Simultaneous Contrast Improvement and Temporal Compression Using Divided-Pulse Nonlinear Compression

G. W. Jenkins,[1,2] C. Feng,[1] and J. Bromage[1]

[1]Laboratory for Laser Energetics, University of Rochester
[2]Institute of Optics, University of Rochester

Temporal contrast is an increasingly important specification for high-energy, ultrafast lasers because prepulses with only a fraction of a percent of the main pulse's energy can ionize the laser's target and modify experimental conditions before the main pulse arrives. To remove the prepulses, many temporal contrast improvement methods have been developed. We are particularly interested in methods such as nonlinear ellipse rotation (NER)[1] that allow simultaneous contrast improvement and spectral broadening.[2,3] Yb laser technology suffers from relatively long pulses (of the order of hundreds of femtoseconds to picoseconds) and requires temporal compression to efficiently pump many applications of interest. With NER, both contrast improvement and temporal compression can be accomplished in a single step.

In this summary, we demonstrate a new method of contrast improvement that allows both contrast improvement and temporal compression in a single step—divided-pulse nonlinear compression (DPNLC). In DPNLC, a high-energy pulse is divided into multiple low-energy pulses that are spectrally broadened through self-phase modulation (SPM) in gas, as illustrated in Fig. 1. After spectral broadening, the low-energy pulses are coherently recombined back into a high-energy pulse and the recombined pulse is compressed to its new transform limit. We have been developing DPNLC to overcome gas-ionization problems encountered at high energies but have found that the ability to apply an unequal nonlinear phase to the low-energy divided pulses allows us to use the method for contrast improvement as well.

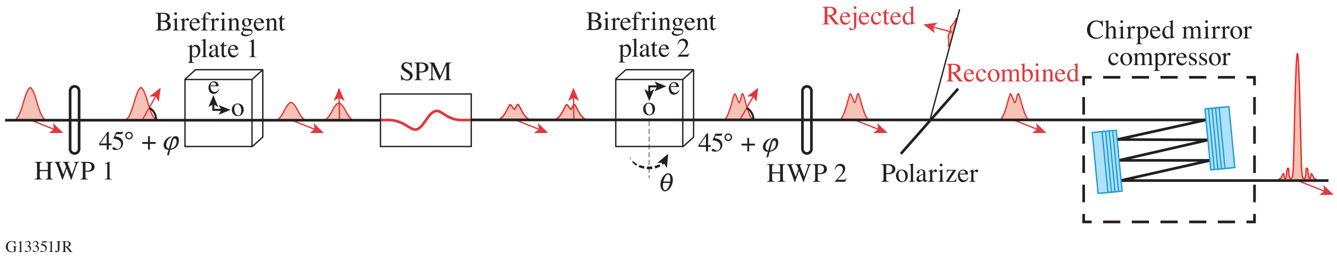

Figure 1
Apparatus for DPNLC. Birefringent plates with extraordinary axis "e" and ordinary axis "o" are used to divide one pulse into two low-energy, orthogonally polarized pulses. Red arrows indicate the pulse's polarization, and the distorted pulse shape after the SPM stage indicates an arbitrary reshaping by nonlinear processes in the SPM stage. After recombination, the polarization is cleaned with a polarizer and the pulse is compressed to a shorter duration with chirped mirrors. The angles φ and θ represent angular alignment errors in polarization and crystal angle of incidence, respectively. HWP: half-wave plate.

In our previous work,[4] we analyzed the alignment tolerances for DPNLC. The final result of our analysis was an expression for the pulse power in each polarization after the recombination step. The output is written as a Jones vector, where the top row is the power in the $\hat{p} = 45° + \varphi$ polarization and the bottom row is the power in the $\hat{m} = 45° + \varphi$ polarization:

$$\bar{P}_{\text{out}}=\frac{e^{-T^2}}{2\sqrt{\pi}}\begin{pmatrix}1+\sin^2(2\varphi)+\cos^2(2\varphi)\cos\left[2\phi_{\text{NL}}\sin(2\varphi)e^{-T^2}+\Delta\phi(\theta)\right]\\ \cos^2(2\varphi)\left\{1-\cos\left[2\phi_{\text{NL}}\sin(2\varphi)e^{-T^2}+\Delta\phi(\theta)\right]\right\}\end{pmatrix},\tag{1}$$

where we have normalized the expression so integrating over time gives a total energy of 1. In Eq. (1), the two most important alignment angles are the incoming polarization error (φ) and the angle of incidence (AOI, θ) on the second birefringent plate. The nonlinear phase accumulated in the SPM stage is represented by ϕ_{NL}, and $\Delta\phi(\theta)=\phi_2(\theta)-\phi_1$ is the difference in retardance between the two calcite plates. We developed a similar equation that describes a typical prepulse after recombination:

$$\bar{P}_{\text{pre}}=\frac{e^{-T^2}}{2\sqrt{\pi}}\begin{pmatrix}1+\sin^2(2\varphi)+\cos^2(2\varphi)\cos\left[\Delta\phi(\theta)\right]\\ \cos^2(2\varphi)\left\{1-\cos\left[\Delta\phi(\theta)\right]\right\}\end{pmatrix}.\tag{2}$$

These equations indicate a simple method to improve the temporal contrast of the pulse train. Equation (2) shows that if the retardance difference [$\Delta\phi(\theta)$] is set to zero, the entire prepulse will be found in the $\hat{p}$ polarization. Then we can apply a polarization alignment error (φ) to rotate the main pulse into the $\hat{m}$ polarization. Finally, we use a polarizer to pass the $\hat{m}$ polarization and reject the $\hat{p}$ polarization, thereby rejecting all of the prepulses.

