Diagnostics of pulse contrast for petawatt laser in SGII

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ABSTRACT

Pulse contrast is an important parameter for ultrafast pulses. It shall be 10^8 or higher in order to avoid effect from noise before main pulse. Diagnostics with cross-correlation can achieve high temporal resolution such as ~7fs. Cross-correlation has advantage in pulse contrast measurement than autocorrelation because it can distinguish noise before or after main pulse. High dynamic range is also essential in pulse contrast measurement. Cross-correlation signal from a single shot is converted into a signal series through fiber array, which can be analyzed by a set of a PMT and an oscilloscope. Noise from nonlinear crystal and scatter needs decrease to improve dynamic range. And pulse power is also discussed in pulse contrast experiments. Time delay τ is generated by travel stage in measurement for repetition pulses. Then energy instability will generate error in this measurement. In measurement for single shot pulse, time delay τ is generated by slant angle of beams. The scanning procession is completed with thousands parts of beam section within a single shot, and error will generated from no uniformity in near field. Performance test of pulse contrast measurement is introduced in subsequent sections. Temporal resolution is testified by self-calibration. Dynamic range is judged by a parallel flat. At last pulse contrast of petawatt laser is diagnosed by a single shot cross-correlator with high confidence. The ratio is 10^{-6} at 50ps before main pulse, and 10^{-4} at 10ps before main pulse.

Keyword: ultrafast lasers, petawatt laser, high power laser, pulse contrast measurement, cross-correlation, optical instruments, ultrafast measurements, ultrafast devices.

Introduction

Pulse contrast is an important characteristic of petawatt lasers in physics experiments; such lasers are important in laser-based particle acceleration and extreme ultraviolet and x-ray source [1–4]. Pulse contrasts of several ultrafast lasers have been improved to 10^{-11} by using double chirped-pulse amplifier and cross-polarized wave [5–8], or saturable absorber [9]. In addition, pulse contrasts of frontends in Orion and PHELIX facilities achieve 10^{-11} by using short pulse optical parametric amplifiers [10, 11]. The ultrafast lasers are diagnosed by Sequoia (Amplitude Technology) because of their low energy and high repetition. Diagnosing pulse contrast on large laser facilities is difficult because of various effects, such as single shot, large scale, and B-integral. Pulse replicator is used in OMEGA EP to observe pulse contrast of a single-shot pulse with a dynamic range of 10^{-6} [12]. Moreover, pulse contrast of 10^{-8} is measured by the photodiode in nanosecond with pulses 1500 J and 10 ps [13]. Furthermore, pulse contrast of 10^{-10} is also measured by the photodiode in nanosecond with pulses 100J and 500fs [10].

In recent diagnostics experiments, a petawatt laser in the Shenguang-II facility can produce 377 J, and the pulse width is changed from 0.5ps to 10ps. In addition, the focus power of this laser can reach ~4.6×10^{19} W/cm^2. To avoid noise

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before the main pulse interacts with the target matter, the noise power must be less than ~10^{12} W/cm^2. Therefore, the pulse contrast of petawatt lasers must be larger than 10^8.

In pulse contrast diagnostics, measurement must simultaneously achieve high resolution and a high dynamic range. Fortunately, decreasing noise during cross-correlation is an effective approach for this research.

Method

To measure pulse contrast of a single-shot, large energy pulse, it is sampled by a pick-off mirror, attenuated by uncoated surface mirror, and goes through a down-collimator. This approach is a usual way to realized diagnostics on large laser facilities. Notably, B-integral is minimized by uncoated surface mirror in diagnostics on ultrafast lasers. For example, B-integral of the pick-off mirror is 1.41 when pulse is 275 J and 1ps. Furthermore, B-integral of whole diagnostics is ≤ 1.97 under this condition. Pulse width of 0.5ps is observed with the low B-integral diagnostics when pulse energy is ~200 J.

