Recent Developments in Femtosecond Technology

M. Lenzner, S. Sartania, Z. Cheng, L. Xu, A. Poppe, Ch. Spielmann, F. Krausz, I.T. Sorokina, E. Sorokin, E. Wintner

Institut für Allgemeine Elektrotechnik und Elektronik, TU Wien, A-1040 Vienna, Austria

The availability of ultrabroad-band sub-10 fs optical pulses from Ti:sapphire laser oscillators allows 0.1 TW-scale pulse generation from compact kHz-rate amplifiers. The amplified sub-20 fs pulses can be compressed below 5 fs using novel techniques for self-phase modulation and dispersive compression. The resultant high-power light pulses comprising less than two oscillation cycles within their intensity-FWHM open up new possibilities in strong-field physics including the study of reversible nonlinear optical processes in solids beyond the 10^{14} W/cm^2 intensity level.

Despite the unmatched results in extreme ultrashort pulse generation with Ti:sapphire since a few years alternative laser materials are under investigation in order to achieve an all-solid-state laser design. The generation of 14 fs pulses from a KLM-modelocked Cr:LiSAF (60 mW average output power) and a similar Cr:LiSGaF laser (100 mW) is reported representing the shortest femtosecond pulses with the highest average power ever produced out of Cr-doped colquiriite laser crystal oscillators.

1. Introduction

The development of novel broadband solid-state laser materials along with concomitant advances in ultrafast all-optical amplitude modulation techniques has resulted in the emergence of a new generation of femtosecond sources over the last few years. Titanium-doped sapphire has been the most successful gain medium among a number of vibronic solid-state laser materials because of its broad bandwidth (approximately 200 nm FWHM centered at 800 nm) and excellent mechanical and thermal characteristics [1]. The discovery of Kerr-lens mode locking (KLM) [2] and novel means of intracavity dispersion control [3] have opened the way to an efficient exploitation of the enormous optical bandwidth of Ti:sapphire for ultrashort pulse generation.

Soon after the first dispersion-controlled KLM Ti:sapphire lasers had been put into operation it was recognized that system performance critically depends on the bandwidth $\Delta\nu_{GDD}$ over which the overall (negative) cavity group delay dispersion (GDD) is approximately constant [4], [5]. This finding led to the development of Ti:sappire oscillators using fused silica prisms [6] introducing the lowest cubic phase dispersion and allowing sechant-hyperbolic-shaped pulses down to 15 fs in duration. Further pulse shortening could be made possible by employing aperiodic (chirped) multilayer dielectric mirrors for intracavity dispersion control [3]. Specifically designed chirped mirrors have been capable of introducing a nearly constant negative GDD over a wavelength range significantly exceeding the largest $\Delta\nu_{GDD}$ achievable with prisms. As a result, mirror-dispersion-controlled (MDC) Ti:sapphire lasers can produce high-quality nearly-transform-limited pulses down to 7.5 fs in duration [7] (Fig. 1). The spectrum of these pulses can be centered at 790 nm with a time-bandwidth product of ≈0,4. The use of dispersion engineered mirrors instead of prisms for GDD control also improves compactness and the reproducibility of system performance. This is because in MDC systems the net intracavity GDD (and hence pulse duration) is insensitive to resonator alignment, in strong contrast to prism-controlled systems.

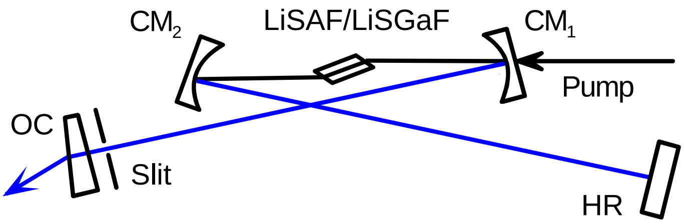

Fig. 1: Typical setup of a MDC femtosecond oscillator

When pursuing the ultimate goal of a really compact all-solid-state femtosecond laser system direct diode pumping of the laser material is a challenge. Thus, during the last years several Cr-doped colquiriite crystals like LiCAF, LiSAF, LiSGaF and others being known already since longer time [8], [9] have invoked new interest because of the availability of new red (670 nm) high power (~500 mW) laser diodes. The insights of optimum laser resonator design for the Ti:sapphire laser have been transferred successfully to the Cr-doped lasers by a number of authors [10] – [13] yielding so far only pulses in the 40-fs region as long as usable average output power is considered to be an essential feature (>50 mW).

