Analysis of Pump-to-Signal Noise Transfer in Two-Stage Ultra-Broadband Optical Parametric Chirped-Pulse Amplification

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Optical parametric chirped-pulse amplification (OPCPA) provides the most viable route for the development of tens to hundreds of petawatt peak-power laser systems.[1] In OPCPA, different mechanisms introduce either isolated pulses or a slowly varying pedestal before the main pulse, therefore degrading its temporal contrast, which is defined as the ratio of the peak power of the main pulse to the power of the light in some predetermined temporal range. When the laser beam is focused to interact with the target, the intensity of the light present before the main pulse can exceed a threshold for irreversible modification of the target (e.g., $\sim 10^{12}$ W/cm^2) and have a detrimental effect on laser–matter interaction. Therefore, understanding the origins of contrast degradation and maximizing the temporal contrast are essential for the development of ultrahigh-peak-power laser facilities.

Pump temporal modulation is one mechanism that can degrade the temporal contrast of the recompressed signal because it induces high-frequency spectral modulation on the chirped signal spectrum during parametric amplification.[2] Pump modulation is commonly introduced by the interference between the main pump pulse and the amplified spontaneous emission (ASE). This modulation is broadband with its bandwidth proportional to the spectral bandwidth of the ASE. Spectrally filtering the ASE of the pump pulse using a narrowband filter is an effective way to reduce the high-frequency pump noise and, therefore, the pump-induced contrast degradation.[3]

In this work, we have investigated, for the first time to our knowledge, the pump-to-signal noise transfer in a two-stage ultra-broadband OPCPA and demonstrated a novel mechanism based on pump-seed delay optimization to reduce the pump-induced temporal contrast degradation by as much as 15 dB (Ref. 4). The results are widely applicable to support the design and development of OPCPA-based ultrahigh-peak-power systems, for which maximizing the temporal contrast is a high priority.

The experimental demonstration was performed in a two-stage ultra-broadband OPCPA system (Fig. 1), which is a subsystem of the Multi-Terawatt–pumped optical parametric amplifier line (MTW-OPAL), i.e., a 0.5-PW, 20-fs, all-OPCPA system.[5] The subsystem consists of an ultra-broadband front end (UFE), two noncollinear optical parametric amplifiers (NOPA4a and NOPA4b), a single pump laser for pumping both NOPA stages, and a grating compressor. In high-power OPCPA systems, it is common to use a single laser to pump several optical parametric amplification stages to reduce experimental complexity and cost. In such a system, the signal amplified in the first stage carries the pump modulations, and amplification in the second stage occurs with a pump pulse having the same modulations. The temporal modulations of the amplified chirped signal and the temporal contrast of the compressed signal pulse, therefore, depend on the difference in pump-seed delay t in different stages, as illustrated in Fig. 1.

We investigated pump pulses with two types of dominating noise, either a 30-GHz sinusoidal modulation or a broadband ASE modulation with ~40-GHz-bandwidth full width at half-maximum (FWHM). Figure 2 plots the experimental and simulation results obtained when NOPA4a and NOPA4b were in the linear amplification regime. The sinusoidally modulated pump pulse represents the case of a multilongitudinal-mode pump laser and was used to facilitate the identification and analysis of the pump-induced contrast degradation. As shown in Fig. 2(a), when the pump-seed delay τ at NOPA4b was equal to zero or to the sinusoidal modulation period T (i.e., $T = 33.3$ ps), and therefore the pump and seed modulations were in phase, the pump sinusoidal modulation introduced an isolated prepulse (postpulse) at –(+)0.64 ps in the cross-correlation signals of the NOPA4b

