Temporal-Contrast Measurements of a White-Light–Seeded Noncollinear Optical Parametric Amplifier

J. Bromage, C. Dorrer, and J. D. Zuegel
Laboratory for Laser Energetics, University of Rochester, 250 East River Road, Rochester, NY 14623-1299
jbro@lle.rochester.edu

Abstract: Ultra-intense optical parametric chirped-pulse systems require front ends with broad bandwidth and high temporal contrast. Temporal cross-correlation measurements of a white-light–seeded noncollinear optical parametric amplifier (NOPA) show that its prepulse contrast exceeds the 120-dB dynamic range of the broadband NOPA-based cross-correlator.

OCIS codes: (190.4970) Parametric oscillators and amplifiers; (320.7100) Ultrafast measurements

1. Introduction

Ultra-intense laser systems are being developed that will use the full potential of deuterated potassium dihydrogen phosphate (DKDP) for high-energy optical parametric chirped-pulse amplification (OPCPA) [1,2]. Noncollinear pumping of DKDP produces broadband gain for supporting pulses as short as 10 fs. Large-aperture DKDP crystals (>400 mm) make it possible to use Nd:glass lasers as kilojoule pump sources [3]. The front ends for these systems must provide broadband pulses centered around 910 nm to match the gain of DKDP when pumped at 527 nm at the optimum noncollinear angle [3]. Their output must be compressible and focusable to maximize the on-target intensity, and the temporal prepulse contrast must be extremely high to avoid perturbing the target before the interaction with the main pulse.

This paper presents temporal contrast measurements of a prototype front end that were first presented in 2011 [4] and have been analyzed further and described in more detail. The front end produces microjoule pulses with 210 nm of bandwidth (full width at 10%) centered at 910 nm. Previous front-end demonstrations used the idler from the first amplifier stage to seed subsequent amplifiers either in a chirped collinear geometry [1] or angularly dispersed geometry

[2]. Here an alternate approach is evaluated, based on the generation of white-light continuum (WLC) in a sapphire plate [4]. This approach simplifies the requirements for the seed oscillator and pump lasers and removes the need to precisely set the spectral chirp of the pump [1] or eliminate the angular dispersion of the idler [2]. Although WLC-seeded noncollinear optical parametric amplifiers (NOPA's) have been used for over a decade as tunable sources of femtosecond pulses [4–6], their prepulse contrast had not been measured using cross-correlators with sufficient bandwidth and dynamic range. In this work, a NOPA-based cross-correlator has been developed [7] for this purpose with a dynamic range, bandwidth, and resolution of 120 dB, 150 nm, and 250 fs, respectively. Measurements over a 350-ps window show that the uncompressed output of a WLC-seeded NOPA has a prepulse contrast that exceeds the 120-dB dynamic range of the cross-correlator up to –5 ps before the main peak.

2. Experimental setup and results

The front end shown in figure 1 is similar to previously reported systems [8–10]. Oscillator pulses were stretched to seed a Yb-doped–fiber chirped-pulse–amplification (CPA) system to produce 250-fs, 11-μJ, 1046-nm pulses at 500 kHz. A portion (1.6 μJ) was weakly focused into a 4-mm sapphire plate to generate the WLC seed [4]. The remainder was frequency doubled, producing 4 μJ for pumping the NOPA, which was a 3.5-mm-thick beta-barium borate (BBO) crystal cut at 21.6°. The NOPA's spectrum and beam profile are shown in figure 1. The spectrum full width at half maximum (FWHM) was 175 nm (full width at 10% = 210 nm) and the pulse energy was 600 nJ [1.3%-rms (root mean square) pulse to pulse]. The internal noncollinear angle in the BBO crystal was set to 2.3° to maximize the bandwidth and minimize spatiotemporal aberrations induced by the angular-dependent gain of the NOPA [10]. The chirp of the WLC and

NOPA (~1300 fs^2) was removed using a standard fused-silica prism compressor to produce 13-fs pulses (1.07× the Fourier transform limit).

