Ti:sapphire regenerative amplifier for ultrashort high-power multikilohertz pulses without an external stretcher

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We report a simple and robust Ti:sapphire regenerative amplifier without prepulse stretching. Pulse stretching by positive group-velocity dispersion and negative third-order dispersion are provided by highly dispersive flint glass prisms inside the regenerative amplifier cavity. Using a single-grating compressor, we obtain transform-limited 60-fs Gaussian pulses at up to a 5-kHz repetition rate with energy of 50 μJ/pulse.

Recent development in solid-state femtosecond lasers, especially Ti:sapphire lasers, has led to a qualitative improvement in ultrashort pulse generation. Pulses of 10-fs duration with a few nanojoules of energy per-pulse have been directly produced from a Ti:sapphire oscillator.[1–4] This level of energy is high enough for many resonant nonlinear optical experiments such as transient absorption, four-wave mixing, and even six-wave mixing.[5] One can achieve a moderate increase in peak power by cavity dumping the Ti:sapphire laser.[6,7] Generation of stable 13-fs pulses with 60 nJ of energy by cavity dumping was reported recently.[7] When higher power and/or tunability is required, chirped-pulse amplification[8] (CPA) in Ti:sapphire has usually been used to amplify femtosecond pulses up to the microjoule-to-joule level of energy.[9–13] Flash-lamp-pumped Cr:LiSAF has also been used to amplify the Ti:sapphire oscillator output.[14]

In the usual CPA system pulses are stretched before injection into the amplifier by two gratings arranged in an antiparallel configuration and separated by a unit-magnification telescope.[15] The amplified pulses are then recompressed by using a pair of parallel diffraction gratings.[16] Pulse durations from such systems with lenses in the telescope appear to be limited to ~100 fs after recompression because of aberrations from the lenses in the telescope and higher-order chirp in the pulse. An all-reflective stretcher/compressor design that eliminates spatial inhomogeneity and higher-order (cubic and quartic) phase errors was developed recently.[17] In this design the gratings in the stretcher and compressor have different angles of incidence to compensate the higher-order phase error. This design was utilized to yield pulses as short as 35 fs.[10] In another approach a prism pair in the regenerative amplifier cavity was used to compensate the third-order material dispersion (TOD), resulting in pulses as short as 30 fs with 30 μJ of energy.[13] Multipass amplification after moderate pulse stretching also results in pulses as short as 21 fs with 500 μJ of energy at a 10-Hz repetition rate.[12] All these CPA systems exploit a grating pulse stretcher and compensate higher-order chirp in one way or another. A disadvantage of these systems is their relative complexity and the requirement for very precise alignment of the stretcher and compressor. For compensation of large cubic phase by using different grating incidence angles in the stretcher and compressor, somewhat higher ruling gratings are necessary. In this case the tolerance of the grating alignment will be smaller. Also, because dispersive gratings are used, even a slight misalignment can cause a spatially varying spectrum. This spatial chirp, however, can be compensated by passing the beam four times in the stretcher. Moreover the alignment depends on the material path length, i.e., the number of round trips in the regenerative amplifier. As an alternative, we report a very simple and robust CPA system without pulse stretching before regenerative amplification. Femtosecond pulses are stretched during the amplification process by the positive group-velocity dispersion (GVD) of the prism material. A single-grating pulse compressor is used to keep the setup simple and less prone to the misalignment. Transform-limited 60-fs pulses can be obtained easily with an energy of 50 μJ at a repetition rate as high as 5 kHz.

A simple way to stretch a pulse is to pass it through a long optical material and utilize positive GVD. To amplify pulses to the 100-μJ level requires that pulses be stretched to at least ~20 ps to avoid nonlinear effects. This requires a path length of ~8.5 m in fused silica, assuming a 40-nm bandwidth centered at 800 nm. Because most optical materials have positive GVD and TOD and the grating pair has negative GVD but positive TOD, recompression poses a problem. An external prism pair can be used in conjunction with a grating pair to null both GVD and TOD, as used previously to produce 6-fs pulses.[18] Because of the large material path length in this case, however, the required prism separation is too large to make this approach practical. One can obtain a large effective prism separation by putting the prism pair in the regenerative amplifier. We have used a prism pair to introduce a negative TOD to the pulse in addition to stretching it with positive GVD. Two pairs of highly dispersive flint glass prisms are inserted into the regenerative amplifier cavity. Unlike in the usual arrangement, the beam passes near the base of the prisms so that the prism pairs have net positive GVD but still have net negative TOD. The ratio of the GVD to TOD can be controlled by a change in either the separation of the prisms or the amount of glass that the beam passes,

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such that it cancels the GVD and TOD of the grating that will be used in the compressor. The injected pulses are stretched inside the regenerative amplifier as they are being amplified by the positive GVD of the prism pairs and other optical elements inside the cavity. The amplified pulses that have positive GVD and negative TOD can now be compressed by a grating sequence, and they are limited by the quartic phase error.