For pulse contrast diagnostics, a high-dynamic-range single-shot cross-correlator (SSCC) is adopted in the experiment [14–16]. Cross-correlation has advantage in pulse contrast measurement than autocorrelation because it can distinguish noise before or after main pulse. During cross-correlation, the measured pulse $I_1(t)$ is determined using a sampling pulse $I_2(t)$ with an optical path delay τ.

$$I_X(\tau) = \int I_1(t) I_2(t-\tau)\, dt \tag{1}$$

The cross-correlation signal $I_X(t)$ is equal to $I_1(t)$ during pulse contrast measurement. Part of the input pulse and second harmonic generation (SHG) generate sampling pulse $I_2(t)$ via the formula $I_2(t) = I_1^2(t)$. $I_X(t)$ is proportional to $I_1(t)$ cubed in small-signal conversion of nonlinear crystals.

$$I_X(\tau) = \int I_1(t) I_1^2(t-\tau)\, dt \propto I_1^3(t) \tag{2}$$

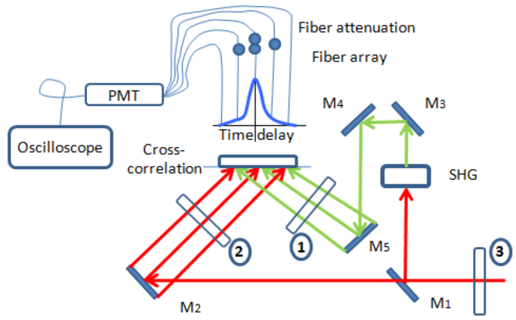
A diagram of an SSCC is shown in Fig. 1(a). The input pulse is initially divided by M_1, and then the transmission region is transformed into measured pulse $I_1(t)$. The pulse passes through M_2 and arrives at a cross-correlation crystal. The reflection region passes through a second harmonic generator and transforms into sampling pulse $I_2(t)$. The pulse subsequently passes through M_3, M_4, and M_5 and arrives at the cross-correlation crystal. The cross-correlation signal $I_X(\tau)$ is obtained after passing through the crystal. Finally, the signal is coupled to a detector composed of fiber array, a photomultiplier tube (PMT), and an oscilloscope.

Saturation of cross-correlation and scattering of the main pulse are important factors in many types of noise. The intensity of the main pulse is smaller than the theoretical value in Eq. (2) because of the high power in crystal. To identify errors from saturation, separate parallel plates are set up at ①, ②, and ③ [Fig. 1(a)], which are also used in autocorrelation [17]. Here, the thickness is d, the index is n, and the respective reflections of the front and back surfaces are r_1 and r_2. The time interval between the reference pulse and the main pulse is $T = 2nd/c$. The ratio between the reference and main pulses is determined by r_1 and r_2.

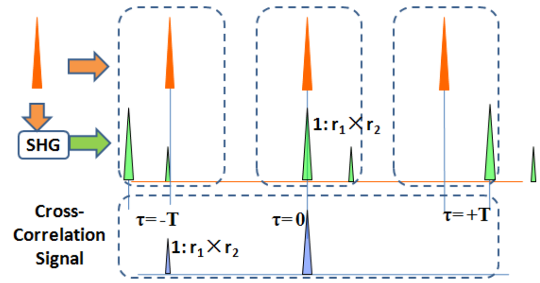
When the parallel plate is set up at ① [Fig. 1(a)], a reference pulse ($r_1 \times r_2$) is added to the sampling pulse. In addition, a reference pulse with ratio ($r_1 \times r_2$) may be observed at $\tau = -T$ in the pulse contrast curve [Fig. 1(b)].

When the parallel plate is set up at ② [Fig. 1(a)], the measured pulse is followed by a reference pulse ($r_1 \times r_2$). Moreover, a reference pulse with ratio ($r_1 \times r_2$) may be observed at $\tau = +T$ in the pulse contrast curve [Fig. 1(c)].

