47-fs diode-pumped $Yb^{3+}:CaGdAlO_4$ laser

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The experimental demonstration of a diode-pumped passively mode-locked femtosecond laser based on an $Yb^{3+}:CaGdAlO_4$ single crystal is reported. The oscillator is directly diode pumped by a high-brightness 5 W fiber coupled laser diode, and pulses are produced by use of a semiconductor saturable-absorber mirror. It permits the production of pulses as short as 47 fs at 1050 nm, which are to our knowledge the shortest laser pulses obtained from an oscillator based on Yb^{3+}-doped bulk materials. The average power is 38 mW, and the repetition rate is 109 MHz. © 2006 Optical Society of America

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In the past decade, many scientific and industrial applications have stimulated research toward more efficient, compact, robust, and cost-effective femtosecond lasers. Diode-pumped ytterbium-doped crystals were shown to be ideal candidates to fill the needs of this new kind of femtosecond oscillator, mainly because they have large emission bands, weak thermal loads in the gain medium, and broad absorption spectra that match the emission bands of high-power InGaAs diode lasers. Thus various ytterbium-doped crystals have been grown and tested in the femtosecond regime. Among these new crystals, double borates such as $Yb^{3+}:Sr_3Y(BO_3)_3$ (Ref. 1) and ytterbium-doped apatite based crystals such as $Yb^{3+}:Sr_3Y_4(SiO_4)_3O$ (Ref. 2) permit the production of particularly short pulses of 69 and 70 fs, respectively, with a greater efficiency for the latter. Some crystals with narrower-emission bands also permit the production of very short pulses: 71 fs with $Yb:KY(WO_4)_2$ (Ref. 3), and recently 61 fs with $Yb:YVO_4$ (Ref. 4) because of the use of the Kerr-lens mode-locking technique. It has the advantage of producing shorter pulses than with a semiconductor saturable-absorber mirror (SESAM) [101 fs with $Yb:KY(WO_4)_2$ (Ref. 5) and 120 fs with $Yb:YVO_4$ (Ref. 6)] but the disadvantages of lower stability and difficulty in self-starting of the mode-locked regime. Nevertheless, until now ytterbium crystals never outdid ytterbium-doped glass, phosphate or silicate, which generated pulses as short as 58 and 61 fs,[7] respectively. But poor thermal conductivities and weak emission cross sections of glasses are strong limitations on the development of laser systems, especially those with high average power. For example, Yb:phosphate has a disastrous thermal conductivity of 0.85 $W\,m^{-1}\,K^{-1}$ and a very weak emission cross section, $0.05\times10^{-20}\,cm^2$. So we are still in need of an ytterbium-doped crystal that exhibits broad and smooth absorption and emission cross sections with high thermal conductivity and a higher emission cross section. The first key point would be to have not only an extra-large emission band but also ultraflatness of the gain. A crystal that meets these criteria seems to have been found in $Yb^{3+}:CaGdAlO_4$.[8]

The ytterbium-doped $CaGdAlO_4$ laser crystal used in the experiment was grown by the Czochralski technique. It was weakly doped in ytterbium at 2 at. % ($\sim2.5\times10^{20}$ ions cm^{-3}), and its thickness was 2.5 mm. The emission and absorption cross sections of this sample were broadband and weakly structured, which might be due to a disordered distribution of Ca^{2+}, Gd^{3+}, and Yb^{3+} ions in a single crystallographic site because of their similar ionic radii. Experiments are in progress to confirm this hypothesis. Moreover, preliminary spectroscopic experiments tend to prove that some Yb sites have spectral shapes that exactly compensate for one another. This leads to an atypical and extraordinary flat gain profile (Fig. 1). Figure 1 shows the gain cross sections for both σ and π polarization of this uniaxial crystal. The σ polarization emission cross section exhibits a flat, smooth, and relatively high ($0.75\times10^{-20}\,cm^2$) plateau that goes from 1000 to 1050 nm. As a consequence, this spectral region is believed to be particularly propitious for the generation of a broad laser spectrum. Thus record pulse durations are expected from this Yb-doped material. Furthermore, note that the π polarization exhibits a high and relatively large peak of absorption centered at 979 nm. In addition to these spectroscopic properties, the thermal conductivity of this crystal is quite interesting, as it reaches $\kappa_a=6.9\ W\,m^{-1}\,K^{-1}$ and $\kappa_c=6.3\ W\,m^{-1}\,K^{-1}$, experimental values measured with our 2%-doped matrix along the a and c axes, respectively. Moreover, the thermal conductivity is not expected to drop with an increase of the doping concentration, as the difference in mass between gadolinium and ytterbium ions is only 10%.[8,9] Thus the thermal conductivity for an undoped sample is negligibly higher than for our 2 at. %-doped crystal. Finally, the upper-state lifetime and the refractive index have been measured to be, respectively, 0.42 ms (Ref. 8) and 1.85.[10]