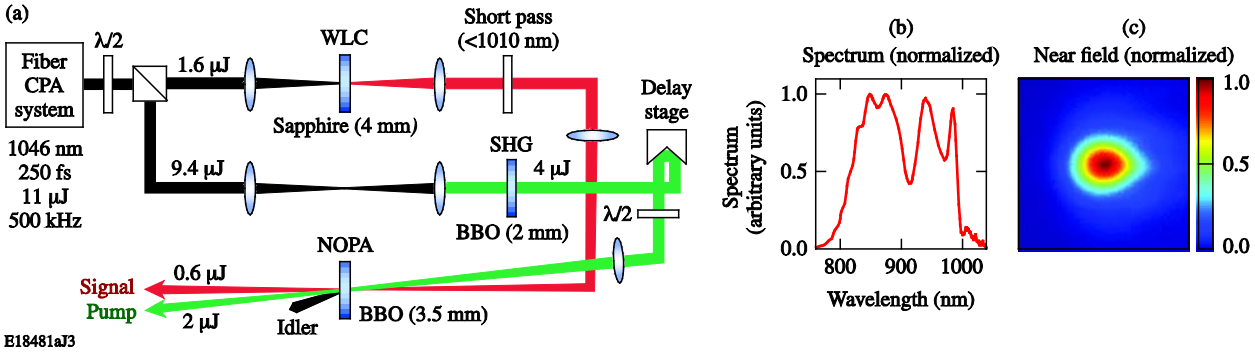

Fig. 1. (a) Experimental setup; (b) NOPA spectrum; (c) NOPA near-field fluence (normalized), imaged at the BBO crystal. BBO: beta-barium borate; CPA: chirped-pulse amplification; NOPA: noncollinear optical parametric amplifier; SHG: second-harmonic generation; WLC: white-light continuum.

A cross-correlator (CC) based on the NOPA process [11] was developed to measure the temporal contrast of the uncompressed pulses directly from the NOPA (see figure 2). The residual NOPA pump pulses (2 μJ, 523 nm, 250 fs) provide the temporal gate by pumping a second, thicker BBO crystal (6 mm, 27.1°) that is aligned noncollinearly for maximum bandwidth. Although this pump beam has been partially depleted by the signal in the NOPA (~50%), and therefore will have a non-Gaussian beam profile, this scheme allows for the maximum available pump pulse energy to be used in both the NOPA and CC, maximizing the gain and dynamic range, which would be significantly reduced if the available power was split between the two crystals. The part of the pulse under test (signal) that temporally overlaps the pump is amplified, producing a non-degenerate idler pulse centered at 1250 nm. The signal pulse

was sampled over a 350-ps range by varying the delay between the pump and signal and measuring the idler with an InGaAs power meter (Agilent 81624B). One feature of NOPA-based CC's is that they provide broadband gain and serve as a preamplifier for the detection system. When optimally configured, the unsaturated gain is 39 dB with a bandwidth of 150 nm.

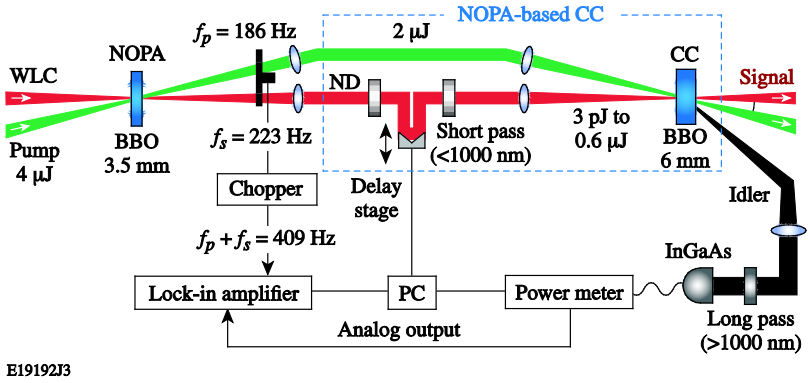

Fig. 2. Schematic for the NOPA and NOPA-based cross-correlator (CC).