The oscillator used here is a home-built Kerr-lens mode-locked Ti:sapphire laser, as described by Asaki *et al.*[1] The laser is pumped by 6-W all-lines output of a Ar^+ laser and produces 20-fs near-Gaussian pulses with a repetition rate of 88.2 MHz. Figure 1 shows a schematic of the regenerative amplifier. It lacks the usual pulse stretcher, and the oscillator output are directly injected to the amplifier. Only a few milliwatts of the oscillator output is used for seeding. A polarizing beam-splitter cube, a Faraday rotator, and a half-wave plate are used to separate the amplified pulse. A Pockels cell (Medox) and thin film polarizer are used for injection and ejection. The regenerative amplifier is pumped by 5 W of a Q-switched and intracavity-doubled Nd:YLF laser (Quantronics 527). Higher pump power produces higher pulse energy with some wings in the pulse. Two pairs of SF11 Brewster prisms are inserted, with the total separation being 65 cm. The beam passes near the base of the prisms. The prism material path length is ~16 cm per round trip. The GVD of the cavity is dominated by the prism pairs. The repetition rate of the system is limited by the Pockels cell, which can be operated at up to 5 kHz. A 1-cm-long Ti:sapphire rod is used, though the pulse duration does not depend on the length of the rod and any size of rod can be accommodated. After ~25 round trips the gain is depleted and the amplified pulse is ejected. At 4.5 kHz, the pulse-ejected energy is 120 μJ. The duration of the pulse is lengthened to ~20 ps. The transverse mode of the amplified beam is clean TEM_{00}. The amplified pulse is compressed by being double passed through a single-grating compressor rather than by the conventional parallel two-grating geometry. The compressor consisted of a 600-groove/mm gold-coated blazed grating (Milton Roy) with an efficiency of 90% and a silver-coated cube retroreflector. The grating incidence angle is set to ~45°, and the compressed pulse duration is insensitive to this angle within a few degrees. This relaxed alignment tolerance is due to the low ruling of the grating used in the compressor. The setup can be made simpler and more compact by use of a single grating with the retroreflector compressor. However, the overall efficiency of the compressor is only 40% because the silver-coated retroreflector has an 85% reflectivity. The compressed pulse has ~50 μJ of energy and a duration of 60 fs. The autocorrelation in a 100-μm β-barium borate crystal is shown in Fig. 2 along with a fit assuming Gaussian pulse intensity profile. The autocorrelation shows that the pulses are clean and are fitted well by a Gaussian. The noise of the compressed pulse is ~2% peak to peak and is limited by the Nd:YLF pump laser.

The current mirror set used in the regenerative amplifier (CVI TLM1) limits the width of the gain spectrum. The spectrum of the amplified pulse matches that of the unseeded regenerative laser, and its FWHM is 18 nm centered near 800 nm, for which the transform-limited pulse duration would be 52 fs (Gaussian). Because the autocorrelation fits well to a Gaussian and has negligible wings, the pulse is close to transform limited. The small discrepancy from the transform-limited value of the pulse duration presumably results from imperfect alignment of the compressor or nonlinear effects in the Ti:sapphire crystal and/or optical materials after compression. A fit to a sech^2 pulse envelope gives a pulse width of 50 fs; however, the spectrum and the autocorrelation shape are more consistent with a Gaussian envelope.

Optimization of the pulse duration can be achieved in several different ways. Once the grating incidence angle in the compressor is fixed, the GVD/TOD

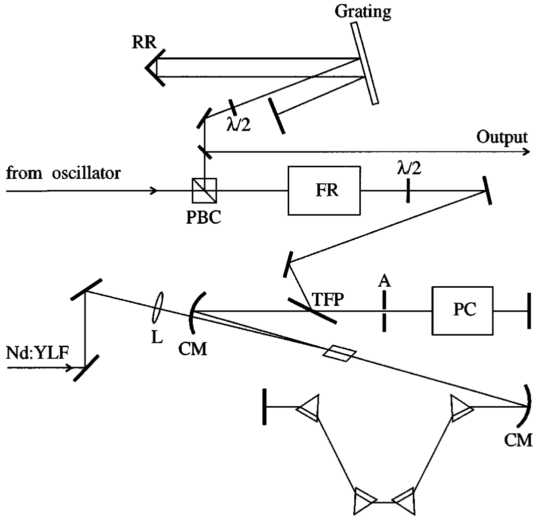

Fig. 1. Schematic of the regenerative amplifier. RR, Ag-coated retroreflector; PBC, polarizing beam-splitter cube; FR, Faraday rotator; TFP, thin-film polarizer; A, 2-mm diameter aperture; PC, Pockels cell; L, 40-cm focal-length lens; CM's, 50-cm radius-of-curvature mirrors.

