Chirped-pulse oscillators: a route to high-power femtosecond pulses without external amplification

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We demonstrate a Kerr-lens mode-locked Ti:sapphire oscillator that generates 130-nJ, 26-fs and 220-nJ, 30-fs pulses at a repetition rate of 11 MHz. The generation of stable broadband, high-energy pulses from an extended-cavity oscillator is achieved by the use of chirped multilayer mirrors to produce a small net positive dispersion over a broad spectral range. The resultant chirped picosecond pulses are compressed by a dispersive delay line that is external to the laser cavity. The demonstrated peak powers, in excess of 5 MW, are to our knowledge the highest ever achieved from a cw-pumped laser and are expected to be scalable to tens of megawatts by an increase in the pump power and (or) a decrease in the repetition rate. The demonstrated source permits micromachining of any materials under relaxed focusing conditions.

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High-energy femtosecond laser oscillators[1,2] with peak powers that exceed several megawatts (without cavity dumping) offer the potential of replacing more-complex and -expensive ultrashort-pulse amplifier systems.[3–7] Applications include the investigation of high-order nonlinear optical processes such as high-harmonic generation, photoemission, and above-threshold ionization as well as three-dimensional binary data storage[8] and fabrication of nanostructures in transparent dielectrics.[9,10] The pulse repetition rate was decreased to 1 MHz (Ref. 11) by use of a suitable imaging delay line, offering the potential for achieving high peak powers at moderate average power levels and allowing the interaction medium to relax between subsequent laser shots (e.g., in the micromachining of glasses[12]).

The major challenge in scaling passively mode-locked femtosecond oscillators to ever-higher peak powers is to prevent ever-stronger nonlinear effects from causing instabilities (increased pulse energy noise, multiple pulsing). Several strategies that rely on a small positive[1] or a large negative intracavity group-delay dispersion[2] (GDD) have been proposed and tested for obtaining stable single-pulse operation at increased pulse energy levels. The latter concept recently resulted in a record peak power of 3.5 MW delivered at an average power of 900 mW from a cw-pumped laser.[2] Unfortunately, this route is not likely to be scalable to significantly higher peak powers because of the excessive intensities in the laser crystal that emerge with increasing pulse energies at short (<100-fs) pulse durations.

In this Letter we present an extended-cavity Kerr-lens mode-locked oscillator in which a combination of the optical Kerr effect that results from a positive nonlinear index of refraction with small positive dispersion over a broad spectral range results in strongly chirped picosecond pulses with a smooth broad spectrum. The emitted pulses can be compressed to less than 30 fs, giving rise to peak powers in excess of 5 MW for the first time to our knowledge from a laser pumped by a cw source. The concept holds promise for scaling the peak power available from these sources far beyond 10 MW.

A schematic layout of the laser is shown in Fig. 1. In addition to the standard components of a Kerr-lens mode-locked, mirror-dispersion-controlled Ti:sapphire oscillator, a multiple-pass telescope consisting of two 2-in.- (5.18-cm-) diameter multilayer mirrors (one is chirped; the other is a high reflector) is introduced into the laser cavity for increasing the round-trip time to more than 90 ns. 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, $\sim$6300 fs^2 at 800 nm). When we optimized the laser for maximum power we

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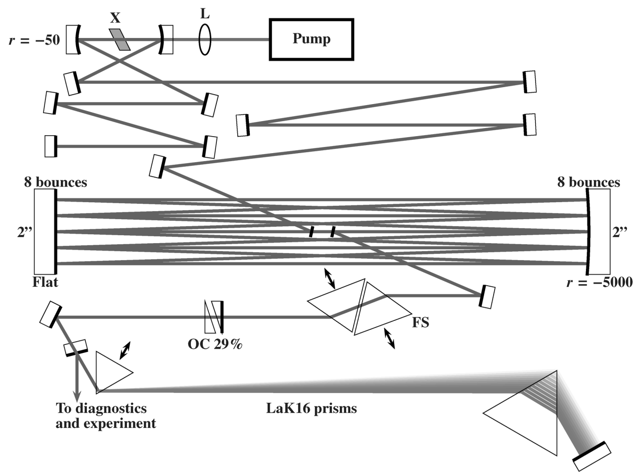

