A method to obtain pulse contrast on a single shot

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A novel method for obtaining a single shot multi-point high dynamic range pulse contrast measurement is presented. We use Dammann gratings to generate multiple beamlets by division of amplitude on ultra-short laser pulses. The analysis results show that this method can achieve high dynamic range in pulse contrast measurement on a single shot by using photomultiplier tube (PMT) detectors and the long working distances to minimize cross talk between channels. Some distortion of pulse shape is also analyzed detailedly with the Dammann grating and its compensation grating, which may degrade the pulse contrast measurement in some degree by pulse stretching and spectrum clipping.

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Ultra-short laser pulses have become an important tool for the study of ultra-fast phenomena and a principal method of generating extremely high-power pulses of laser radiation. The ultra high intensity laser pulses have been used in areas of research including multi-photon ionization, high-harmonic generation, laser-plasma interaction, and X-ray laser development. When ultra high intensity, ultra short laser pulse-plasma interacts with a solid target, the intensity of prepulse must be lower than $\sim 10^{10}$ W/cm^2 to avoid the interaction with the preformed plasma. As the peak power at the focus generated by optical parametric chirped pulse amplification (OPCPA) technique can achieve 10^{19} W/cm^2 or above[1−3], the dynamic range of the temporal pulse needs to be $\sim 10^{-9}$ or better.

There are two ways to realize pulse contrast measurement. One is based on the second order autocorrelation, which has simple configuration, and just needs lower energy input. The other is based on the third order cross-correlation, which has an advantage of distinguishing prepulses from postpulses. So the pulse contrast measurements for peta-watt laser systems are all based on the third order cross-correlation[4−7]. These correlators tend to be either scanning or single shot. Scanning correlators using a photomultiplier tube (PMT) detector are capable of measuring the contrasts up to 10^{10} (see commercial Sequoia from Amplitude Technologies or other references). However it provides only one sample point per shot. Single shot correlators are hard to get a high dynamic range results in pulse contrast measurement because of the detector's low dynamic range (typically $\sim 10^5$ for a high speed charge coupled device (CCD)'s dynamic range)[4]. Although Christophe's pulse replicator is compact and ingenious to generate multiple beamlets[10], it needs high energy for very low transmittance.

We have made some research on pulse contrast measurement under the second order autocorrelation and third order cross-correlation. And a calibration method was presented under the second order autocorrelation to testify the pulse contrast measurement[8,9]. All these work is taken on an oscillator GLX-200-HP-1053, because a stable OPCPA system is not set up. By combining the high dynamic range scanning correlator with the need for a single shot measurement, the multi-point correlator is conceived to give several measurement points at different delays and individual PMTs. In this letter, we present a novel solution to give a range of such points using Dammann gratings.

In past measurements on a single shot, the fundamental wave and harmonic wave, separated by a Wollaston prism, were tilted by a Fresnel bi-prism, and crossed with each other on the sum crystal. The optical path delay of this method is determined by the crossing beam width and the angle between the two beams. Different position of temporal delay is decided by different beamlet divided by wavefront. This method is unable to get large temporal window, and there is no report of high dynamic range in pulse contrast measurement[4]. Our method for pulse contrast measurements is based on division by amplitude of an ultra-shot single pulse instead by wavefront. So it is the same as Christophe's method.

Dammann grating is a kind of binary optical elements that can generate many beamlets by averaging, and does not need a strict requirement for coatings on it[11,12]. We need two gratings for the fundamental wave 1ω and the harmonic wave 2ω, so the grating functions are

$$\begin{cases} d_{1\omega} \sin \theta_i = m\lambda_{1\omega} \\ d_{2\omega} \sin \gamma_i = n\lambda_{2\omega} \end{cases}, \tag{1}$$

where $d_{1\omega}$ and $d_{2\omega}$ are the constants of fundamental and harmonic grating, m and n are the diffraction orders of fundamental wave and harmonic one, respectively. θ_i and γ_i are the diffraction angles of fundamental wave and harmonic one, $i = 1, 2, 3, \cdots$. $\lambda_{1\omega}$ and $\lambda_{2\omega}$ are the wavelengths of the fundamental beam and harmonic beam. The schematic of the measurement setup is shown in Fig. 1.