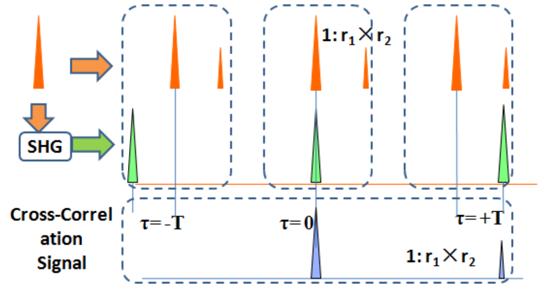
When the parallel plate is set up at ③ before the SSCC input [Fig. 1(a)], the measured pulse is followed by a reference pulse ($r_1 \times r_2$), and a reference pulse $(r_1 \times r_2)^2$ is added to the sampling pulse because of SHG. In the pulse contrast curve, a reference pulse with ratio $(r_1 \times r_2)^2$may be observed at $\tau = -T$ [Fig. 1(d)]. Another reference pulse with a ratio ($r_1 \times r_2$) may also be observed at $\tau = +T$. The error of saturation can be analyzed from the difference between the measured and theoretical values of the reference pulse ratios.



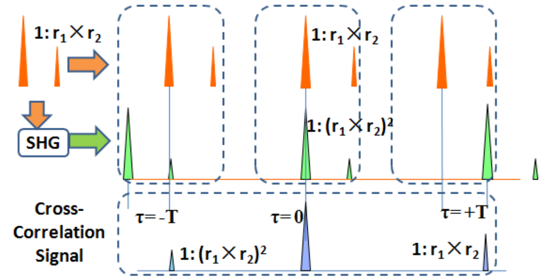
a) A single-shot cross-correlator with three parallel plates for calibration.



b) Schematic of a pulse contrast when a plate is set up in the SSCC at ①.



c) Schematic of a pulse contrast when a plate is set up in the SSCC at ②.



d) Schematic of a pulse contrast when a plate is set up before the SSCC input at ③.

Fig. 1 Diagram of a single-shot cross-correlator for saturation test.

Scattering noise is also critical to high dynamic range measurement. Scattering noise is restrained by using a slit attenuator or a dot mirror [18]. High reflectivity is observed on a tiny area of a mirror, but anti-reflectivity on else.

Time delay τ is generated by travel stage in measurement for repetition pulses. Then energy instability will generate error in this measurement. In measurement for single shot pulse, time delay τ is generated by slant angle of beams. The scanning procession is completed with thousands parts of beam section within a single shot, and error will generated from no uniformity in beam section (near field). When the time delay of a SSCC is achieved by an angle Φ between the measured pulse and the sampling pulse, distribution of near field of laser pulses should be uniform. But near field sometimes has defects in measurement, as shown in Fig. 2a.

There are many sources to affect near field in a large laser system. A part of beam section will become higher intensity because of self phase modulation in high power laser facility. Small damage point of optics in laser transmission maybe generate by ghost beam. Transmittance of pickoff mirror perhaps is not uniform. And near field will be deteriorated when diagnostics does not work on image plane.

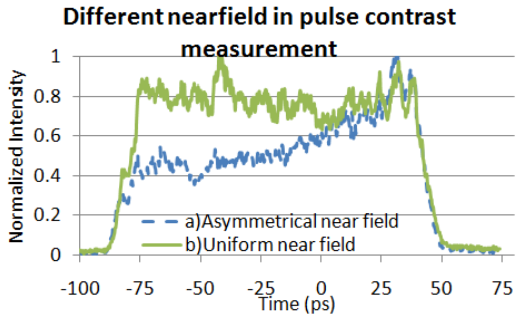
There are two methods to descript near field in a high power and large laser system. One is fill factor, which is defined as a ratio of maximum to average in a CCD image. Fill factor has used for many years, especially in Shen Guang II facility. Then fill factor of the asymmetrical near field is 0.55 in Fig. 2a. And fill factor of the uniform near field is 0.69.