Figure 2 represents the experimental setup used for the generation of ultrashort pulses. The 2.5 mm

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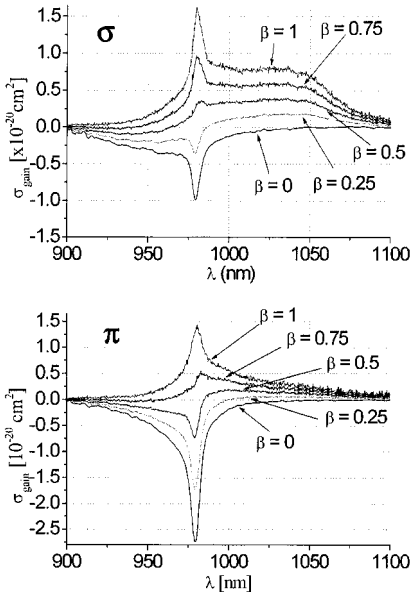

Fig. 1. Gain cross sections for σ and π polarization. β is the population inversion and is linked to the gain cross section by $\sigma_{\text{gain}}=\beta.\sigma_{\text{emissi}}-(1-\beta)\sigma_{\text{absorp}}$, where σ_{emissi} and σ_{absorp} are the emission ($\beta=1$) and the absorption ($\beta=0$) cross sections, respectively.

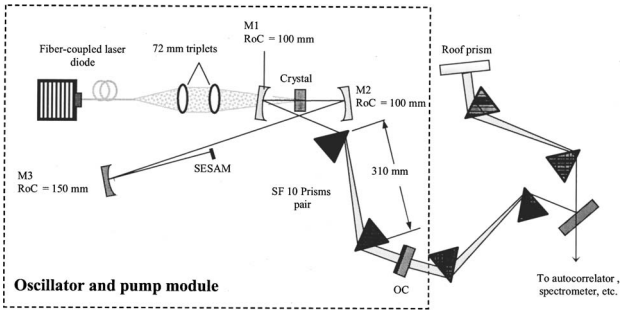

Fig. 2. Experimental setup of the femtosecond oscillator plus an extracavity spatial dispersion compensator and a double-pass positive dispersion prism compressor: RoC's, radii of curvature; OC, output coupler; M1, M2, two dichroic mirrors (high reflection at 1040 nm and high transmission at 980 nm). M3 focuses the laser mode onto the semiconductor mirror.

long, 2 at. %-doped, antireflection-coated $Yb^{3+}:CaGdAlO_4$ crystal is directly diode pumped by a high-brightness fiber-coupled laser diode from Unique-Mode with a 50 μm fiber-core diameter and a numerical aperture of 0.22. The crystal is oriented to have a laser polarization along the σ axis. The laser diode emitted as much as 4.6 W of power at 979 nm and was collimated and focused by use of two 72 mm focal-length triplets. In these conditions the corresponding absorbed pump power was 2.7 W. The use of triplets instead of standard doublets allows aberrations of the optics to be reduced, which is crucial when one is using high-brightness high-numerical-aperture fiber-coupled diodes. In our case, the pump beam was thus focused to a diameter of 60 μm into the crystal with the 1:1 triplets instead of 90 μm with 1:1 doublets; the aberrations of the optics were taken into account. The crystal was placed in contact with a water-cooled copper heat sink by use of 100 μm thick indium foil. The laser mode was focused into the crystal by two dichroic concave mirrors, each with a radius of curvature of 100 mm. The laser waist was calculated, with the *ABCD* matrix formalism, to be 27 μm $\times$ 24 μm into the gain medium and can be efficiently matched to the pump laser beam. A SESAM designed to operate at a central wavelength of 1040 nm was used to start and stabilize the mode locking. This device has a saturation fluence and a modulation depth of $\sim$120 μJ cm^{-2} and 1%, respectively. The laser mode was focused with a 150 mm radius-of-curvature mirror onto the semiconductor mirror to dimensions calculated to be 25 μm $\times$ 23 μm (always with the *ABCD* matrix formalism). We compensated for the dispersion of the crystal material with a pair of SF10 prisms separated by 310 mm. We then compensated for the spatial dispersion outside the cavity with another pair of SF10 prisms placed after the output coupler. A double-pass SF10 prism compressor was finally used to compensate for the residual spectral chirp.

