Sub-20-fs, kilohertz-repetition-rate Ti:sapphire amplifier

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A simple four-pass Ti:sapphire amplifier is seeded by sub-10-fs pulses generated from a mirror-dispersion-controlled Ti:sapphire laser. Pulses of 17–18-fs duration with energies up to 50 and 100 μJ have been produced at repetition rates of 2 and 1 kHz, respectively. Because of the absence of a pulse stretcher, this performance is achieved from an extremely compact system.

Ultrashort-pulse kilohertz-repetition-rate amplifiers have been powerful tools for ultrafast spectroscopy because they simultaneously offer high pulse energies and the possibility of use of sensitive signal-averaging techniques.[1] Until recently, kilohertz-rate amplification of femtosecond pulses could be performed only in complex dye laser systems. The evolution of kilohertz femtosecond dye amplifiers culminated in the generation of submicrojoule-energy 16-fs pulses from a sophisticated multistage amplifier system.[2] In this Letter we report amplification of pulses of comparable duration to the 100-μJ-level in a much more compact, reliable, and user-friendly solid-state laser, which uses Ti:sapphire as the gain medium.

The discovery of self-mode locking in a Ti:sapphire oscillator[3] was soon followed by a demonstration of kilohertz amplification of 150-fs pulses up to 1 mJ in a Ti:sapphire laser system.[4] Subsequent advances in femtosecond pulse generation from Ti:sapphire oscillators led to the generation of pulses in the 10–20-fs range,[5] thus provoking much interest in amplifying pulses well below 100 fs. Recently, regenerative amplification of 55- and 30-fs pulses was demonstrated at kilohertz repetition rates.[6,7] Regenerative amplification is a well-established technique for the efficient generation of microjoule- and millijoule-energy ultrashort pulses from solid-state lasers with excellent beam quality. To preclude excessive peak intensities in the amplifier, the seed pulse is temporally expanded by a dispersive delay line and recompressed after amplification (chirped-pulse amplification).[8] After being seeded into a resonator containing the amplifying medium, the pulse experiences gain over many round trips. It enters and leaves the cavity via a Pockels cell/dielectric polarizer system, which is passed in every round trip. The extinction ratio of the polarizer must be severely compromised if cumulative higher-order dispersion effects are to be kept at a low level for broad-bandwidth pulses, constituting a major limitation to shorter pulse generation from regenerative amplifiers.

This limitation is absent in multipass amplifiers, in which the pulse slicer is passed only once and the selected pulse then propagates a number of times along slightly different paths through the gain region of the amplifier medium. The necessary overlap between the seed beam and the pumped region limits the number of passes; therefore high single-pass gain is required. Recently, the amplification of 26-fs pulses to the terawatt level at a repetition rate of 10 Hz was demonstrated in a two-stage multipass amplifier.[9] Another limitation originates from previous implementations of the chirped-pulse-amplification concept, which employed sophisticated pulse expansion–compression systems.[6,7,10] These setups not only add considerable complexity but require a higher overall gain to compensate for the losses. The higher gain, in turn, implies a more severe gain-narrowing effect, which ultimately limits the shortest pulse duration achievable from an amplifier at a given energy level. Whereas these systems are indispensable in terawatt-scale systems,[9,11] they can be replaced by a more compact and efficient scheme, as we demonstrate below.

In this Letter we report a novel approach to amplifying extremely short optical pulses to moderate (submillijoule) energy levels. Seeding a multipass Ti:sapphire amplifier with ultrabroad-bandwidth (90–100-nm, 40–45-THz) pulses leads to a substantial natural pulse broadening because of the material dispersion of the system components and hence to an automatic implementation of the chirped-pulse-amplification concept. Pulse stretching by the dispersion of additional optical materials was demonstrated recently.[12] The moderately stretched amplified pulses can then be recompressed with a low-dispersion prism pair in combination with standard and specially designed high-reflecting mirrors for cubic dispersion control. This approach combines an extremely high overall system throughput and bandwidth with the benefits of an unprecedented simplicity and compactness.