It has another characteristic that these beamlets' diffraction angles increase with the diffraction order. So the beamlets' optical paths increase in the plane of the Dammann grating and its compensation grating. When the fundamental and harmonic grating are set symmetrically, different optical paths are distributed between these beamlets. That is to say, the optical delay component is deleted from every pair of beamlets. This method of pulse contrast measurement by a single shot also needs $m = n$ and $\theta_i = \gamma_i$. So it can be inferred that $d_{1\omega} = d_{2\omega}$.

Optical path delay is depended on the distance of L between the Dammann grating and its compensation grating when the diffraction angles are fixed. We can get these functions from Fig. 1(b) as

$$\begin{cases} OPD_1 = L/\cos\theta_1 - L/\cos\gamma_5 \\ OPD_2 = L/\cos\theta_2 - L/\cos\gamma_4 \\ OPD_3 = L/\cos\theta_3 - L/\cos\gamma_3 \\ OPD_4 = L/\cos\theta_4 - L/\cos\gamma_2 \\ OPD_5 = L/\cos\theta_5 - L/\cos\gamma_1 \end{cases}. \quad (2)$$

The optical path difference of the middle pair of Fig. 1(b) is set to zero. So $OPD_3 = 0$. And from Eqs. (1) and (2), we can derive that $OPD_1 = -OPD_5$ and $OPD_2 = -OPD_4$. It is found that the optical path differences of side pairs are symmetric and they increase one by one. So the functionality of this measurement in temporal range and resolution depends on the optical path difference OPD_i and the distance L. Using typical values of $OPD_2 = -3$ mm (–10 ps), $d_{2\omega} = 100$ μm, $\lambda_{2\omega} = 0.526$ μm, it can be calculated that $\theta_2 = 0.905°$, $\theta_4 = 2.114°$, and $L = 1346.85$ mm. Thus we can get that the time spacing of sample points in the ten picosecond timescale.

We can see that the new method's advantage is that the pair of a Dammann grating and its compensation grating can provide multiply beamlets on average. Because of the long working distances, cross talk between channels could be minimal. For that gratings will introduce some dispersion[13,14], we need to consider the dispersion and spectrum clipping of these gratings.

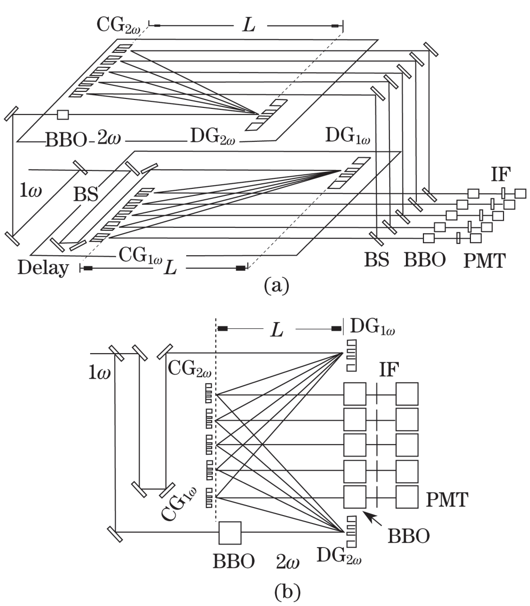

Fig. 1. Schematic of (a) configuration and (b) vertical view of the measurement setup. BS: beamsplitter; DG$_{1\omega}$: fundamental Dammann grating; CG$_{1\omega}$: fundamental compensation grating; DG$_{2\omega}$: harmonic Dammann grating; CG$_{2\omega}$: harmonic compensation grating; IF: Interference Filter; PMT: photomultiplier tube. L : distance between Dammann grating and compensation gratings.

