High dynamic range multi-channel cross-correlator for single-shot temporal contrast measurement

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Abstract. We have developed a multi-channel cross-correlator for high dynamic range (>10^10), single-shot temporal contrast measurements. The correlator utilizes a third-order cross-correlation technique and has a reference channel, to be normalized by the measured peak intensity, and four independent optical delay lines. The measurement results of the shot-to-shot temporal contrast clearly show the intensity fluctuations of short pre-pulses at -4.5 ps and -26 ps before main pulse.

1. Introduction

The temporal contrast of an ultra-high intensity laser, which is defined as the ratio between the peak and pre-pulse intensities, is a crucial parameter for laser–plasma interaction experiments because of the influence of the pre-formed plasma before the arrival of the main pulse on the laser-plasma interaction. This interaction has been strongly indicated in experiments of particle acceleration [1] [2]; thus, it is important to measure the temporal contrast of a high-power laser pulse. Recently, several methods have been developed for the measurement of temporal contrast, using instruments such as FROG [3], Wizzler [4], and SPIDER [5]. These spectral techniques can measure a precise pulse duration and temporal contrast within 10’s of ps over a dynamic range of 10^6. Moreover, a scanning cross-correlator has been widely used for temporal contrast measurements with a wide temporal range (>100 ps) and high dynamic range (>10^6-10^10) [6] [7]. However, because of the low repetition rate of the high-power laser system, the intensity fluctuations due to energy, temporal and spatial properties of the pump laser and/or seed laser, and so on, a shot-to-shot contrast measurement is required. For this reason, several techniques that enable a single-shot measurement have been developed; for example, the cross-correlator based on a pulse replicator [8], fiber-array [9], and time-frequency coding [10]. These and the above-mentioned spectral techniques can typically achieve the single-shot measurement with picosecond time resolution and a time window of up to ~30 ps.

We have developed a multi-channel cross-correlator (MCCC) [11] that can carry out the shot-to-shot contrast measurement with a maximum dynamic range of >10^10 and the maximum time window up to > 200 ps. The MCCC is based on a third-order cross-correlation technique, which is typically used as the delay-scanning correlator. The MCCC has four independent delay lines and channels that can measure the temporal contrast with a single-shot operation. In comparison with the commercial
instrument and previous studies, one advantage of using the MCCC is that it has a high dynamic range of \(>10^{10}\) owing to the independent channels and a high fluence of the incident laser. Secondly, the MCCC has a reference channel that can measure the shot-to-shot peak intensity [7]. Because the pre-pulse intensity is normalized by the peak intensity, it can identify the real fluctuations of the pre-pulse intensity.

In this paper, we report a single-shot measurement of the temporal contrast using the MCCC system. We demonstrate the maximum high dynamic range and present the results of the delay-scanning temporal contrast, which are compared to the results of a commercial cross-correlator (SEQUOIA by Amplitude Technologies). Moreover, we demonstrate the shot-to-shot temporal contrast, clearly showing intensity fluctuations of the short pre-pulses at -4.5 ps and -26 ps.

**Figure 1.** Setup of a multi-channel cross-correlator (MCCC). ND: neutral density filter, PL: polarizer, WP: half-wave plate, SFG: second-frequency generation crystal, TFG: third-frequency generation crystal, PR: prism, PMT: photomultiplier tube.

### 2. Experimental method

We have demonstrated a single-shot temporal contrast measurement using the MCCC, based on the third-order cross-correlation technique [7]. The cross-correlation technique is widely used for the estimation of the temporal profile. In this technique, the third harmonic pulse is generated by mixing the first and the second harmonic pulses in a nonlinear crystal. The temporal profile of the pulse can be measured by varying the delay time \(\tau\). In order to achieve the single-shot measurement using the MCCC, the third harmonic signal is normalized by the peak intensity \(I_0 = \tau\) with a reference channel in every shot. Note that this peak intensity cannot be expressed as the absolute value. In order to decide the real peak intensity, it is necessary to measure the laser energy and the pulse duration, the focal spot size on target with an extra instrument.

In the experiment, along with the MCCC, the JLITE-X laser system at KPSI (JAEA) [12] is used. Figure 1 shows the setup of the MCCC. The input laser pulse, with a pulse energy of < 8 mJ, diameter of 4 mm, pulse duration of 50 fs, and central wavelength of 800 nm, is split by a half-wave plate and two polarizers. The frequency of the s-polarized pulse is doubled by a 0.5-mm-thick type-I BBO crystal (a diameter of 5mm). The MCCC setup separates the s-polarized and p-polarized pulses into four channels and delivers them to each third-frequency generation crystals through a delay line. The energy branching ratio for the channels is 1-ch: 2-ch: 3-ch: 4-ch = 9: 0.1: 0.45: 0.45. Each channel has an optical delay (the minimum time step being >13 fs) from -950 ps to -150 ps (1-ch), and from -450 ps to +80 ps (2-4-ch). The fundamental and the second harmonic pulses are crossed on a 0.2-mm-thick type-I BBO crystal for the third harmonic generation. A photomultiplier tube (PMT, R759, Hamamatsu Inc.) measures the intensity of the third-order frequency pulse, which is generated in the crystal, after the pulse passes through a slit, 2–4 dichroic mirrors, a fused silica prism, neutral density (ND) filters, and a band pass filter with a center wavelength of 266 nm. The PMTs are calibrated with the combination of photodetectors (Thorlabs, DET210) and ND filters. Additionally, SEQUOIA is also used to cross-calibrate the MCCC in the temporal contrast measurement experiment. The incident laser energy into SEQUOIA is found to be less than 3 mJ/cm\(^2\).
3. Experimental results and discussion

The dynamic range measurement results with the MCCC by changing the optical density of the filters are shown in Fig. 2. The dynamic range increases to $\sim 10^{12}$ with the increase of the fluence of the incident laser. The dynamic range is defined as the ratio between the signal of the third harmonic and noise. The third harmonic intensity $I_3$ is proportional to the cube of the fundamental harmonic intensity $I_0$ in the third-order correlator [7]. The slight difference between the fitting result and the cubic law in Fig. 2 may result from the phase mismatch, group velocity mismatch, or energy loss in the optical devices.