Several techniques were used to minimize noise that would otherwise limit the dynamic range of the CC. Since the signal and idler are non-degenerate, background noise from signal scattering in the CC crystal is reduced by placing a long-pass filter (Schott RG1000, 7 mm thick) before the power meter. Further rejection of scattering and parametric fluorescence from the CC is obtained using a lock-in detection technique as previously demonstrated for second-order autocorrelators [12,13]. The pump and signal beams are chopped at 186 and 223 Hz, respectively, and the idler component at the sum frequency (409 Hz) from the analog output of the InGaAs power meter is measured using a lock-in amplifier. As a result of the spectral filtering and lock-in detection, all of the available pump and signal energy can be used without saturating the detection system when sampling a low-intensity temporal region of the pulse under test. Calibrated neutral-density filters are inserted in the signal path when sampling the main

peak to ensure that the pump pulse is not depleted and, therefore, that the idler power is proportional to the attenuated signal intensity. The CC dynamic range of 120 dB results from the combination of the neutral density filters (60 dB), the adjustable gain of the InGaAs power meter (40 dB), and the dynamic range of the lock-in detection scheme (20 dB).

A cross-correlation measurement of the uncompressed NOPA pulse is shown in figure 3. The CC noise floor was determined to be 120 dB below the peak by blocking either the pulse under test or the CC pump. Apart from several discrete peaks, the prepulse contrast up to 5 ps before the main peak exceeds the 120-dB CC dynamic range. Note that the width of the uncompressed pulse (~300 fs) has not been deconvolved from these measurements. Therefore, if the peak intensity increase from compressing the pulse from 300 fs to 13 fs is ~13 dB, the compressed pulse contrast exceeds 133 dB.

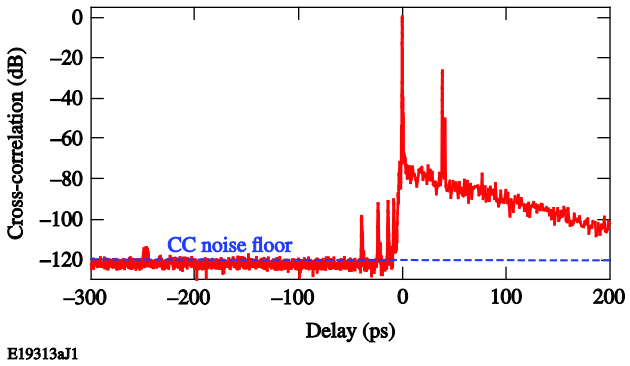

Fig. 3. Cross-correlation scan.

Determining whether discrete peaks are real prepulses or artifacts caused by gate or pump postpulses is a problem common to all cross-correlators. For a NOPA-based device, however, the main pump pulse provides much more gain for the signal than is provided by lower-intensity pump noise. (The necessary by-product of gain, a parametric fluorescence background, is

mitigated using the two-frequency lock-in technique.) Moreover, the nature of each peak (whether it is an actual prepulse on the signal-under-test or a measurement artifact created by a postpulse on the pump) can be determined from its scaling with the intensity of the pump (shown schematically in figure 4). A prepulse on the signal that overlaps with the main pump pulse experiences the maximum small-signal gain; therefore, the CC peak scales exponentially with the pump field [14]. In terms of the pump intensity I_P, the small-signal scaling on a logarithmic scale is $\mathrm{CC}\,(\mathrm{dB}) \sim \sqrt{I_P}$. Alternatively, when a weak pump postpulse overlaps with the main signal peak, the CC gain is much lower. In this "small-pump" limit, the CC peak scales linearly with I_P; therefore, on a logarithmic plot, CC (dB) ~ $\log_{10}$ (I_P).