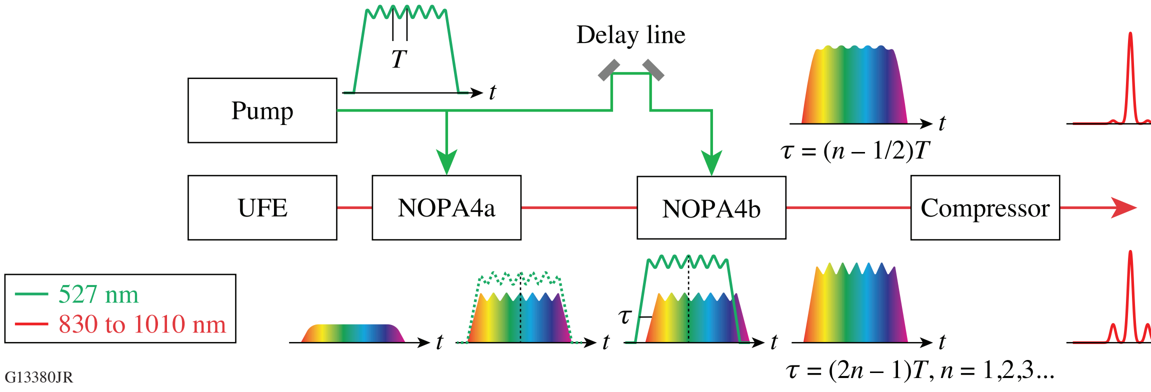

Figure 1
Experimental layout of the two-stage ultra-broadband OPCPA together with the illustrative pump and signal pulses propagating through the system. The delay line controls the pump-seed delay τ with <50-fs temporal resolution.

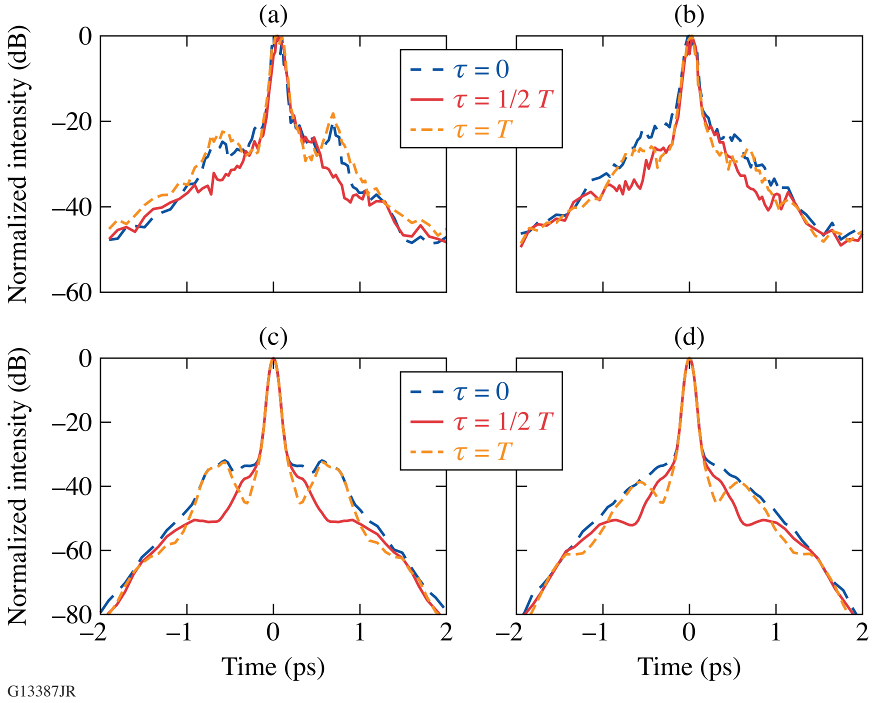

Figure 2
The [(a),(b)] measured and [(c),(d)] simulated cross-correlation signals of the compressed NOPA4b pulses at different pump-seed delays, when both NOPA4a and NOPA4b were operated in the linear regime. T = 33.3 ps corresponds to a modulation frequency equal to 30 GHz. [(a),(c)] The case of a pump pulse with both ASE and 30-GHz sinusoidal modulations; [(b),(d)] the case of a pump pulse with ASE modulation only.