By replacing the SESAM with a high-reflector mirror and with a 2% output coupler we obtained as much as 250 mW of cw laser radiation at 1040 nm at maximum pump power. Introducing the SESAM into the cavity, we achieved mode locking and observed broad emission spectra. We obtained a spectral broadness of as much as 24.7 nm centered at 1050 nm, as shown in Fig. 3. Despite this ultrabroad spectrum, the pulse duration directly after the output coupler of the laser was only 110 fs; the output pulses were thus clearly not Fourier-transform limited. The total chirp could not be fully compensated for intracavity, as in these conditions a stable regime could not be obtained with such a broadband emission. Then, to compensate for the residual chirp, we used an extracavity prism compressor. After this compressor we measured the autocorrelation trace represented in Fig. 4. With a spectrum as large as 24.7 nm, we obtained pulses as short as 47 fs, which represent a $\Delta t\Delta v$ product equal to 0.316. These are to our knowledge the shortest pulses produced from an ytterbium-doped bulk material based oscillator. The repetition rate was 109 MHz. The average power at the output of the oscillator and after the prism compressor was 48 and 38 mW, respectively. We obtained stability for this ultrashort pulse regime by reducing the incident pump power to 3 W, corresponding to an absorbed pump power of 1.9 W.

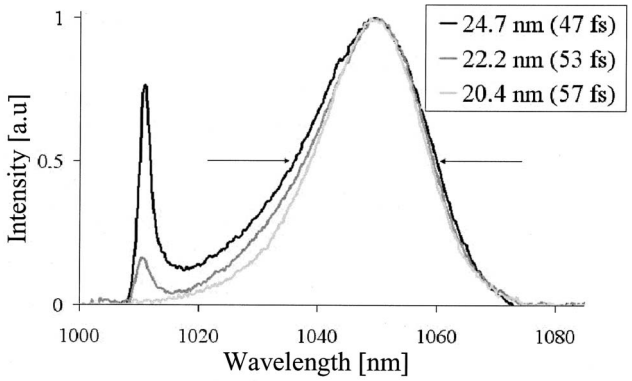

Fig. 3. Spectrum of the mode-locked laser.

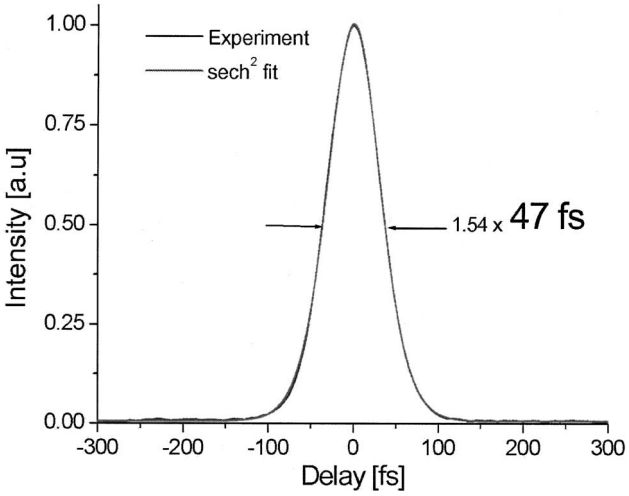

Fig. 4. Autocorrelation trace for the 47 fs pulses.