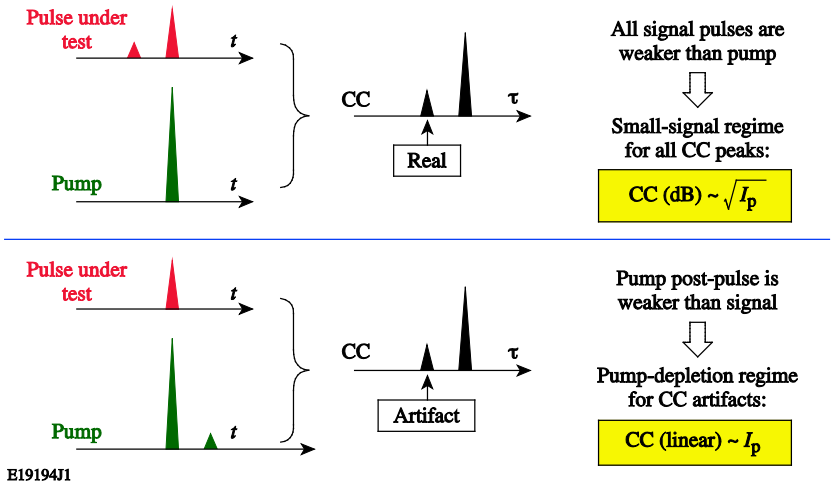

Fig. 4. Schematic showing the different intensity scalings to determine whether cross-correlation peak is caused by a true prepulse before the pulse under test, or is an artifact caused by the CC pump postpulse.

Measurements of the discrete peaks are shown in figure 5. To emphasize any artifacts, the maximum peak gain of the CC was reduced from 39 to 17 dB by halving the thickness of the CC

crystal and increasing the pump spot size. The magnitude of each peak was measured as the pump polarization was rotated using a half-wave plate to vary the amplitude of the phase-matched component of the pump along the crystal axis. The normalized intensity of the pump in terms of the half-wave-plate angle is $\hat{I}_{\mathrm{P}} = \cos^2(2\theta)$. Figure 5 shows that all peaks before the main one scale following the small-pump scaling, $\mathrm{CC}\,(\mathrm{dB}) \sim \log_{10}\left(\hat{I}_{\mathrm{P}}\right)$, and are therefore artifacts from pump postpulses. Therefore, the prepulse contrast for the uncompressed pulses does not exceed 120 dB.

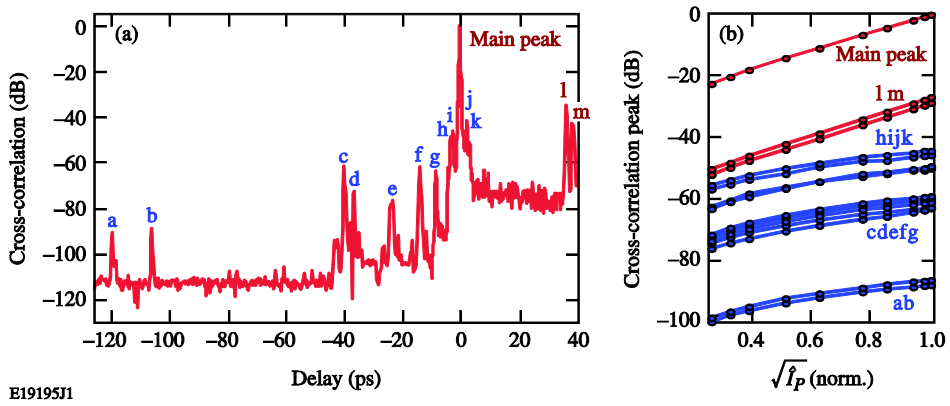

Fig. 5. (a) Cross-correlation scan taken at reduced CC gain (17 dB) to emphasize artifacts from pump postpulses. (b) Magnitude of each peak for varying normalized pump field $\left(\sqrt{\hat{I}_{\mathrm{P}}}\right)$. The red curves correspond to the main pulse under test and crystal reflections; the blue curves correspond to artifacts produced by CC pump postpulses.

