Cr:YAG Chirped Pulse Oscillator

E. Sorokin, V.L. Kalashnikov
Institut für Photonik, TU Wien, Gusshausstrasse 27/387, A-1040 Vienna, Austria. E-mail: e.sorokin@tuwien.ac.at

J. Mandon, G. Guelachvili, N. Piqué
Laboratoire de Photophysique Moléculaire, CNRS, Université Paris-Sud, Bâtiment 350, 91405 Orsay Cedex, France

I.T. Sorokina
Department of Physics, Norwegian University of Science and Technology, N-7491 Trondheim, Norway

Abstract: We demonstrate the chirped pulse operation in the positive dispersion regime of the Cr⁴⁺:YAG laser. The pulses are readily compressed in 3.2 m of silica fiber to ~120 fs, and generate supercontinuum in high-nonlinearity fibers.

©2008 Optical Society of America
OCIS codes: 140.4050 Mode-locked lasers, 140.3070 Infrared and far-infrared lasers

Femtosecond laser sources producing high energy pulses directly from the oscillator are of interest for applications in high-field physics, micro-machining, frequency conversion, gas sensing etc. Several methods of pulse energy scaling of femtosecond oscillators have been successfully demonstrated, including cavity-dumping [1], extended cavity high-energy lasers operating in the soliton regime [2,3], as well as chirped-pulse oscillators (CPO) [4-7]. The latter approach is an attractive way to scaling of pulse energy in femtosecond lasers, as it does not require any additional equipment. The rationale behind this approach is that increasing the pulse energy by reducing the repetition rate (introducing the optical delay line into the resonator) causes instability beyond certain intracavity pulse energy because of nonlinear interaction inside the active medium. If the laser operates in a chirped-pulse mode, the nonlinear phase shift decreases, allowing for the further energy scaling, in analogy with chirped-pulse amplifiers. So far, the CPO has only been demonstrated with Ti:sapphire.

In this paper, we report the first demonstration of the chirped-pulse operation of a SESAM-controlled Cr⁴⁺:YAG laser. We observe generation of stable spectra and easily compressible pulses that could be used for supercontinuum generation and for spectroscopic measurements.

The experimental setup is sketched on Fig. 1. The laser is based on a 20-mm Cr:YAG crystal, pumped by a Nd:YVO₄ laser (Spectra-Physics mod. Millenia IR). The mode-locked operation is provided by a commercial SESAM (BATOP mod. SAM-1550-1). For dispersion compensation, we employ two different sets of chirped-mirrors [8]. At 4 W of pump power, the laser emitted ~100 mW of average power, at 145 MHz of repetition rate. With a low output coupling, the intracavity pulse energy was reaching 130 nJ. In a standard negative dispersion regime with pulse duration of the order of 70 fs and tight focusing, the ~2 MW peak power is already causing instabilities and multi-pulsing due to the nonlinear interaction in the crystal and probably in the SESAM as well. The modes of operation in the negative dispersion regime were either harmonic modelocking with multiplication factor of 1-9, or noisy (chaotic) modelocking regime. This resonator is thus a good model of a low repetition rate high energy oscillator with excessive pulse energy.
Changing the dispersion, the laser could be transferred to a qualitatively different stable single-pulse state of operation, which could be identified as a positive dispersion chirped-pulse regime. In this regime, the pulses exist in the resonator with a significant positive chirp and a π-shaped spectrum with sharp edges is expected [4-7]. It is also predicted that the positive dispersion regime should exist only in the relatively narrow range of dispersion values very close to zero, much lower than the accuracy of our dispersion data for the chirped mirrors and the SESAM.

In Fig. 2, we are plotting the typical pulse output spectra and autocorrelation traces of the pulse observed in this operation mode. It can be seen, that the spectrum does not significantly depend upon the intracavity power. This guarantees that this mode of operation is sufficiently stable for the applications. More importantly, the chirp is to a significant portion linear, allowing recompression. In the 1.5 µm spectral region, the recompression is exceptionally easy: a piece of a single-mode silica fiber does the job (Fig. 2, right graph). A propagation distance of 3.2 m in the SMF-28 fiber results in a (still slightly chirped) ~120 fs pulse form an initial width of 1.4 ps. After compression, the pulse can be launched into a piece of a highly nonlinear PCF [8], to produce a broad supercontinuum (Fig. 3). Without compression, no noticeable broadening was observed.

