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Chirped-pulse oscillators for the generation of high-energy femtosecond laser pulses

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Abstract

This paper reports on a novel approach for producing high energy femtosecond pulses without external amplification. The so-called chirped-pulse oscillator (CPO) concept is based on an extended-cavity oscillator, operating at small net positive intracavity group delay dispersion (GDD), over a broad spectral range by the use of chirped multilayer mirrors. The resultant chirped picosecond pulses are compressed by a dispersive delay line external to the laser cavity. Utilizing this technique, sub-30 fs pulses with an energy exceeding 200 nJ at a repetition rate of 11 MHz were produced. The demonstrated peak power in excess of 5 MW is the highest ever achieved from a cw-pumped laser and is expected to be scaleable to tens of megawatts by increasing the pump power and/or decreasing the repetition rate. The demonstrated source allows micromachining of any materials under relaxed focusing conditions.

Keywords: Ablation Field; Femtosecond laser; Femtosecond; Micromachining; Ultrafast

1. INTRODUCTION

Recently it has been demonstrated that femtosecond lasers are excellent tools for a wide range of applications from inertial fusion (Canaud *et al*., 2004; Ramirez *et al*., 2004), the generation of intense bursts of X-rays (Limpouch *et al*., 2004; Issac *et al*., 2003), and the microstructuring of nearly all kinds of solid material (Di Bernardo *et al*., 2003). The main features of material processing with femtosecond laser pulses are efficient, fast, and extremely localized energy deposition, low deformation and ablation thresholds, and minimal or no thermal and mechanical damage of the substrate material. This allows one to produce microstructures with very high precision and reproducibility. At present, two different kinds of femtosecond light sources are readily available, both of which have certain disadvantages when it comes to material processing:

(1) Femtosecond oscillators are relatively simple and robust systems, typically operating at around 100 MHz. The output energies, however, are in general too low to reach the ablation threshold of most relevant materials.

(2) Amplifier systems, typically based on the chirped pulse amplification (CPA) concept, are highly complex and expensive (Sartania *et al*., 1997). Moreover, the repetition rate of these systems usually is in the kHz-range. These systems are overkill for micromachining applications because the pulse energy has to be attenuated (for high precision micromachining it is necessary that the fluency of a single light pulse is not too far above the damage threshold of the material to be processed), which results in a relatively low average output power and consequently in a low process speed. This limits the achievable throughput, moreover, effects the overall process quality. For example, in waveguides written with a 1 kHz source (and therefore at very slow translation speeds), evidence of small microbends has been observed. These contribute significantly to transmission losses. A MHz system would enable one to write much faster, hence making the process less susceptible to pointing/position jitter.

We therefore attempted to strike a new path. By inserting a so-called multipass cell (Herriott *et al*., 1964) into a femtosecond oscillator, the repetition rate can be decreased by a factor of up to 20 with a corresponding increase of the output energy. Therefore, the ablation threshold can easily be reached and it should become possible to guarantee both, a superior quality of the ablation and a high throughput using a relatively simple laser system (Poppe *et al*., 1999).

However, the major challenge in scaling passively mode-locked femtosecond oscillators to very high peak powers, is to prevent excessive nonlinear effects from causing instabilities, that is, an increased pulse energy noise and, in particular, the onset of multiple pulsing. Two different techniques

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have already been suggested in order to maintain single-pulse operation, even at very high energy levels: to implement highly negative net-intracavity dispersion, resulting in a relatively low spectral bandwidth, or a positive one in a prism-controlled Ti:Sapphire oscillator (Cho *et al.*, 2001). Utilizing the first concept, a peak power of 3.5-MW delivered at an average power of 900 mW was already demonstrated (Kowalevicz *et al*., 2003). Unfortunately, this route is not scaleable to higher peak powers because of the excessive intensities in the laser crystal emerging at higher pulse energies at the short (< 100 fs) pulse durations. While a net positive intracavity GDD holds promise for circumventing this problem, as it results in the generation of strongly-chirped picosecond pulses with a substantially lower peak intensity, the absence of broadband dispersion control did not allow the generation of smooth, ultrabroad emission spectra (and hence compression to ultrashort ($\ll 100$ fs)) pulse duration in this operation mode before.

