators [2–4].

Lately, major research efforts have focused on reducing the pulse duration using this technology. Yb:YAG is the most commonly used crystal in TD laser oscillators, and recent publications report remarkable progress in terms of pulse duration with this material. Using the Kerr effect to decrease the pulse duration has allowed the generation of 200 fs pulses with 17 W and 270 fs pulses with 45 W of average power [5]. Another way to obtain shorter pulses consists in using crystals exhibiting broader emission bandwidths. In particular, sesquioxide crystals in combination with optimized semiconductor satuble absorber (SESAM) saturable absorbers enabled the generation of 142 fs pulses using Yb:Lu$_2$O$_3$ [6]. 235 fs pulses at 23 W average power [7] and even sub-100 fs pulses have been demonstrated using Yb:LuScO$_3$ [8]. In all these efforts, the generation of shorter pulses is obviously associated with lower average powers because of the high sensitivity of TD lasers to intracavity losses.

Other crystals with even broader bandwidths—such as Yb:KYW, Yb:KLuW, and Yb:YCOB—have also been used in TD laser configuration to produce short pulses [9–11]. These crystals have shown interesting performances in terms of pulse duration, but tungstate and borate crystals suffer from low thermal conductivities of around 3 W/m/K (9.7 W/m/K for undoped YAG) and from mechanical and structural anisotropy. Moreover, the easy cleavage of the tungstates and their inconsistent quality are serious obstacles for reliable high-power operation. This limits their use in high-average-power TD lasers.

In the present Letter, we present the first femtosecond TD oscillator using the very promising crystal Yb:CaGdAlO$_4$ (Yb:CALGO), which combines advantageous thermal and spectroscopic properties. It has already demonstrated interesting results in a TD oscillator in CW operation [12] and in bulk configuration with sub-50 fs pulses at low power [13,14] and 94 fs pulses with an average power of 12.5 W [15]. Here we show promising results with the generation of sub-200 fs pulses over a broad tuning range from 1032 to 1046 nm at Watt-power levels, as well as an average power of 28 W with 300 fs pulses or 20 W with 197 fs pulses. Compared with the above mentioned results of Kerr-lens mode-locked Yb:YAG and SESAM mode-locked Yb:Lu$_2$O$_3$, these results show the excellent potential of Yb:CALGO, and the analysis of our results indicate approaches to further scale the average power.

The properties of Yb:CALGO are quite unique, with a very broad and smooth emission spectrum. Moreover, the mechanical and thermal properties of Yb:CALGO, including thermal conductivity, refractive index, and hardness, are very similar to those of Yb:YAG, making this crystal very suitable for TD laser configurations [12], also with respect to the required polishing, coating, and mounting processes. Design tradeoffs to consider for TD gain media are the doping level and the thickness. For the TD geometry, a high doping level is desirable to obtain good absorption in a thin crystal but usually leads to a reduction of the thermal conductivity and—beyond a certain limit—to severe degradation of laser performance, for instance due to excessive nonradiative decay. A thin crystal allows higher pump power densities due to its lower thermal resistance and reduced thermo-optic effects. However, depending on the maximum number of pump passes available, absorption should remain high.

The first experiments are performed with a 2% doped, 350 μm thick Yb:CALGO crystal glued on a copper mount. The crystal diameter is 6 mm, and it is cut for the laser beam to propagate along the σ axis, with access to both σ and π polarization. The access to the π polarization of this uniaxial crystal is interesting for two reasons. First, the absorption is higher on the π polarization. Second, the access to two polarizations allows a broader tunability. A standard pumping unit with 24 passes as commercially provide by the Institut für Strahlwerkzeugewas used together with a pump spot diameter on the disk of 1.9 mm.

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The pump emits an unpolarized beam at 980 nm [12]. The cavity design is shown in Fig. 1. Per roundtrip, the resonator beam passes the TD crystal eight times, with a beam waist diameter of 1.2 mm. The measured small-signal gain is 1.15 (per roundtrip). The shortest pulses are obtained using a SESAM with a modulation depth of $\Delta R = 2\%$ and a saturation fluence of $50\ \mu\mathrm{J/cm}^2$, and with an output coupler transmission of 3%. The beam waist diameter on the SESAM is 0.6 mm. The dispersion introduced by the two gires tournois interferometer (GTI) mirrors is $1200\ \mathrm{fs}^2$ per round trip.