The other is fluence beam contrast, which is provided by C. A. Haynam in 2007 [19].

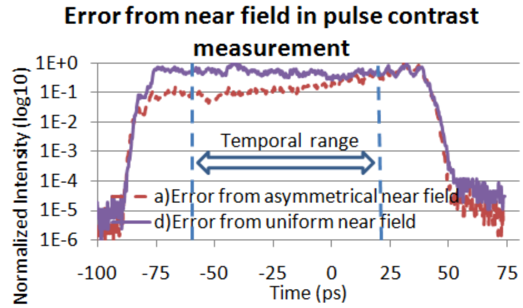
$$Fluence\ beam\ contrast = \sqrt{\frac{1}{mn}\sum_{i=1}^{m}\sum_{j=1}^{n}\left(\frac{F(x_i,y_j)-\bar{F}}{\bar{F}}\right)^2} \quad (3)$$

In Eq. (3), $F(x_i, y_j)$ is pixelated fluence from near field camera image, $\bar{F}$ is average fluence of image. Then fluence beam contrast of the asymmetrical near field is 0.34. And fluence beam contrast of the asymmetrical near field is 0.26.

Simulations of asymmetrical and uniform near field are derived through Eq. (2), as shown in Fig. 2b. Temporal range of the SSCC is 75ps when Φ is 66° [20]. It is observed that error from near field is about 1dB even if it is calculated in an asymmetrical near field. Error from a uniform near field can be ignored in pulse contrast measurement.



a) Section-lines of near field in a petawatt laser



b) Simulations of error from near field in pulse contrast measurement

Fig.2 Simulation of error from near field in pulse contrast measurement

Experiment

Temporal resolution is testified by self-calibration. In self-calibration method, the autocorrelator is calibrated by the measured pulse itself [21]. Each delay time corresponds to a different peak position. In this experiment, time delay unit (M_3 and M_4) are moved to generate time delay in Fig. 1a). There are 101 fibers in fiber array of the SSCC. Peak position is changed from 25th fiber to 74th fiber in fiber array when the movement of time delay unit is 5.5mm (Fig. 3). So temporal resolution of this SSCC is

$$\rho = \frac{z\times 2}{c\times \text{Number of fibers}} = \frac{5.5\text{mm}\times 2}{0.3\text{mm/ps}\times(74-25)\text{fibers}} = 0.75\text{ps/fiber} \qquad (4)$$

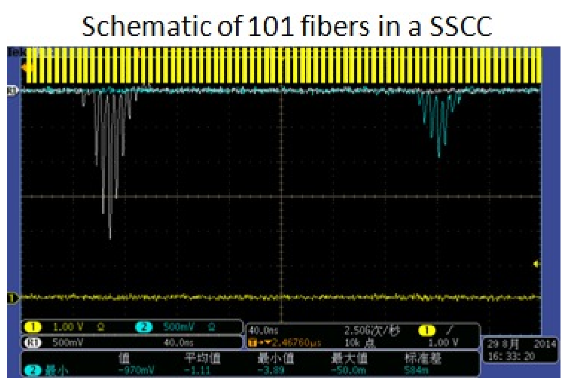
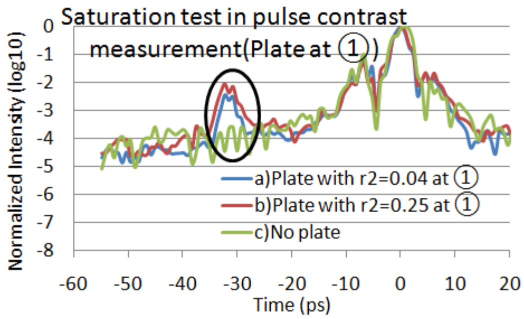


Fig.3 Temporal resolution in calibration experiment.