Suppose that the measured pulse is not chirped after compression by a compressor. It will be stretched in temporal and clipped in spectrum when it transmitts through the pair of a Dammann grating and its compensation grating. The width of output pulse can be derived from Kirchhoff-Fresnel integral[15] as

$$\tau_{\text{out}} = (\tau_{\text{in}}^2 + \frac{8\ln 2\beta^2 L^2}{\sigma^2} + \frac{4\ln 2k\beta^2 L}{\tau_{\text{in}}^2 + \frac{8\ln 2\beta^2 L^2}{\sigma^2}})^{1/2}, \quad (3)$$

where τ_{in} is the input pulse width, τ_{out} is the output pulse width, σ is the $1/e$ radius at the beam waist, $k = 2\pi/\lambda$, and λ is the wavelength. $\beta = -m\lambda/(2\pi cd \cos\theta)$, where m is the number of the diffraction order, c is the speed of light in vacuum, d is the Dammann grating constant, and θ is the angle between the incident and diffracted rays.

It is found from Fig. 2 that the higher the diffraction order is, the wider the output pulse width is. And fundamental wave is easier to be stretched. When $m = 33$, the input pulse width is 500 fs, and L is 1000 mm. The output pulse width is 603 fs when $d_{1\omega} = 200$ μm, and 530 fs when $d_{2\omega} = 100$ μm. The number of sample points for the correlator is given by $2m$ and is limited by the pulse width as shown in Fig. 2. When the pulse width is 500 fs, we can get 10 points on either side, and with 1 ps 17 points on either side. With a 50-fs system the usable points would be only 1 on either side. Thus this method is only suitable for long pulse laser systems. So we need to constrain the output pulse width with this function

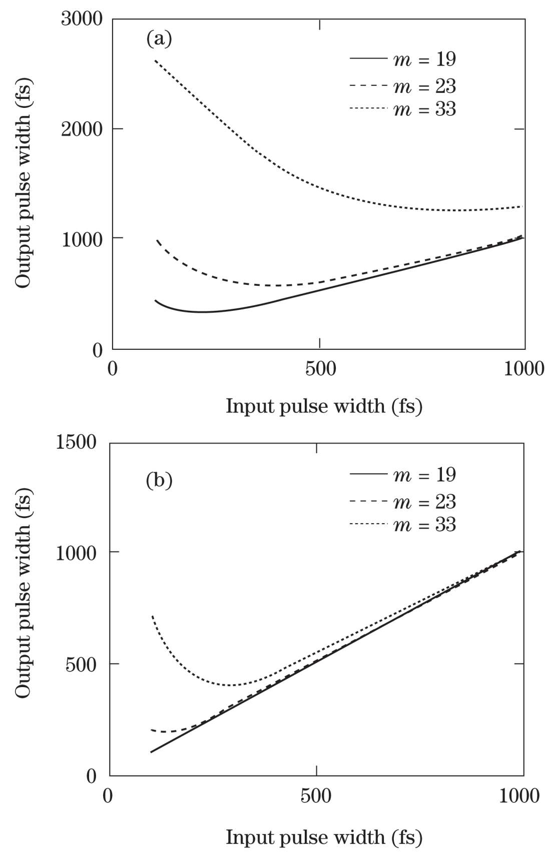

Fig. 2. Pulse stretched by gratings pair with L=1000 mm at wavelength of (a) 1053 nm and (b) 527 nm.

when the pulse width is 500 fs:

$$\tau_{\text{out}}^2 = (1+\eta)^2\tau_{\text{in}}^2, \tag{4}$$

where $\eta = (\tau_{\text{out}} - \tau_{\text{in}})/\tau_{\text{in}} \cdot 100\%$. From Eqs. (1), (3), and (4), the relationship of d and m can be deduced as

$$d^2 = [\lambda^2 + \frac{\lambda^4}{(2\pi c)^2\beta^2}]m^2, \tag{5}$$

where $\beta^2 = (B+C)/A$, $A = 2\cdot(8\ln 2L^2)^2/\sigma^4 + 2\cdot(4\ln 2kL)^2$, $B = (2\eta-1)\cdot 8\ln 2L^2\tau_{\text{in}}^2/\sigma^2$, and $C = 8\ln 2L\tau_{\text{in}}^2((2\eta+1)^2L^2+k^2)^{1/2}/\sigma^2$. So d should increase with m as shown in Fig. 3. It is obviously demonstrated that d is proportional to m, and the distortion of output pulse width can be decreased by selecting proper m and d. But the diffraction efficiency will fall when the constant d becomes larger.