We successfully demonstrated and quantified contrast improvement using these steps. Our laser system is a homebuilt Yb-doped, thin-disk regenerative amplifier that emits 1.2-ps pulses at a wavelength of 1030 nm, a repetition rate of 1 kHz, and an average power of 10 W. The pulses are coupled into a 1.8-m-long, 500-μm-inner-diam, hollow-core fiber (HCF) filled with 1.7 bar of argon for spectral broadening. The pulses accumulate 8.4 rad of nonlinear phase in the HCF. A 12-mm-thick, x-cut calcite plate divides the pulses in two before the HCF, and an identical plate recombines the pulses after the HCF, as previously illustrated in Fig. 1. A half-wave plate (HWP1) is placed before the first birefringent plate to carefully control the incoming polarization error φ, and a second HWP (HWP2) is placed after the last birefringent plate to select either the $\hat{p}$ or $\hat{m}$ polarization for transmission through the recombination polarizer.

First, we measured the original contrast of the laser system. The apparatus in Fig. 1 was aligned with zero alignment errors and measured near-perfect recombination into the $\hat{p}$ polarization (97.3% limited by a 2.5% p-polarization reflection on the polarizer). With this alignment, both the main pulse and prepulses are transmitted by the polarizer with maximum efficiency. The original contrast of the laser was measured by attenuating the beam with a set of neutral-density (ND) filters and then focusing it onto a photodiode. On the photodiode, both the main pulse and prepulses could clearly be seen, as shown in Fig. 2. The maximum prepulse height is 1.9 mV, while the main pulse is 2.3 V; therefore, the initial contrast of the laser is ~10^{-3}.

Next, we applied a polarization angle error to improve the contrast. We rotated HWP1 until the energy of the main pulse in the $\hat{m}$ was maximized (found at a HWP angle of 3°). Then we rotated HWP2 to transmit the $\hat{m}$ polarization and reject the $\hat{p}$ on the polarizer. We made the same photodiode measurement and found that the prepulses were rejected to below our measurement sensitivity, as shown in Fig. 2. The main pulse was transmitted with high efficiency and measured at 1.7 V.

To quantify the contrast improvement, we removed the ND filters until the prepulses became visible again. We removed 3.5 optical density of the ND filters; we then made fine adjustments to the AOI of calcite plate 2 and the angle of HWP2 to minimize the prepulses and measured a prepulse signal of 0.7 mV. This puts the new contrast of the pulse train at ~10^{-7}—an improvement of four orders of magnitude.

Finally, we compressed the contrast-improved pulse using a series of chirped mirrors (–43,000-fs group-delay dispersion) and measured the compressed pulse in a second-harmonic frequency-resolved optical gating system. The measured pulse was excellent, compressed with a FWHM pulse duration of 187 fs, close to its transform limit of 180 fs. The compressed pulse with-

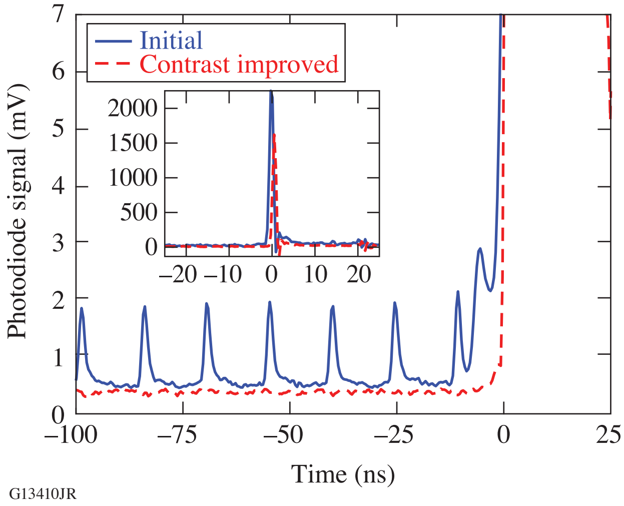

Figure 2
Captured photodiode signals from the pulse train. A train of prepulses with a maximum signal of 1.9 mV is clearly seen before the main pulse, which starts at time = 0. After the HWP's are rotated to improve the contrast, the prepulses are rejected and completely unmeasurable. At the same time, the height of the main pulse is reduced only from 2.3 V to 1.7 V, as shown in the inset.

out contrast improvement was compressible to a similar duration (186 fs with a transform limit of 185 fs) with the same chirped mirrors. Therefore, the contrast improvement method enables temporal compression equivalent to standard HCF operation.

In conclusion, we demonstrated a new method for temporal contrast improvement—divided-pulse nonlinear compression. By slightly misaligning the calcite plates used for pulse division and recombination, we rotated the polarization of the main pulse and rejected problematic prepulses on a polarizer. We measured four-orders-of-magnitude temporal contrast improvement and 72% efficiency for the main pulse, values comparable with other state-of-the-art temporal contrast improvement methods. Simultaneously, we compressed the pulse from 1.2 ps to 187 fs.

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