Under these conditions, 135 fs pulses are generated with a corresponding spectral bandwidth of 9.5 nm centered at 1043 nm. The time-bandwidth product is 0.35. The average power is 1.3 W (for 66 W of pump power), and the repetition rate is 45 MHz (29 nJ pulse energy). The autocorrelation and the spectrum of these 135 fs pulses are shown in Fig. 2 (red curves), and the laser beam profile is shown in Fig. 1. The intracavity polarizer is used to control the polarization close to the σ axis of the crystal but introduces additional losses, probably due to a depolarization in the crystal because of a misalignment of the crystal axes with respect to the cavity plane. This static depolarization leads to an additional leakage of about 530 mW from the thin-film polarizer (TFP).

The pulse duration of 135 fs was limited by the onset of double-pulse operation. The stable mode-locked regime ranged from 700 mW with 170 fs pulses to 1.3 W with 135 fs pulses ($\Delta\lambda = 9.5$ nm), then switched to a double pulse regime with a power of 1.6 W and 160 fs pulses ($\Delta\lambda = 8$ nm).

By tuning the angle θ of the TFP, wavelength tunability is obtained because of the wavelength dependence of the TFP versus the incident angle of the beam. The laser is tunable from 1038 nm, with 160 fs pulses and an average power of 1.3 W, to 1046 nm, with 145 fs pulses and an average power of 1.1 W. This tunability is illustrated in Fig. 2. By changing the polarization of the laser by 5° using the TFP, with the same cavity and SESAM, 1.7 W of average power is obtained with a slightly increased pulse width of 158 fs. The central wavelength is 1032 nm in this configuration, with a spectral bandwidth of 8 nm (blue curve in Fig. 2).

For 90 W of pump power, the highest power obtained is 10.5 W for 390 fs pulses using a SESAM with a modulation depth of $\Delta R = 0.5\%$ and by removing the TFP from the cavity, clearly indicating the low gain of the material and the subsequent strong sensitivity of the cavity to losses. Indeed, the unsaturated losses ($\Delta R_{\mathrm{ns}} = 0.5\%$) of the SESAM with 0.5% of modulation depth are significantly lower than those of the SESAM with 2% modulation depth (3%).

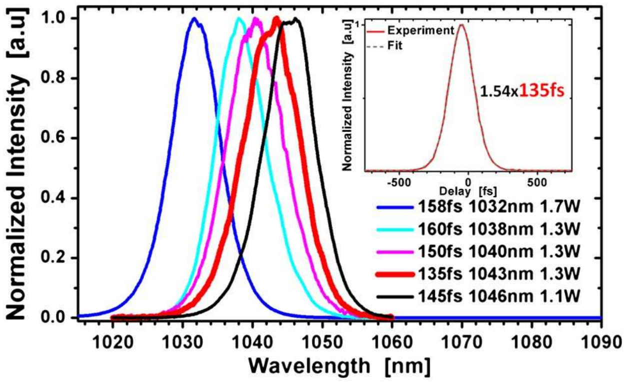

Fig. 2. (Color online) Spectrum and autocorrelation traces (inset) of 135 fs pulses from a Yb:CALGO TD oscillator.

In order to increase the power, the oscillator setup is modified to be compatible with a pump source with 230 W output power, as shown in Fig. 3. The pump spot diameter on the disk is 2.9 mm, and the laser beam waist diameter is 2.1 mm. In this configuration, a thermally induced astigmatism occurs for pump power around 130 W. In order to overcome this problem, the 2% doped, 350 μm thick crystal is glued on a diamond mount for better heat removal. In this case, in a multimode configuration we obtained up to 86 W in CW operation, with an optical-to-optical efficiency of 37.5%.

The cavity schematically depicted in Fig. 3 is optimized to operate in single transverse mode operation with $M^2 = 1.1$. The average power in TEM_{00} CW operation was 50 W with 6% of output coupling. After inserting a SESAM with 0.5% of modulation depth (BATOP GmbH) and a saturation fluence of $90\ \mu\mathrm{J/cm}^2$ (with a 1.3 mm laser beam waist diameter on the SESAM) as well as GTI mirrors with a total group velocity dispersion (GVD) of $2000\ \mathrm{fs}^2$, we obtained 300 fs pulses with an average output power of 28 W and with $M^2 = 1, 08$. The repetition rate was 23 MHz, which corresponds to a pulse energy of 1.3 μJ. In order to reduce the pulse duration, a 3 mm thick antireflection-coated fused-silica plate is inserted in the cavity (Fig. 3) to induce self-phase modulation. In this configuration, 197 fs long pulses with an average output

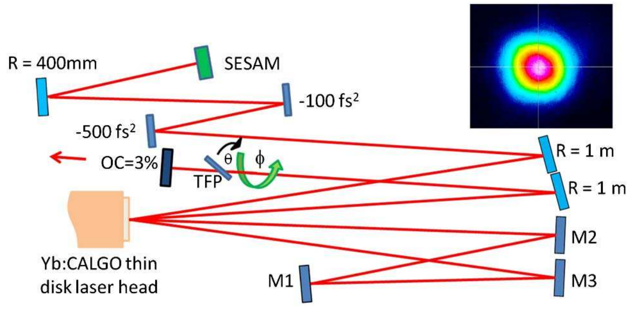

Fig. 1. (Color online) Experimental setup (left): M1, M2, M3: plane HR mirrors; OC, output coupler; TFP, thin-film polarizer (3 mm thick). The beam profile for this cavity for 135 fs pulses is also given on the right.