To verify that we are indeed operating in the positive dispersion regime and to understand the nature of the spectrum asymmetry, we performed a numerical simulation. The analysis based on the generalized complex cubic-quintic nonlinear Ginzburg-Landau model [6]. The model takes into account: i) Gaussian gain-band centered at 1.5 μm; ii) six-order super-Gaussian spectral loss net-band centered at 1.53 μm; iii) two-, third- and fifth-order dispersions approximating the experimental net-GDD; iv) self-phase modulation inside Cr:YAG; v) power-dependent saturable nonlinear gain produced by the Kerr-lensing inside crystal.

The results of simulations are presented in Fig. 4, where the influence of different factors on the oscillator characteristics is shown. First of all, we found that operation in the negative dispersion regime is unstable against the
multipulsing, as it was also observed in the experiment. The stable single-pulse regime can be provided only at very high level of negative GDD (-9900 fs$^2$ for 80 nJ intracavity energy). The stable pulse is soliton-like and has the ~230 fs width. The comparatively narrow symmetric spectrum centered at 1.51 $\mu$m (gray curve in Fig. 4, a).

![Figure 4](WF4.pdf)

Figure 4. (a) - spectral profiles: GDD at $\omega_0$=1.53 $\mu$m is +200 fs$^2$ (red and blue curves) and -9900 fs$^2$ (gray curve); intracavity energy is 80 nJ. For the dashed blue curve the spectral losses are not taken into account. (b) - pulse profiles inside a fiber for the input pulse corresponding to red solid curve in (a). Propagation lengths are indicated, minimum pulse width ~ 80 fs.

In the positive dispersion regime, the stable single-pulse solution could be obtained for GDD values between +150 fs$^2$ and +200 fs$^2$. The pulses are chirped, have picosecond widths and wide (>50 nm) spectra with truncated edges. If only gain and GDD spectral profiles are taken into account, the oscillator spectrum is centered at 1.5 $\mu$m and has the asymmetry (dashed blue curve in Fig. 4, a), which is opposite from that observed experimentally. In simulations the higher-order GDD increases the spectral power in regions, where GDD is most positive [6], i.e. at short-wavelength side of the spectrum. In order to agree with the experiment, it is necessary to take into account the spectral dependency of losses (OC and chirped mirrors) in the resonator. In this case, the spectrum asymmetry is reversed (solid red curve in Fig. 4, a) that matches the observation. The asymmetry is somewhat less than in the experiment because the model takes into account only the unsaturated loss profile. In the mode-locked operation, the losses are modified due to the absorption saturation in the SESAM, which is not known. In addition to asymmetry of the spectrum, the non-uniform loss profile also increases the pulse chirp. The model picosecond pulse can be down- compressed outside of the cavity, illustrated by Fig. 4, b. Propagation inside a fused silica fiber compresses the pulse from 1.1 ps (black curve) down to 80 fs (blue line). Part of energy is lost in the satellites formed due to spectrally-dependent chirp of the input pulse [7,9]. The predicted optimal fiber length is less than the experimental, because the model underestimates the spectral asymmetry. Summarizing, we have demonstrated for the first time the chirped-pulse operation of the Cr:YAG laser. The output pulses have ~50 nm spectral width and allow convenient compression in a piece of a silica fiber down to ~120 fs duration. After the compression, the pulses possess sufficient peak power to produce broad supercontinuum in a nonlinear fiber. The operation regime is sufficiently stable to use the oscillator in spectroscopic measurements.

This work is accomplished in the framework of the Programme Pluri-Formation de l’Université Paris-Sud “Détection de traces de gaz” 2006-2009 and the Austrian FWF Foundation, project P17973.