One unexpected feature of the CC measurements is the exponential tail following the main CC peak. The tail has a time constant of 29 ps, an intensity contrast greater than 80 dB, and an energy contrast of 56 dB. It was found that the temporal modulation was repeatable from scan

to scan (as shown in figure 6) and therefore is not random noise. Furthermore, very similar scans were measured at a later time when the crystal used to generate the WLC was changed from sapphire to undoped YAG. Lastly, figure 7 shows measurements of the unamplified WLC, where the NOPA pump was temporally shifted 15 ps before the seed. These measurements suggest that the tail is not caused by gain in the NOPA. Unfortunately, the dynamic range for the reduced signal level was not sufficiently high (~63 dB) to determine whether the tail was also present with the pulse of fluorescence created by the pump pulse. Therefore, it has not been determined if the tail is a result of the WLC process or if it is caused by the CC optics. Nonetheless, there are typically additional picosecond-pumped NOPA stages before the stretcher, with at least 50 dB of gain, that would suppress the tail to an insignificant level [15]. Furthermore, the temporal contrast after the main pulse is only an issue in a CPA system when self-phase modulations during the amplification of the chirped pulses leads to weaker, satellite prepulses [16].

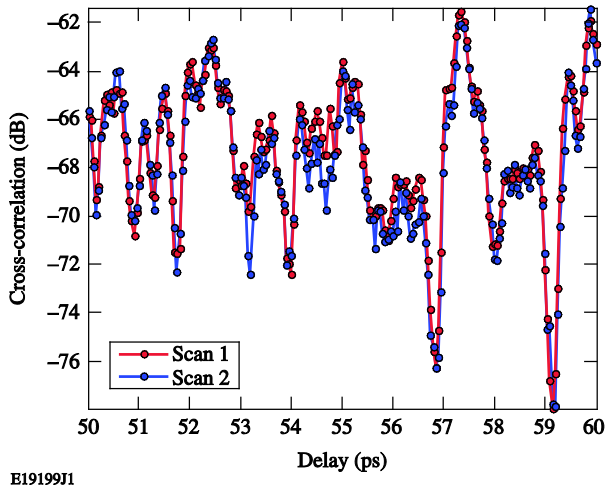

Fig. 6: Section of the post-pulse tail, showing the repeatability from scan to scan.

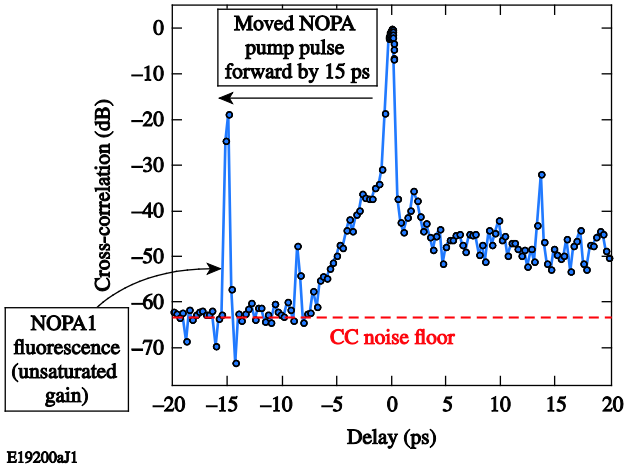

Fig. 7: Cross-correlation scan when the NOPA pump pulse was temporally shifted 15 ps before the seed pulse. This shows that a tail is present when there is no gain in NOPA 1.

3. Conclusions

This paper reports the first broadband, high-dynamic-range, temporal contrast measurements of a WLC-seeded NOPA. The NOPA-based cross-correlator that was developed for this purpose has a dynamic range, bandwidth, and resolution of 120 dB, 150 nm, and 250 fs, respectively. A simple technique for distinguishing between real prepulses and pump artifacts for any cross-correlator based on parametric amplification has been demonstrated. Measurements over a 350-ps window show that the uncompressed output of the WLC-seeded NOPA has a prepulse contrast that exceeds the 120-dB dynamic range of the cross-correlator up to 5 ps before the main peak. These results, combined with a previous analysis of the WLC-seeded NOPA [10], supports its potential as a front end for ultra-intense OPCPA systems.

Acknowledgment

This material is based upon work supported by the Department of Energy National Nuclear Security Administration under Award Number DE-NA0001944, the University of Rochester, and the New York State Energy Research and Development Authority. The support of DOE does not constitute an endorsement by DOE of the views expressed in this article.