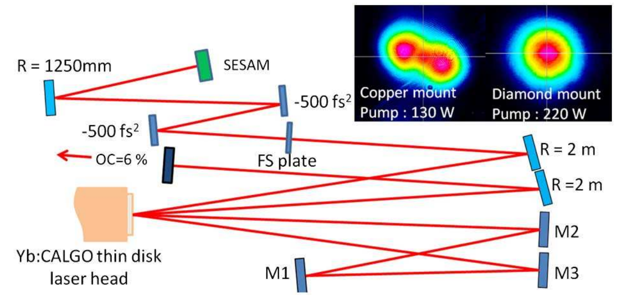

Fig. 3. (Color online) Experimental setup (left): M1, M2, M3: plane HR mirrors; OC, output coupler; antireflection fused-silica (FS) plate. The beam profiles for this cavity are also given on the right for two different mounts.

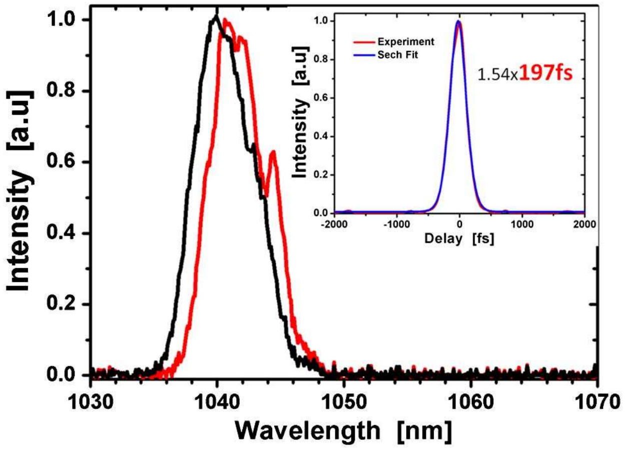

Fig. 4. (Color online) Spectrum for 20 W, 197 fs pulses (black curve) and 28 W, 300 fs pulses (red curve); inset: autocorrelation trace for 197 fs pulses.

power of 20 W (with $M^2 = 1, 12$) were obtained, corresponding to an energy of 0.9 μJ. The autocorrelation and spectral traces are plotted in Fig. 4. The spectrum is centered at 1040.5 nm with a bandwidth of 6 nm, leading to a time-bandwidth product of 0.33. With the diamond module, the laser stays naturally linearly polarized, without a polarizing element, along the σpolarization where the gain is the highest.

Concerning the Yb doping concentration, in the case of Yb:CALGO the choice of a high doping level, typical in TD lasers, is not straightforward. First, it was experimentally found that in CALGO the thermal conductivity decreases with increasing doping much faster than expected from a substitution of Gd by Yb [16]. We therefore assume that this might be due to a partial substitution of Yb with Ca because the divalent calcium cation size is only 5% larger. Assuming a substitution ratio of 80% to 20% for Gd and Ca, respectively, the model is in good agreement with the experimental data. Second, it is known that, for the 2% doped Yb:CALGO, the broad bandwidth of Yb:CALGO is due to a precise spectral compensation of two Gd^{3+} substitution sites [17], but for higher ytterbium concentration the emission profile becomes more structured. This aspect is still under study and motivated our use of 2% doped crystal. In further work our aim will be to use higher doping concentrations so that the optical efficiency in ultrafast operation, which is currently limited to 13%, can be improved significantly.

In conclusion, we demonstrate the first femtosecond Yb:CaGdAlO$_4$ TD oscillator. The production of 135 fs pulses is performed at low power (1.3 W) due to a lack of gain in the material and the high nonsaturable losses of the SESAM used. A broad tunability from 1032 to 1046 nm for sub-200 fs pulses is also demonstrated at low power. The highest powers obtained are 28 W for 300 fs pulses and 20 W for sub-200 fs pulses. The corresponding efficiencies of 13% and 9%, respectively, could be increased in the future, and the results obtained so far represent a first step with Yb:CALGO in TD laser configuration. The final goal of high-power, sub-100 fs TD oscillators will require some advances, especially regarding gain limitation and polarization, which could be done by optimizing the doping level, the orientation of the Yb:CALGO TD, and by optimizing the parameters of the low loss SESAM.

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