For peta-watt lasers have a wide spectrum, the pulse contrast is deteriorated after the gratings pair[16] :

$$I_{\text{output}}(t) = |\text{FT}^{-1}\{[I_{\text{input}}(\lambda)k(\lambda)]^{1/2}\}|^2, \tag{6}$$

where $k(\lambda)$ is a wavelength-dependent clipping ratio of the grating pair, $I_{\text{input}}(\lambda)$ is the intensity spectral profile of the input pulse, $I_{\text{output}}(t)$ is the intensity temporal profile of the output pulse, and $\text{FT}^{-1}\{\}$ is an inverse Fourier transform.

In order to detect more temporal positions, larger number of diffraction order is needed. And a longer distance L is required for placing compensation gratings. The spectral width of input pulse is 3.4 nm, and we assume just all spectrum has passed the gratings pair. It is derived that spectrum clipping from the gratings pairs does not degrade pulse contrast, even if there is some energy loss on each spectrum. Noise generation by the gratings pair is lower than 10^{-10} at 10 ps before the main pulse, until diffraction order m is 69 or above with $L =$ 1000 mm.

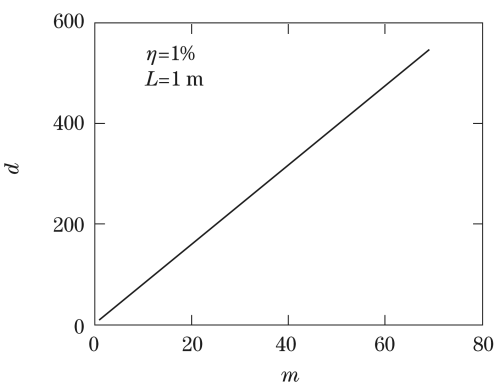

Fig. 3. Relationship between grating constant d and diffraction order m.

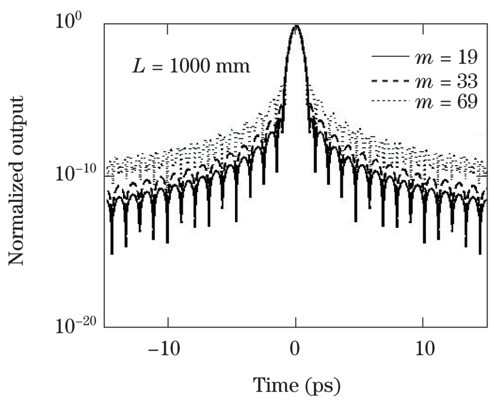

Fig. 4. Degradation of pulse contrast from the compensation grating.

In conclusion, we present a feasibility to obtain a multi-points high dynamic range pulse contrast measurement by a single shot. For it adopts division by amplitude instead by wavefront, it has some advantage of pulse contrast measurement with high dynamic range after OPCPA. The larger diffraction order degrades the pulse contrast, and needs larger constant d to avoid pulse stretching. So the number of beamlets from the Dammann grating is confined. A proper selection is that the distance L is 1000 mm, diffraction order m is 19, constant $d_{1\omega}$ is 200 μm, and constant $d_{2\omega}$ is 100 μm. And ten beamlets are available on either side of each Dammann grating. The effect from spectrum clipping can be neglected when the wider compensation grating is used. Although it is complicated to setup some 3rd harmonic stages all running at optimal performance, it will be a useful way to obtain high dynamic range because of the use of PMTs. Based on the experiments with PMT detectors, it is easy for running at 10^{-8} or better.

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