4. References

[1] Tang Y, Ross I N, Hernandez-Gomez C, New G H C, Musgrave I, Chekhlov O V, Matousek P and Collier J L 2008 Optical parametric chirped-pulse amplification source suitable for seeding high-energy systems *Opt. Lett*. **33** 2386

[2] Lozhkarev V V *et al.* 2006 200 TW 45 fs laser based on optical parametric chirped pulse amplification *Opt. Express* **14** 446

[3] Lozhkarev V V, Freidman G I, Ginzburg V N, Khazanov E A, Palashov O V, Sergeev A M and Yakovlev I V 2005 Study of broadband optical parametric chirped pulse amplification in a DKDP crystal pumped by the second harmonic of a Nd:YLF laser *Laser Phys*. **15** 1319

[4] Bromage J, Dorrer C and Zuegel J D 2011 Temporal contrast measurements of a noncollinear optical parametric amplifier seeded by white-light continuum in *[Advances in Optical Materials]* OSA Technical Digest (CD), Optical Society of America, Paper JWC2

[5] Reed M K, Steiner-Shepard M K, Armas M S and Negus D K 1995 Microjoule-energy ultrafast optical parametric amplifiers *J. Opt. Soc. Am. B* **12** 2229

[6] Wilhelm T, Piel J and Riedle E 1997 Sub-20-fs pulses tunable across the visible from a blue-pumped single-pass noncollinear parametric converter *Opt. Lett*. **22** 1494

[7] Shirakawa A, Sakane I, Takasaka M and Kobayashi T 1999 Sub-5-fs visible pulse generation by pulse-front-matched noncollinear optical parametric amplification *Appl. Phys. Lett*. **74** 2268

[8] Divall E J and Ross I N 2004 High dynamic range contrast measurements by use of an optical parametric amplifier correlator *Opt. Lett*. **29** 2273

[9] Andersen T V, Schmidt O, Bruchmann C, Limpert J, Aguergaray C, Cormier E and Tünnermann A 2006 High repetition rate tunable femtosecond pulses and broadband amplification from fiber laser pumped parametric amplifier *Opt. Express* **14** 4765

[10] Schriever C, Lochbrunner S, Krok P and Riedle E 2008 Tunable pulses from below 300 to 970 nm with durations down to 14 fs based on a 2 MHz ytterbium-doped fiber system *Opt. Lett*. **33** 192

[11] Bromage J, Dorrer C and Zuegel J D 2010 Angular-dispersion-induced spatiotemporal aberrations in noncollinear optical parametric amplifiers *Opt. Lett*. **35** 2251

[12] Divall E J and Ross I N 2004 High dynamic range contrast measurements by use of an optical parametric amplifier correlator *Opt. Lett*. **29** 2273

[13] Braun A, Rudd J V, Cheng H, Mourou G, Kopf D, Jung I D, Weingarten K J and Keller U 1995 Characterisation of short-pulse oscillators by means of a high-dynamic-range autocorrelation measurement *Opt. Lett*. **20** 1889

[14] Curley P F, Darpentigny G, Chériaux G, Chambaret J P and Antonetti A 1995 High dynamic range autocorrelation studies of a femtosecond Ti:sapphire oscillator and its relevance to the optimisation of chirped pulse amplification systems *Opt. Commun*. **120** 71

[15] Cerullo G and De Silvestri S 2003 Ultrafast optical parametric amplifiers *Rev. Sci. Instrum*. **74** 1

[16] Bromage J, Dorrer C, Millecchia M, Bunkenburg J, Jungquist R and Zuegel J. D 2012 A front end for ultra-intense optical parametric chirped-pulse amplification in *[Conference on Lasers and Electro-Optics 2012]*, OSA Technical Digest (online), Optical Society of America, CTh1N.7

[17] Schimpf D N, Seise E, Limpert J, Tünnermann A T 2008 The impact of spectral modulations on the contrast of pulses of nonlinear chirped-pulse amplification systems *Opt. Express* **16** 10664