In this paper, we report on an extended-cavity Kerr-lens-mode-locked oscillator, in which broadband chirped multilayer mirrors allow stable operation at a small positive net intracavity GDD, over an extended spectral range in spite of the large number of bounces on mirrors needed for a compact arrangement. In combination with the optical Kerr effect, resulting from a positive nonlinear index of refraction, the small positive dispersion which is nearly constant over a broad spectral range, results in strongly-chirped picosecond pulses with a smooth broad spectrum allowing compression to less than 30 fs, and the generation of pulses with peak powers in excess of 5 MW.

2. EXPERIMENT

The experimental setup is depicted in Figure 1. A frequency doubled Nd:YVO$_4$ laser with an output power of up to 10.2 W, operating in cw (Coherent Verdi V10), is pumping the Ti:Sapphire crystal (2.9 mm path length, 67% absorption). Two curved mirrors with an ROC of 50 mm, high reflective for the laser wavelength, centered at 800 nm and high transparent for the pump wavelength of 532 nm are used, to focus the resonator beam into crystal. The total GDD is controlled by various bounces off different chirped dielectric mirrors while the fine tuning can be accomplished by a pair of Brewster angled fused silica (FS) prisms arranged in close proximity to each other. The chirped mirrors were selected to yield; aside from some residual fluctuations; nearly constant mean net cavity GDD over the wavelength range of 700–900 nm. The multipass cell consists of two mirrors with a diameter of 2 inches, one of them a flat mirror whereas the other one a concave type with a ROC of 5 m.

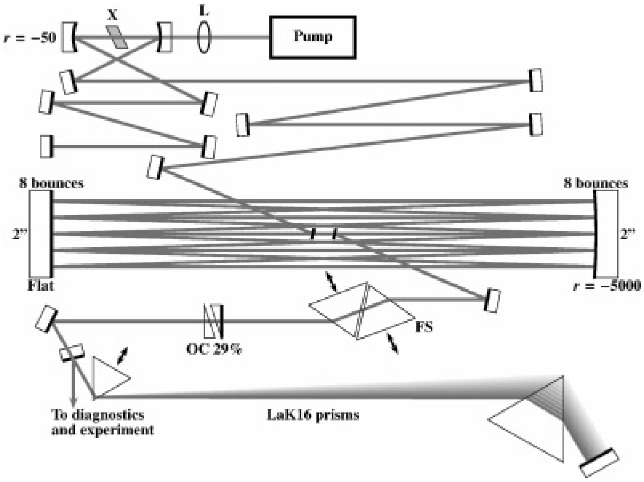

Fig. 1. Schematic of the high energy oscillator

There are in total 16 reflections per round trip realized on each of these telescope mirrors which are separated by approximately 73 cm to preserve the q-parameter. This results in an effective resonator length of 13.6 m, tantamount to a repetition frequency of 11 MHz.

The picosecond chirped pulses emitted by the oscillator are compressed by double passage through a dispersive delay line consisting of a pair of Brewster-angled LaK16 prisms (prism separation 140 cm, total GDD ~ 6300 fs^2 at 800 nm).

3. RESULTS

When optimizing the laser for maximum power, special care was taken to observe possible multiple pulsing by monitoring the laser output simultaneously with a fast (< 0.5 ns) photodiode, a high-resolution spectrometer and a second-order intensity autocorrelator with an extended scanning movement (equal to 0.5 ns), to cover the full time range between two successive pulses. In addition to this monitor diagnostics a SPIDER apparatus was used for accurate femtosecond pulse characterization.

Operating the laser with minimum insertion of the fused silica prisms, which corresponds to net negative intracavity dispersion, we found out that quite high pulse-to-pulse fluctuations were unavoidable at virtually any pump power level (compare Fig. 3). Moreover, by slowly increasing the pump power it turned out, that, starting at about 3.5 W, splitting of the laser pulse into two or more pulses inside the laser cavity could be observed. These additional pulses were either separated some tens of ns from the main pulse, or only 0.8–3 ps apart. If the pump power is increased further, more and more additional pulses arose. In this case a situation emerges, where there is one relatively strong and a large number of weak pulses circulating inside the resonator. In total, these satellite pulses can carry a considerable amount of energy, but as each pulse is orders of magnitude smaller than the main pulse, they are very hard to detect.