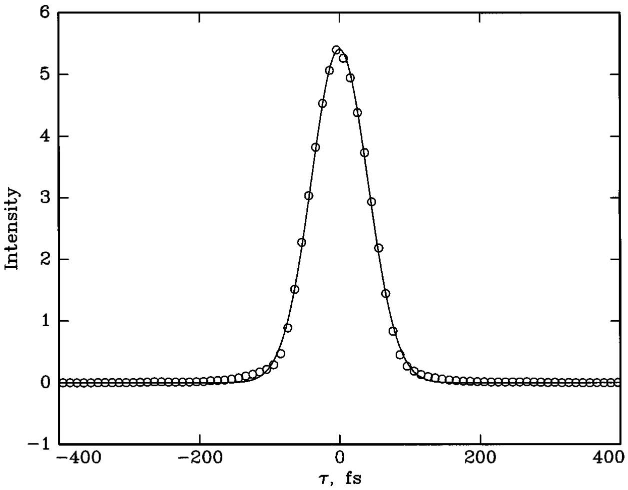

Fig. 2. Autocorrelation of the amplified pulse. The solid curve is a fit assuming 60-fs Gaussian pulse envelope function.

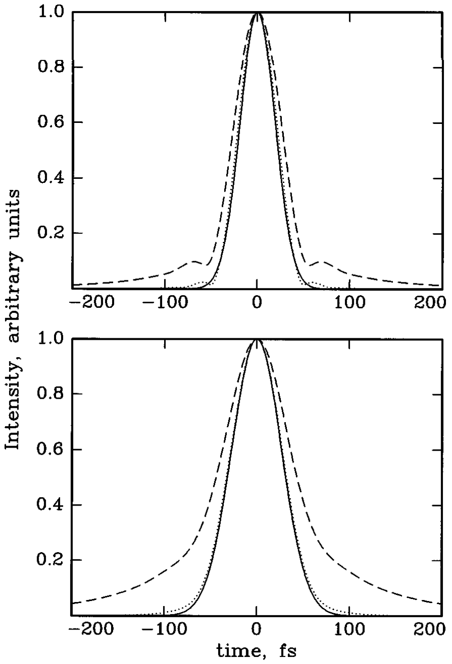

Fig. 3. Pulse envelope (top) and its autocorrelation (bottom) for a 20-nm FWHM Gaussian with residual quartic phase. Solid curve, no chirp; dashed curve, quartic phase of -8×10^6 fs^4; dotted curve, quartic phase of -2×10^6 fs^4.

ratio to be compensated is determined. One can vary the amount of the glass traversed in one of the prisms slightly, which will change the GVD/TOD of the pulse before compression. An alternative is to vary the grating-incidence angle to change the GVD/TOD of the compressor. We use the former method. In this arrangement gratings with a low number of grooves per millimeter should be used. More densely ruled gratings have higher TOD/GVD and make it difficult to null both GVD and TOD. For example, a grating with 1800 grooves/mm and a 70° angle of incidence has a TOD/GVD of 2.3 fs, whereas a 600-groove/mm grating at a 45° angle of incidence has a TOD/GVD of 1.1 fs.[19]

The compressed pulse from our amplifier has residual quartic phase error. We calculated the pulse envelope to determine the effect of the residual quartic phase error. Figure 3 shows the pulse envelopes and the corresponding autocorrelations for pulses with residual quartic phase. In the current setup, the quartic phase is estimated to be -2×10^6 fs^4, mainly from the prism pair in the cavity, and it has negligible effect on the pulse (Fig. 3, dotted curves). When the pulse has a wider spectrum, the residual quartic phase becomes nonnegligible. Interestingly, however, there is some cancellation between positive GVD and a negative quartic term. Calculation shows that current design can compress pulses with 30-nm bandwidth to the Gaussian transform limit, 31 fs.

In this Letter we have described amplification of femtosecond pulses to more than 50 μJ/pulse without prepulse stretching. By introduction of highly dispersive glass prisms in the regenerative amplifier cavity, both pulse stretching by positive GVD and application of negative TOD to the pulse can be achieved. Thus a single-grating compressor can compensate both GVD and TOD simultaneously. It was shown that effect of the residual quartic phase error is negligible. This design can be used to obtain transform-limited pulses in other types of amplifier with moderate peak powers such as a cw-pumped Ti:sapphire regenerative amplifier,[11] for which TOD compensation is difficult because the pulses are stretched inside the cavity by positive GVD from the optical elements as in the current design. The current design should also be especially suitable for lamp-pumped regenerative amplifiers such as Cr:LiSAF, for which long gain media are essential.

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