The delay-scanning temporal contrast was measured, and the results are compared with those obtained with the commercial cross-correlator. Fig. 3 shows the temporal contrast measured by 1-ch of the MCCC and SEQUOIA. Each point shows the average of 5 shot number/time at 8 mJ/cm$^2$. The scanning results of 1-ch are in good agreement with SEQUOIA data. The intensity (at $\sim 10^{-5}$), from -200 ps to -30 ps, mainly results from the amplified spontaneous emission of a regenerative amplifier [14]. The short pre-pulses in the range of -30 ps to -4 ps (the arrows in Fig. 3) are due to the slight cavity misalignment of the regenerative amplifier.

In the single-shot temporal contrast measurement, we measured the intensity fluctuations of a short pre-pulse. The peaks at -4.5 ps and -26 ps are attributed to the delays of 4-ch and 1-ch, respectively. The pre-pulse intensity and the time delay of each channel is precisely decided from the measurement results of the scanning contrast ratio for each channel. The other channel is used for the detection of the noise level, when the second harmonic pulse is dumped before the crystal for the third harmonic generation. The fluctuations at a given time measured in 500 shots are shown in Fig. 4. The pre-pulse intensity is normalized by peak intensity in every shot. The RMS of the pre-pulse at -4.5 ps and -26 ps are 51% and 39%, respectively. The fluctuation in a short pre-pulse is caused by variations in the main pulse, such as variation of the laser energy or the temporal and spatial profiles. For example, in the high gain amplification of the regenerative amplifier (a gain of approximately $10^6$), taking into account the small energy fluctuation of 1.5% (RMS) with the pump energy (Surelite-10, Continuum), the fluctuation of the output energy can be estimated to be $\sim 24\%$ by using a small signal gain equation [15]. This estimation is not completely consistent with the experimental results; it is possible that this inconsistency is a result of the fluctuation of pump energy. To determine the origin of the intensity fluctuation, it is necessary to measure the energy, and the temporal and the spatial properties of the pump lasers and seed laser simultaneously.
4. Conclusion
We have developed and tested a multi-channel cross-correlator for the single-shot measurement of the temporal contrast with a high dynamic range (>10^10). In the delay-scanning temporal contrast measurement, a good agreement between the results produced by both the MCCC and the commercial cross-correlator was observed. In the single-shot measurement, the shot-to-shot pre-pulse intensity at -4.5 ps and -26 ps was observed in 500 shots. The difference of the two intensity fluctuations is likely due to the origin of the pre-pulses. However, to further investigate the source of the shot-to-shot fluctuations observed in this experiment, more detailed measurements of the physical parameters of the laser are necessary. Moreover, by using the information of the pre-pulses shot by shot obtained with the MCCC, hydrodynamic simulation enables us to characterize the plasma density profile and temperature caused by the pre-pulse.

[Figure 4: The shot-to-shot fluctuation of pre-pulse intensity at -4.5 ps (circle) and -26 ps (triangle) in 500 laser shots. The noise level of the PMT is shown in blue.]

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References
[1] Baton S D, et al. 2008 Phys. Plasmas 15 042706
[2] Batani D, J et al. 2010 New J. Phys. 12 045018
[3] Yellampalle B, Kim K and Taylor A J 2008 Opt. Lett. 33 2854
[4] Moulet A, Grabielle S, Cornaggia C, Forget N and Oksenhendler T 2010 Opt. Lett. 35 3856–8
[5] Dorrer C, De Beauvoir B, Le Blanc C, Rousseau J P, Rane S, Rousseau P, Chambaret J P and Salin F 2000 Appl. Phys. B Lasers Opt. 70 1644–6
[6] Luan S, Hutchinson M H R, Smith R A. and Zhou F 1993 Meas. Sci. Technol. 4 1426–9
[7] Divall E J and Ross I N 2004 Opt. Lett. 29 2273–5
[8] Dorrer C, Bromage J and Zuegel J D 2008 Opt. Express 16 13534–44
[9] Wang Y, et al. 2014 Sci. Rep. 4 3818
[10] Collier J, C Hernandez-Gomez, R Allott, C Danson, and Hall A, 2001 Laser Part. Beams 19,231
[11] Kon A, Nishiuchi M, Kiriyama H, Ogura K, Mori M, Sakaki H, Kando M and Kondo K, “High dynamic range cross-correlator for shot-to-shot measurement of temporal contrast”, Jpn. J. Appl. Phys. (to be submitted).
[12] Mori M, et al.2008 IEEE Trans. Plasma Sci. 36 1872–7
[13] Itatani J, Faure J, Nantel M, Mourou G and Watanabe S 1998 Opt. Commun. 148 70–4
[14] Koechner W, 1996 Solid-State Laser Engineering (Springer, Berlin, Heidelberg 1996)