compressed pulses. When the pump-seed delay was set to half the modulation period (i.e., 1/2 T = 16.7 ps) such that the pump and seed modulations had a π phase shift, the pre- and postpulse were strongly suppressed, resulting in the reduction of contrast degradation up to 15 dB. In the more-general case of a pump with broadband ASE modulation, a slowly varying broad pedestal was observed in the compressed pulse and a 10-dB reduction of the contrast degradation at τ = 1/2 T [Fig. 2(b)] was obtained. The simulated cross-correlation signals [Figs. 2(c) and 2(d)] well reproduced the pump-seed-delay–dependent effect.

When NOPA4a and NOPA4b were operated closer to saturation, the measured cross-correlation signals [Fig. 3(a)] showed negligible dependence on the pump-seed delay, which was reproduced by the simulations [Fig. 3(b)] where the limitations in spectral acceptance of the second- and third-harmonic generations in the high-dynamic-range scanning third-order cross-correlator (SEQUOIA®, Amplitude Technologies) were taken into account. These simulations also confirmed, however, that the negligible dependence on pump-seed delay is due to the limited spectral acceptance of the cross-correlator. In the absence of spectral band-

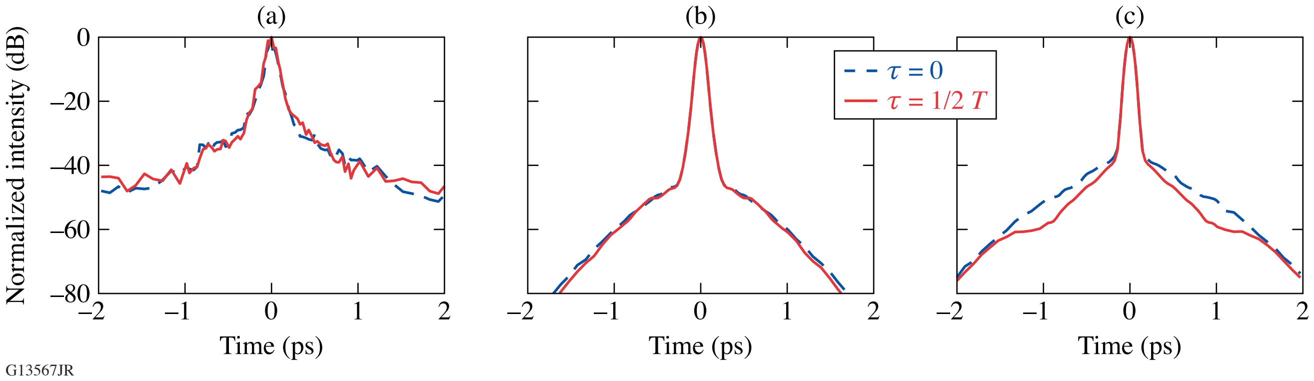

Figure 3
The (a) measured and [(b),(c)] simulated cross-correlation signals of the compressed NOPA4b pulses, when both NOPA4a and NOPA4b were operated closer to saturation and with pump ASE modulation. The spectral acceptance of the third-order harmonic generation in the cross-correlator was limited to 90-nm FWHM using a tenth-order super-Gaussian spectral filter to obtain the results in (b) or kept at >180 nm for the full signal bandwidth for getting the results in (c). Results obtained with only two, instead of three, pump-seed delays are presented for easier visualization of the delay-dependent contrast effect.

width limitation, both cross-correlation signals [Fig. 3(c)] and compressed pulses (simulation not shown) from simulations revealed the delay-dependent contrast effect. Therefore, the pump-seed delay can serve as a simple and cost-effective tool to minimize the pump-induced contrast degradation in a multi-stage OPCPA, even when parametric amplifiers are operated in saturation.

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