In contrast, after insertion of a larger amount of fused silica and therefore operating at net positive dispersion, we found out that the maximum available pump power (up to 10.2 W) could be applied to the oscillator without any signs of multiple pulsing or continuous-wave (cw) breakthrough. The largest output power of more than 2 W directly out of the oscillator was obtained using an output coupler (OC) with a transmission as high as 29%. This is, to our knowledge, by far the highest average output power ever generated with an extended cavity Ti:Sapphire oscillator. As we used Brewster prisms for compressing the pulses, the transmission losses could be kept below 5%. Taking into account the repetition rate of 11 MHz, this corresponds to pulse energy of 180 nJ behind the compressor. The resulting pulse train was found to be very stable with maximum pulse-to-pulse peak power fluctuations of less than 3 %. The minimum pulse duration, measured with the SPIDER apparatus, was 35 fs.

Because the full available pump power could be used without any indications of limitations or saturation, we believe that our approach is scaleable to even high average powers by using stronger pump lasers, or by pumping the gain medium from both sides and/or to higher pulse energies by further reducing the repetition rate of the laser.

Further optimization of the net cavity GDD, the pump power and the KLM parameters permitted the generation of high-energy 26-fs pulses (Fig. 2). The significantly broader emission spectrum and corresponding shorter pulse duration was achieved by compromising the output power: it had to be reduced to ~1.5 W in these experiments. The SPIDER measurements summarized in Figure 2 indicate that the residual high-order spectral phase at the edges of the spectrum carried by the pulses limits further shortening of the pulses in this mode of operation.

Depending on the position of the Ti:Sapphire crystal relative to the resonator beam and the exact position within the stability range, an interesting operation regime of the oscillator was found, where every second pulse contains a larger amount of energy and a lower one, respectively (see Fig. 3). This regime of so-called period doubling, results in a significant increase in the pulse energy of every second pulse. In contrast to observations made in a standard oscillator (Cote & Van Driel, 1998), we did not see any difference in the beam size between the normal operation regime and the period doubling. Unfortunately, this regime depends very critically on the overall cavity alignment and the crystal position. However, once it is established, it remains stable over a long period of time. From the pulse train shown in Figure 3c, pulse energy of the stronger pulses as high as 220 nJ can be derived. The period doubling regime can be of

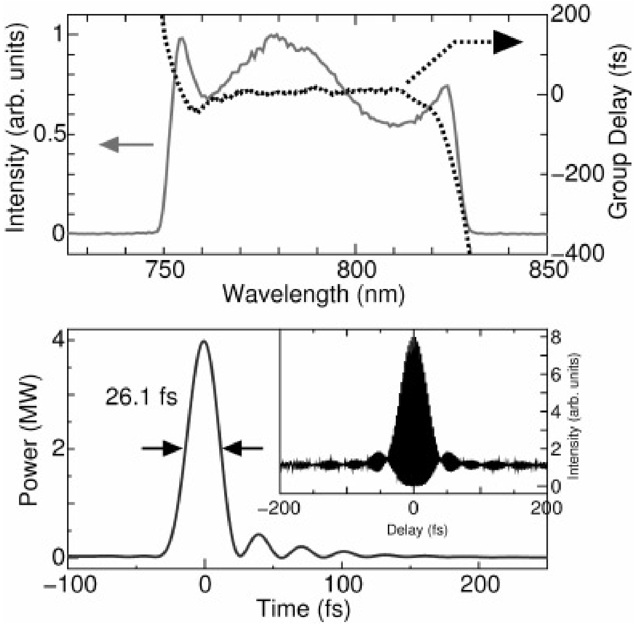

Fig. 2. The SPIDER measurement results of the compressed 130 nJ pulses. (**a**) Retrieved spectral phase and intensity spectrum of the pulses. (**b**) The temporal profile of the pulses obtained with inverse Fourier transform of (a). The measured interferometric autocorrelation trace is also shown in the inset.