The seed pulses for our amplifier are generated from a mirror-dispersion-controlled Kerr-lens mode-locked Ti:sapphire laser.[13] The oscillator reported in Ref. 13 has been improved and is now capable of generating nearly bandwidth-limited 8-fs pulses if operated with a 3%-transmitting output coupler.[14] For seeding the amplifier we use an 8% output coupler, which yields slightly longer 9–10-fs pulses at a 80-MHz repetition rate with an average power of 100–150 mW when pumped with 3–3.5 W of power from a small-frame argon laser (all lines). As a unique feature of the mirror-dispersion-controlled Ti:sapphire laser, the mode-locked spectrum is as broad as 90–100 nm and centered between 780 and 790 nm. The same spectral

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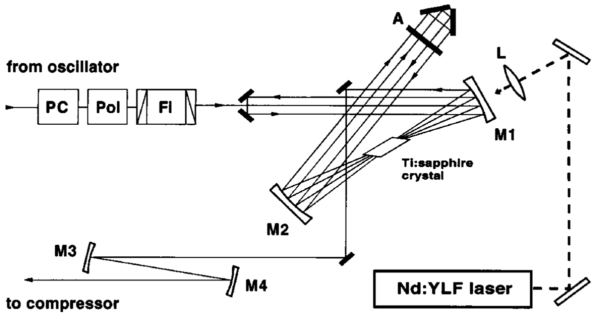

Fig. 1. Schematic of the confocal multipass amplifier. The radius of curvature of focusing mirrors M1 and M2 is 30 cm. PC, Pockels cell; Pol, Berek's polarization compensator; FI, Faraday isolator including two polarizers; A, multiple aperture; M3, M4, collimating telescope; L, lens (f = 15 cm).

width can be obtained from prism-dispersion-controlled Ti:sapphire lasers only in the wavelength range centered around 850 nm,[15,16] which is poorly matched with the gain profile of the amplifier.

A schematic diagram of the amplifier is shown in Fig. 1. The Pockels cell selects single pulses from the 80-MHz pulse train at a repetition rate between 1 and 5 kHz, depending on that of the pump laser of the amplifier, with an extinction ratio of $>10^3$. A Berek compensator allows for any polarization transformation between the Pockels cell and the Faraday rotator, providing a convenient means of changing the polarization for transmitting the full train for alignment purposes or switching single pulses for amplification. A special broadband Faraday rotator (Gsaenger FR 820 BB) surrounded by two MacNeille polarizers[17] provides an isolation of >50 dB over a wavelength range of 680–1200 nm, with a transmittivity peaking near 820 nm and having a 50% bandwidth of $\approx$350 nm. The finite bandwidth and some wavelength mismatch of the isolator and reflective optics in the amplifier reduce the spectral width of the pulse to 65–70 nm. This time-independent isolation was found to be necessary (in addition to the time-dependent isolation provided by the Pockels cell) to prevent amplified spontaneous emission (ASE) in the reverse direction from reaching the oscillator. This reverse ASE did not disturb the oscillator noticeably, but when it is reflected back by the output coupler it experiences the same high gain as the seed pulse and hence gives rise to considerable background.

The selected pulses passing through the pulse slicer and isolator are dispersively broadened by a factor of $\approx$300 to a duration of 3 ps. The amplifier uses a 6-mm-long, highly doped (0.20%) Brewster-cut Ti:sapphire slab (Crystal Systems) at the focus of an astigmatically compensated confocal four-pass amplifier formed by two dichroic mirrors (f = 150 mm, 40-mm diameter) and retroreflectors, as shown in Fig. 1. A multiple aperture in the beam path prevents the onset of laser action in the high-gain amplifier. The Ti:sapphire crystal is pumped by a cw-pumped, intracavity frequency-doubled, Q-switched Nd:YLF laser (BMI, Model 621-D), which deliver 300-ns pulses at a repetition rate variable between 1 and 5 kHz with a maximum average power of 12 W. The crystal absorbs 64% of the incident pump energy in the first pass, with the transmitted portion backreflected into the crystal to achieve an overall absorption efficiency of $>80\%$. Pumping the amplifier with an energy of 6 mJ at a 2-kHz repetition rate produces an effective single-pass gain of ≈ 18, yielding a total gain of $\approx 10^5$. From the single-pass gain we calculate the pump fluence on the first crystal face as $\approx 5\ \mathrm{J/cm^2}$, at which safe operation without the risk of damage is possible owing to the comparatively long pump pulses.