Fig. 1. Schematic of the oscillator. The distance between 2-in. telescope mirrors is 75 cm. Ti:sapphire crystal length, 2.9 mm; pump absorption, 67%; maximum output average power behind the compressor, 1.9 W at 10.2 W of pump power. r, radius of curvature; L, lens; X, Ti:sapphire crystal; OC, output coupler.

took special care 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 (0.5-ns) scanning range. In addition to the monitor diagnostics, spectral phase interferometry for direct electric-field reconstruction (SPIDER) was used for accurate femtosecond pulse characterization. Fine tuning of the nominal cavity GDD in this wavelength range was accomplished by a pair of Brewster-angled fused-silica (FS) prisms arranged in close proximity in the cavity. In the regime of positive GDD it was found to be difficult to initiate Kerr-lens mode locking (KLM), in agreement with earlier investigations.[13,14] To overcome this problem we set one of the FS prisms to produce a negative cavity GDD for startup. Under these circumstances KLM started easily, but a broad spectrum supporting 30-fs pulses was always accompanied by substantial instabilities in the negative dispersion regime, as revealed by a noisy autocorrelation trace. Once KLM built up, the FS prism was moved back to the position of an optimum positive cavity GDD, yielding a smooth spectrum extending over some 70 nm.

Careful investigation of the various modes of operation (at different values of the cavity GDD) revealed substantial qualitative and quantitative differences. Optimization of operation in the regime of negative GDD (from -600 to -300 fs^2) yielded pulses of ~20-fs in duration directly from the laser cavity. However, pulse-to-pulse fluctuations at these pulse durations are substantial at virtually any pump power; single-pulse, cavity-round-trip operation is feasible only up to some 3.5 W of absorbed pump power. Pumping the laser more strongly unavoidably results in splitting of the laser pulse into two or more pulses inside the laser cavity. Changing the cavity dispersion to a sufficiently high positive value (~500 fs^2) results in robust and highly stable single-pulse operation [see Fig. 2(a)] at any power levels currently available for pumping this laser. A smooth emission spectrum in the range 760–820 nm along with a similar autocorrelation trace was recorded at the maximum pump power of 10.2 W available from our pump source, which corresponds to an absorbed pump power of slightly above 7 W and yields 180-nJ, 30-fs pulses at an average power of ~2 W behind the extracavity prism compressor. This combination of peak and average power from a femtosecond laser oscillator is, to the best of our knowledge, unparalleled to date.

Careful optimization of the net cavity GDD, the pump power, and the Kerr lens mode-locked parameters permitted the generation of high-energy 26-fs pulses (Fig. 3). We achieved the significantly broader emission spectrum and correspondingly shorter pulse duration by compromising the output power: It had to be reduced to ~1.5 W in these experiments. The SPIDER measurements summarized in Fig. 3 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.

Above the critical value of cavity GDD the slope efficiency of the laser was found to be similar to that measured in cw operation, with only a slight decrease in the slope at the highest pump power levels available. This finding suggests that the technique is scalable to substantially higher pulse energies. Whereas KLM generally tends to become unstable below the critical value of positive GDD (for the given pump power applied),[15–17] we found an operation regime (within the operational range of positive GDD) that exhibits stable and reproducible modulation of the pulse energy at half the repetition rate of the laser [Fig. 2(b)] in a way similar to that reported in Ref. 18. The energy of every other pulse reaches 220 nJ in this mode of operation, which may prove useful for some applications (e.g., micromachining).