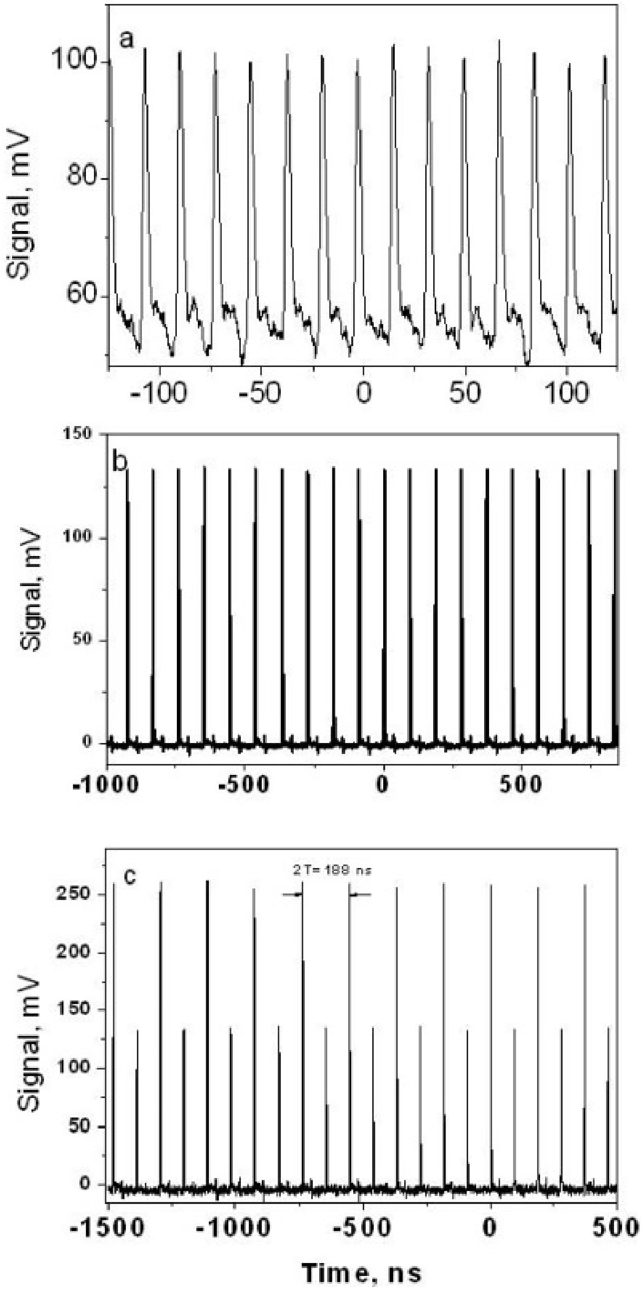

Fig. 3. The pulse train in different operational modes of the oscillator. **A**: regime of negative dispersion and femtosecond pulses inside the cavity; **B**: positive dispersion regime; **C**: the period doubling mode (positive dispersion regime).

great interest for nonlinear scientific experiments and material processing applications.

As stated before, there are a couple of reasons, making a long cavity, high energy Ti:Sapphire oscillator the perfect tool for micromachining applications in transparent dielectric materials. First of all it is known, that the damage threshold in such materials becomes lower for shorter pulses. Therefore, less energy has to be deposited into the material, minimizing the debris deposition around the fabricated structure and maximizing the quality of the process. Additionally, the damage threshold changes from a stochastic behavior for long pulses to a deterministic one for short pulses (Lenzner, 1999), allowing to adjust the laser energy in a way, that only the center of the transversal intensity distribution exceeds the ablation threshold. In that way, structures smaller then the size of the focal spot can be generated (Korte *et al*., 2000). On the other hand, an ultrahigh precision usually comes with the drawback of low efficiency of the overall machining process, because only a very small volume is ablated per laser shot. As the presented oscillator operates at a repetition rate in the MHz range, compared to amplifier systems, usually operating at a few kHz, much higher ablation rates can be achieved.

To prove if all the energy is really concentrated in a single output pulse in our laser, and that no pulse splitting has occurred, we performed ablation experiments in glass samples. The pulses behind the compressor were focused onto the surface of a BK7 substrate by means of different optics. Even by using a lens with a numerical aperture (NA) as low as 0.15, surface damage could be achieved. Taking into account the given damage threshold of BK7 at a 30 fs pulse duration this is a clear evidence, that the pulse energy must be significantly larger than 150 nJ, which directly proves the single pulse operation of the oscillator.