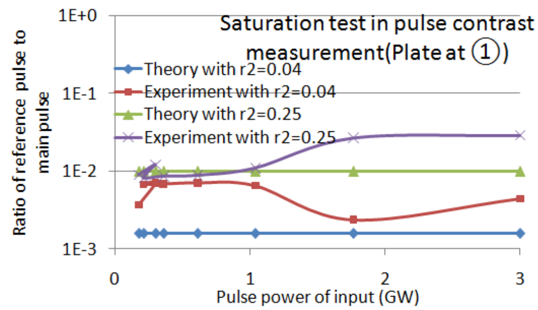
For dynamic range test, two kinds of plates are used in experiment. One is $r_1 = 0.04$ and $r_2 = 0.04$, which generates a reference pulse with ratio 1.6×10^{-3} when the plate is placed at ① or ②. Moreover, the ratio of the reference pulse at $\tau = -T$ is to be 2.56×10^{-6} when plate is placed at input ③. The other is $r_1 = 0.04$ and $r_2 = 0.25$, which generates a reference pulse with ratio 1×10^{-2} when the plate is placed at ① or ②. Furthermore, the ratio of the reference pulse at $\tau = -T$ is to be 1×10^{-4} when plate is placed at input ③. Any noise from uncertain factor can be easily observed in case of $r_2 = 0.25$. To explore saturation of main pulse in cross-correlation, input energy is changed from 0.17mJ to 3mJ when pulse width is ~1ps. This approach can help check the fluctuation of reference pulse ratio under different input power.

Experiment result is shown in Fig. 4. Reference pulses are measured with different ratio at theoretical positions $-T$

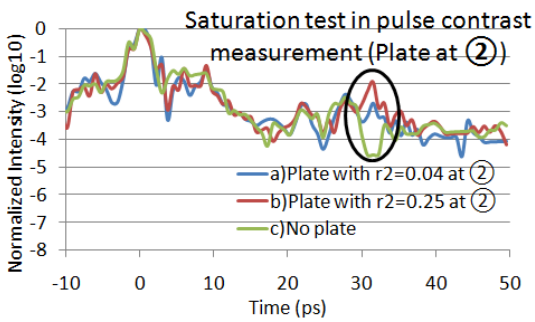
and +T [Figs. 4(a), 4(c), 4(e) and 4(f)]. T is ~30ps when a fused silicon plate is used and its thickness is 3.0 mm. Reference pulses are measured at both positions $-T$ and $+T$ [Figs. 4(e) and 4(f)]. Notably, reference pulse with ratio 1×10^{-4} is distinguishable [Fig. 4(e)]. However, reference pulse with ratio 2.56×10^{-6} is covered by scattering noise [Fig. 4(e)].



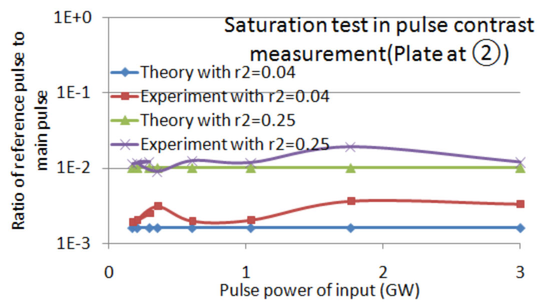
(a) Reference pulses at τ = -T when a plate is at ①.



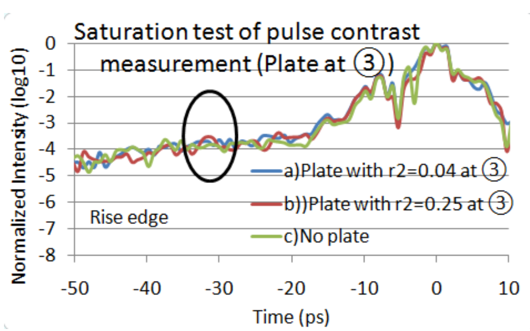
(b) Difference between theoretical and experiment value in case ①.