Furthermore, a narrow peak can be seen on the short-wavelength side of the emission spectrum. This peak appeared near 1010 nm, which corresponds to the cutoff wavelength of the dichroic mirrors. Absorption of the laser light and thus uncontrolled high-order dispersion is to be expected in this spectral region and according to us might be responsible for the continuum peak in the spectrum. However, with more negative dispersion in the cavity we succeeded in getting rid of this peak, and we could observe the continuum-peak-free spectrum shown in Fig. 3. Under these conditions we obtained 57 fs pulses with a spectral bandwidth of 20.4 nm and an average power of 50 mW.

In conclusion, we have presented what is to our knowledge the first experimental diode-pumped femtosecond laser based on an Yb-doped $CaGdAlO_4$ crystal. Furthermore, we demonstrated what we believe are the shortest laser pulses produced from an ytterbium-doped bulk material. With a 2 at. %, 2.5 mm long Yb:$CaGdAlO_4$ crystal, we obtained pulses as short as 47 fs, centered at 1050 nm with an output power of 38 mW. In the configuration presented we had to compensate for a residual positive chirp outside the cavity. Because the development of $CaGdAlO_4$ was recent, the intrinsic group-velocity dispersion of this crystal is not known yet, and the residual positive chirp explanation has not been fully validated, but we believe that it comes mainly from the two dichroic mirrors. Nevertheless, with their high thermal conductivity and atypical ultraflat and relatively high emission cross section, we believe that Yb-doped $CaGdAlO_4$ crystals are particularly suitable for the generation of unprecedented ultrashort pulses from Yb-doped bulk material based oscillators with high average power and thus could be a good alternative to present-day industrial femtosecond oscillators based on Yb:$KGd(WO_4)_2$ crystals. Furthermore, in contrast to the method used recently to achieve extremely short pulse durations with Yb:$KY(WO_4)_2$ and Yb:YVO_4 [71 fs (Ref. 3) and 61 fs,[4] respectively], we used not Kerr-lens mode locking but SESAM-assisted mode locking, which had the advantage of being self-starting and more stable and robust.

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References

1. F. Druon, S. Chenais, P. Raybaut, F. Balembois, P. Georges, R. Gaumé, G. Aka, B. Viana, S. Mohr, and D. Kopf, Opt. Lett. **27**, 197 (2002)
2. F. Druon, S. Chenais, P. Raybaut, F. Balembois, P. Georges, R. Gaumé, P. H. Hausmesser, B. Viana, D. Vivien, S. S. Dhellemmes, V. Ortiz, and C. Larat, Opt. Lett. **27**, 1914 (2002).
3. H. Liu, J. Nees, and G. Mourou, Opt. Lett. **26**, 1723 (2001).
4. A. A. Lagatsky, A. R. Sarmani, C. T. A. Brown, W. Sibbett, V. E. Kisel, A. E. Troshin, N. V. Kuleshov, V. N. Matrosov, T. A. Matrosova, and M. I. Kupchenko, in *Conference on Lasers and Electro-Optics (CLEO) Europe* (Optical Society of America, 2005), paper CPD 1.
5. P. Klopp, V. Petrov, U. Griebner, and G. Erbert, Opt. Express **10**, 108 (2002)
6. V. E. Kisel, A. E. Troshin, V. G. Shcherbitsky, N. V. Kuleshov, V. N. Matrosov, T. A. Matrosova, M. I. Kupchenko, F. Brunner, R. Paschotta, F. Morier-Genoud, and U. Keller, Opt. Lett. **30**, 1150 (2005).
7. C. Hönninger, F. Morier-Genoud, M. Moser, U. Keller, L. R. Brovelli, and C. Harder, Opt. Lett. **23**, 126 (1998)
8. J. Petit, P. Goldner, and B. Viana, Opt. Lett. **30**, 1345 (2005)
9. R. Gaumé, B. Viana, D. Vivien, J. P. Roger, and D. Fournier, Appl. Phys. Lett. **83**, 1355 (2003)
10. A. A. Lagatskii, N. V. Kuleshov, V. G. Shcherbitskii, V. F. Kleptsyn, V. P. Mikhailov, V. G. Ostroumov, and G. Huber, IEEE J. Quantum Electron. **40**, 1235 (2004)