Chirped mirrors as they have been developed for the Ti:sapphire laser proved to be too lossy for resonators containing the lower gain Cr-doped media. Hence, dielectric Gires-Tournois mirrors (GTM) have been developed causing lower losses due to a smaller penetration depth of the radiation within the structure. Their GDD is relatively high and adjustable but highly nonlinear hardly allowing to break the 40-fs pulse limit. Only recently, new dielectric materials and further optimized layer sequences allowed to create chirped mirrors which could be employed as straightforward as in the Ti:sapphire lasers [14] yielding pulse durations in the sub-20 fs regime at reasonable average powers as it will be reported later in more detail.

The present sub-10 fs MDC-KLM Ti:sapphire oscillators are ideally suited for seeding high-power femtosecond amplifier systems. The extremely broad bandwidth (≈120 nm) of the emitted sub-10 fs pulses centered at the gain peak of Ti:sapphire allows the implementation of chirped-pulse amplification (CPA) in a fairly simple and compact system. This is because, due to their ultrabroad bandwidth, the seed pulses can be substantially broadened by introducing a relatively small amount of GDD. In fact, the pulse duration increases to several picoseconds upon passage through the usual system components used for isolation and pulse selection. Additional broadening up to tens of picoseconds can be readily induced by introducing a piece of highly dispersive SF57 glass (Schott) without adding notable complexity. In the following, it will be depicted how 5 fs pulses could be generated by further amplification and an optimized pulse compression technique.

2. Sub-TW Pulse Generation

The pulse energy can be boosted beyond the millijoule level in a single-stage 8-pass "bow-tie" amplifier without excessive nonlinearities emerging in the amplifier crystal. Owing to the moderate amount of positive GDD to be compensated for, pulse recompression following amplification by a simple and high-throughput (≈80 %) double-prism sequence. The residual high-order phase dispersion of the system (up to fourth order) is eliminated by specially designed chirped mirrors. The absence of an extra pulse stretcher and lossy diffraction gratings significantly reduces system complexity and (indirectly) gain narrowing, respectively, as compared to conventional CPA systems. The described system currently produces 20 fs pulses beyond the millijoule level at a repetition rate of 1 kHz [15]. This performance comes in combination with excellent stability, pulse energy fluctuations are less than ±3 %.

The high-power 20 fs pulses can be uniformly self-phase modulated across the beam profile in a microcapillary filled with some noble gas, as recently proposed and demonstrated (with 140 fs seed pulses) by M. Nisoli, S. DeSilvestri, and O. Svelto [16]. Suitable choice of the nonlinear medium (Kr, Ar, Ne, etc.), the channel diameter of the fused silica capillary, the length of the hollow waveguide, and the pressure of the noble gas allows controlling spectral broadening and the output beam profile. The pulses exiting the waveguide are propagated through an ultrabroad-band high-throughput dispersive system providing nearly optimum chirp compensation over the wavelength range of 650 – 950 nm [17]. Key components of the dispersive delay line include AR-coated thin fused silica wedged plates and chirped mirrors designed and manufactured by R. Szipöcs and K. Ferencz at the Research Institute for Solid State Physics in Budapest (Hungary). This compressor currently delivers 0.25 mJ, 5 fs pulses, which are focusable to intensities beyond 10^{17} W/cm^2 representing the world's shortest optical pulses.

The entire setup consisting of the MDC oscillator, multipass amplifier, recompression stage, and pump sources occupies an area of approximately 2 m^2 on the optical table. This compactness combined with the ruggedness and reliability of solid-state components make this system a versatile tool for a broad range of experiments in nonlinear optics and related fields. Furthermore, the unique performance described above holds out the promise of pushing the limits of nonlinear optics.

3. Prismless Cr:LiSAF and Cr:LiSGaF Lasers

It was a great challenge to improve the technology of dielectric chirped mirrors so as to make them suitable for LiSAF and LiSGaF lasers. New types of low loss chirped mirrors have been developed at the above mentioned Solid-State Physics Institute, Budapest, involving new dielectric layer materials with different steps of the index of refraction. New algorithms allowed further optimization of the dispersion properties, both aspects currently being filed for patent.

In this paper, we report the shortest, to our knowledge, pulses obtained in MDC-mode-locked Cr:LiSAF and Cr:LiSGaF lasers of a duration of 14 fs at the substantial output power for Cr-lasers of 100 mW at 1.6 W incident 647 nm power.