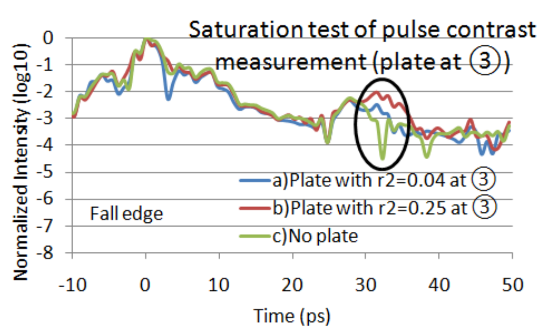
(c) Reference pulses at τ = +T when a plate is at ②.



(d) Difference between theoretical and experiment value in case ②



(e) Reference pulses at τ = -T when a plate is at ③ (Rise edge).



(f) Reference pulses at τ = +T when a plate is at ③ (Fall edge).

Fig. 4 Saturation test in the single-shot cross-correlation with parallel plates.

Ratio difference between theoretical and measurement value versus input power is shown in Figs. 4(b) and 4(d). The difference is random and fluctuant with increasing input power. On average, the measured values approximately 3.5 times the theoretical values are obtained in the experiments. The value is 0.54 dB when calculated using log10.

Scattering of the main pulse generates noise with a ratio of 10^{-4} in the experiments. A slit attenuator is set up just behind the cross-correlation crystal to decrease scattering noise from the main pulse. This method effectively improves the dynamic range of pulse contrast measurements (Fig. 5). Thus, the error from scattering is greater than 1 dB, and the error from saturation is 0.54 dB. The dynamic range of pulse contrast measurements is above 6 dB when these two effects are considered.

Conclusion

After considering saturation and scattering noise of main pulse with B-integral of sampling mirror and down-collimator, diagnostics system gives a precise measurement by a high-dynamic-range (10^{-10}) SSCC on the petawatt laser. In the SSCC, the cross-correlation signal of a single-shot pulse is converted from parallel to serial using the fiber array to address issues with the PMT, which is highly sensitive. The pulse contrast of a large-energy petawatt laser with full gain is obtained after SSCC testing, and results are shown in Fig. 6. Based on the results of diagnostics, the noise of the petawatt laser is below 10^{-6} at -53ps and below 10^{-5} at –30ps when the pulse energy is 198J and the pulse width is 0.5ps.

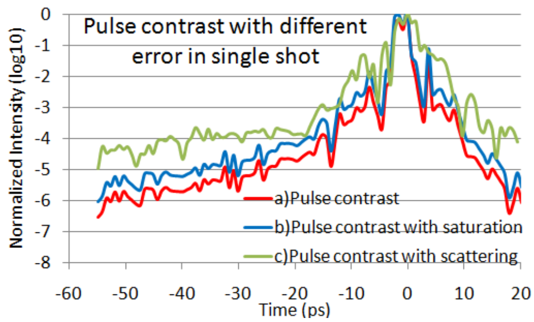


Fig. 5 Measurement error from saturation and scattering.

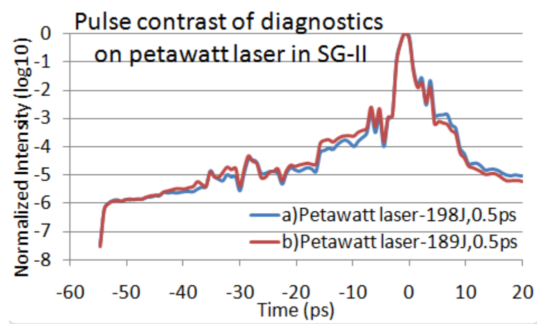


Fig. 6 Pulse contrast curve of the petawatt laser.

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