After amplification the chirped 3-ps pulses are recompressed in a compressor that comprises dispersive mirrors and a low-dispersion FK5 (Schott) prism pair. An additional source of positive third-order dispersion (TOD) is required because the positive TOD of system components (materials and mirrors) is overcompensated by the negative TOD of the prism pair when the overall group-delay dispersion is zero. To this end chirped dielectric mirrors[18] with negative group-delay dispersion and positive TOD have been designed and manufactured at the Research Institute of Solid State Physics in Budapest, Hungary. The dispersive characteristics of these special mirrors along with those of the prisms and other system components will be described in detail elsewhere.[19] With 16 reflections off the chirped mirrors (group-delay dispersion approximately $-50\ \mathrm{fs^2}$, TOD $\approx 100\ \mathrm{fs^2}$) the prisms are 5 m apart. This rather large separation was achieved with a folding mirror and leads to a beam size at the second prism of $\approx$4 cm. This combination of dispersive elements results in a virtually complete elimination of

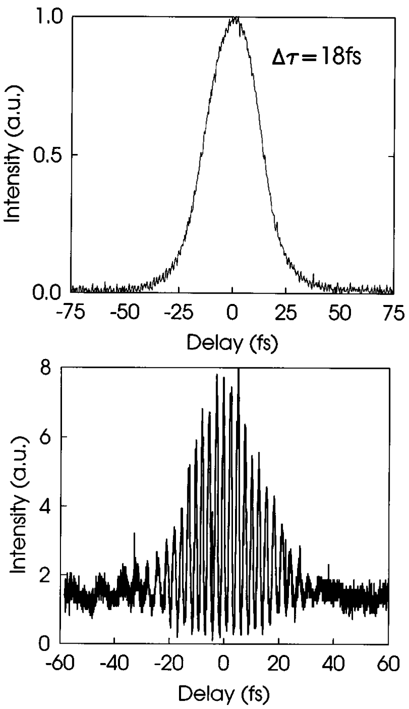

Fig. 2. Intensity and interferometric autocorrelation traces of the amplified pulses. A sech^2 shape was assumed for determination of the pulse width. The signal-to-noise ratio of this interferometric autocorrelation is at the limit of what can be measured. The difficulties arise from the fact that resolution of the fringes requires a slow scan speed (<1 Hz).

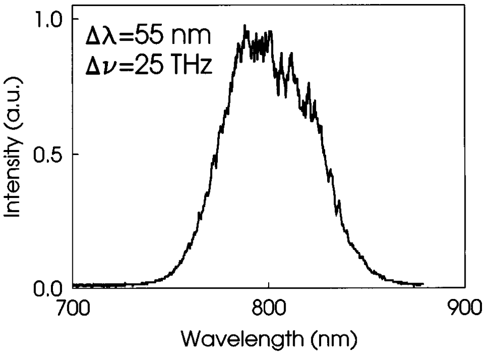

Fig. 3. Spectrum of the amplified pulses.

TOD in the system, with a residual fourth-order dispersion of $\approx -2 \times 10^4$ fs^4.

This simple, low-loss compressor is capable of recompressing the unamplified pulses after a stretching by more than a factor of 300 to ≈15 fs (spectral width 65–70 nm.[19] With the amplifier in operation, the pulse duration increases to 17–18 fs as evaluated from the fringe-resolved and background-free autocorrelation traces shown in Fig. 2. This is a consequence of gain narrowing in the amplifier, which reduces the spectrum to approximately 55 nm (Fig. 3). The corresponding time–bandwidth product of ≈0.45 indicates that the pulse carries some residual chirp, a conclusion that is consistent with the calculated dispersion parameters of the amplifier system.

These measurements were carried out at a repetition rate of 2 kHz and with a pump energy of ≈6 mJ, leading to a compressed pulse energy of ≈50 μJ owing to the high throughput (>80%) of the compressor. The ASE level is typically between 3% and 5%, depending on the alignment of the amplifier. This can be substantially reduced by use of either a Pockels cell or spatial filtering. If the repetition rate is lowered to 1 kHz the pump laser can deliver higher-energy pulses. However, increasing the pump energy gives rise only initially to an increase in the compressed pulse energy to approximately 100 μJ (at a pump energy of ≈7 mJ). Under these operating conditions the relative ASE energy content is 10%, which grows dramatically if the pump energy is further increased, inhibiting any notable increase of the amplified pulse energy. Therefore we may conclude that effective ASE suppression inside the multipass amplifier is required if higher output pulse energies are to be achieved. The pulse-to-pulse energy fluctuation is <10%, which is attributed to the 1–2% energy fluctuation of the pump source and to the fact that the amplifier is far from being saturated. No evidence of nonlinear effects was observed, in agreement with the estimated value of the B integral of 0.2.

In conclusion, we have demonstrated 18-fs optical pulses amplified to the 100-μJ energy level, yielding a peak power in excess of 5 GW. These represent the most powerful sub-20-fs pulses ever obtained to our knowledge. With some modifications and improvements this system should be capable of amplifying even shorter pulses to the millijoule level. Owing to its unique performance, compactness, and reliability, this kilohertz amplifier promises to become an important tool for high-resolution ultrafast spectroscopy.

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