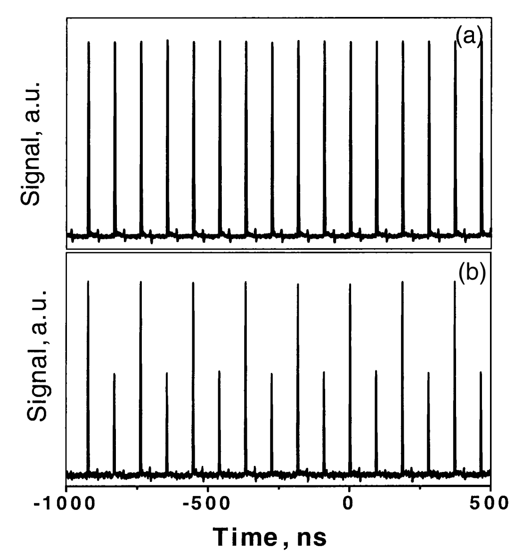

Fig. 2. Pulse train in different operational modes of the oscillator: (a) positive dispersion regime with picosecond pulses; (b) period doubling mode (also in the positive dispersion regime).

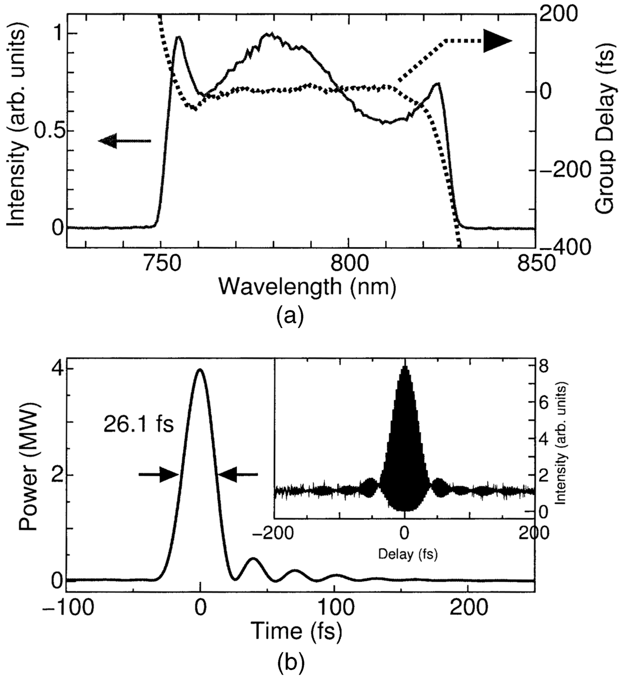

Fig. 3. SPIDER measurement results for the compressed 130-nJ pulses (7 W of pump power). (a) retrieved spectral phase and intensity spectrum of the pulses. (b) Temporal profile of the pulses obtained with the inverse Fourier transform of (a). The measured interferometric autocorrelation trace is shown in the inset of (b).

Our preliminary experiments have revealed that the multimegawatt peak powers produced by this laser are sufficient for machining even the hardest dielectrics such as crystalline quartz and sapphire. Compared with complex few-kilohertz repetition-rate femtosecond amplifier systems operated at a few watts of average power, the source presented here offers—beyond its relative simplicity—the advantage of combining a comparable machining speed with substantially higher (nanometer-scale) machining precision (owing to the inherently higher pulse-to-pulse stability of a cw-pumped mode-locked laser oscillator and to near-threshold machining at much smaller beam diameters). The peak-power scalability of the chirped-pulse oscillator described here holds promise for developing a compact, efficient driver based on the chirped-pulse oscillator concept for a wide range of nonlinear frequency converters including optical parametric generation and amplification in crystals and high-harmonic generation on surfaces or in gas targets. Coherent radiation over a wide spectral range covering virtually all frequencies from the far infrared (a few terahertz) to the extreme ultraviolet (tens of petahertz) may become available with unprecedented characteristics (e.g., controlled frequency comb and controlled waveform).

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