Using an aspheric lens with a NA of 0.4 for focusing the beam onto the same sample, and carefully adjusting the pulse energy just slightly above the damage threshold and by selecting single output pulses using an extracavity Pockets cell, we tried to generate damage spots with a diameter as small as possible. Because only a standard light-optical microscope was available, an exact analysis of the resulted structure was not possible. However, from the measurement we can estimate, that circular ablation spots with a diameter of around 500 nm were generated on the surface of the BK7 substrate, showing the potential of this laser source for nanomachining applications.

4. CONCLUSIONS

In conclusion, a powerful 220 nJ–35 fs, or 130 nJ–26 fs, respectively, Ti:Sapphire oscillator has been demonstrated at an 11 MHz repetition rate, with an unprecedented stability and reliability. The concept of using a positive regime of net dispersion is up-scalable to even higher pulse energies as no limitations like those in the regime of negative net dispersion have been found. As direct proof that all the energy is really concentrated in a single output pulse, ablation experiments using low-NA lenses have been performed. The combination of a high enough energy, a high repetition rate and an almost perfect beam profile makes this sources a promising tool for precision micromachining applications.

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REFERENCES

Canaud, B., Fortin, X., Garaude, F., Meyer, C. & Philippe, F. (2004). Progress in direct-drive fusion studies for the laser megajoule. *Laser Part. Beams* **22**, 109–114.

Cho, S.H., Kärtner, F.X., Morgner, U., Ippen, E.P., Fujimoto, J.G., Cunnighan, J.E. & Knox, W.H. (2001). Generation of 90-nJ pulses with a 4-MHz repetition rate Kerr-lens mode-locked Ti:Al_2O_3 laser operating with net positive and negative intracavity dispersion. *Opt. Lett.* **26**, 560.

Cote, D. & van Driel, M. (1998). Period doubling of a femtosecond Tisapphire laser by total mode locking. *Opt. Lett.* **23**, 715.

Di Bernardo, A., Courtois, C., Cros, B., Matthieussent, G., Batani, D., Desai, T., Strati, F. & Lucchini, G. (2003). High-intensity ultrashort laser-induced ablation of stainless steel foil targets in the presence of ambient gas. *Laser Part. Beams* **21**, 59–64.

Herriott, D., Kogelnik, H. & Kompfner, R. (1964). Off-axis paths in spherical mirror interferometers. *Appl. Opt.* **3**, 523.

Issac, R., Wirthig, J., Brunetti, E., Vieux, G., Ersfeld, B., Jamison, S.P., Jones, D., Bingham, R., Clark, D. & Jaroszynski, D.A. (2003). Bright source of K alpha and continuum X rays by heating Kr clusters using a femtosecond laser. *Laser Part. Beams* **21**, 535–540.

Korte, F., Adams, S., Egbert, A., Fallnich, C., Ostendorf, A., Nolte, S., Will, M., Ruske, J.P., Chichkov, B.N. & Tünnermann, A. (2000). Sub-diffraction limited structuring of solid targets with femtosecond laser pulses. *Opt. Exp.* **7**, 41.

Kowalevicz, A.M., Jr., Zare, A.T., Kaertner, F.X., Fujimoto, J.G., Dewald, S., Morgner, U., Scheuer, V. & Angelow, F. (2003). Generation of 150-nJ pulses from a multiple-pass cavity Kerr-lens mode-locked Ti:Al_2O_3 oscillator. *Opt. Lett.* **28**, 1597.

Lenzner, M. (1999). Femtosecond Laser-Induced Damage of Dielectrics. *Int. J. Mod. Phys. B* **13**, 1559.

Limpouch, J., Klimo, O., Bìna, V. & Kawata, S. (2004). Numerical studies on the ultrashort pulse K-alpha emission sources based on femtosecond laser-target interactions. *Laser Part. Beams* **22**, 147–156.

Poppe, A., Lenzner, M., Krausz, F. & Spielmann, Ch. (1999). A sub-10-fs, 2.5-MW Ti:sapphire oscillator. *Conference on Ultrafast Optics*. Switzerland: Ascona.

Ramirez, J., Ramis, R. & Sanz, J. (2004). One-dimensional model for a laser-ablated slab under acceleration. *Laser Part. Beams* **22**, 183–188.

Sartania, S., Cheng, Z., Lenzner, M., Tempea, G., Spielmann, Ch., Krausz, F. & Ferencz, K. (1997). Generation of 0.1-TW 5-fs optical pulses at a 1-kHz repetition rate. *Opt. Lett.* **22**, 1562.