Having optimized the net intracavity GDD by taking the measured dispersion data for LiSAF and LiSGaF crystals into account, a most simple and compact resonator design has been realized. The cavity is a standard X-cavity, consisting of only two curved (R = 100 mm) dispersive mirrors, the active medium, a high reflector end mirror and an output coupler varying from 0.4 to 2.3 %. The Cr:LiSAF crystal used had a length of 2.8 mm and 0.8 % Cr content, the Cr:LiSGaF crystal was 4 mm long with 0.75 % of Cr. The implemented dispersive mirrors exhibited a maximum GDD of ≈80 fs^2 (Fig. 2).

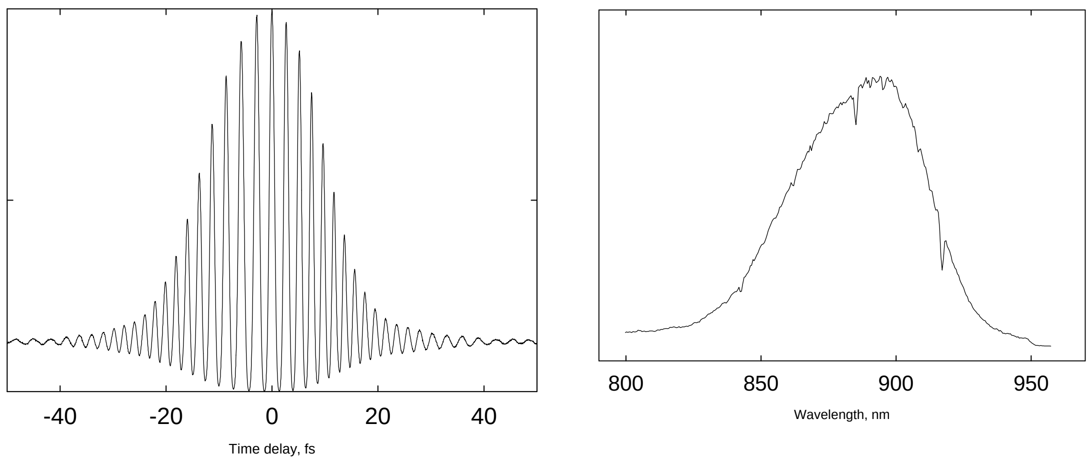

Fig. 2: Interferometric autocorrelation trace and spectrum of the shortest pulses out of a Cr-doped laser

The autocorrelation trace and the measured spectrum of the mode-locked laser pulses centered around λ = 880 nm and having a bandwidth FWHM of 70 nm allow to calculate a duration of 14 fs and a time-bandwidth product $\Delta\tau\Delta\nu = 0.32$ using a $sech^2$ pulse shape fit indicating nearly transform limited pulse quality.

As a next step efficient diode pumping of this oscillator will be realized involving at least 4 of the presently available moderate power AlGaInAs array diodes emitting ~500 mW. After this is realized the Cr-doped colquiriite laser could be an interesting more compact alternative for some applications to the well established Ti:sappire femtosecond laser oscillator.

4. Conclusion

In conclusion, we demonstrated the first successful realization of 5 fs (< 2 optical cycles) laser pulses of 0.25 mJ energy via compression of amplified pulses originating from a MDC Ti:sappire oscillator and being self-phase modulated in a microcapillary. These pulses are focusable to intensities beyond 10^{17} W/m^2 and may be capable of pushing the current limit of coherent X-ray generation by laboratory scale experiments to shorter wavelengths than 6 nm reaching the important water window.

Furthermore, we showed what is to our knowledge the first generation of nearly transform-limited 14 fs pulses from prismless KLM Cr:LiSAF and Cr:LiSGaF lasers having average powers of up to 100 mW. The laser setup is characterized by extreme compactness, comprising only two dispersive mirrors, replacing conventional cavity mirrors, giving rise to high stability of the mode-locked operation.

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The 5 fs compression experiment has been performed in collaboration with M. Nisoli, S. DeSilvestri and O. Svelto from the Politechnico Milano (Italy). The cooperation with R. Szipöcs and K. Ferencz from the Research Institute for Solid-State Physics in Budapest (Hungary) for the development of the different versions of chirped mirrors is gratefully acknowledged. We also would like to thank the suppliers of the LiSAF and LiSGaF crystals, A. Cassanho of VLOC, Tarpon Springs, and H.P. Jenssen, University of Central Florida, Orlando, Florida for their support.

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