Progress of diagnostics for coherent beam combination on ultrashort pulse

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ABSTRACT

Ultrashort pulse is important to exploring laser acceleration in many areas, such as fast ignition, advanced radiography capability. Petawatt laser should not only improve output energy on a single beam, but also combine multi-beams coherently. Diagnostics of temporal and phase synchronization is developed for coherent beam combination on a 10ps laser pulse. When two pulses are guided into the diagnostics, one goes through a temporal delay unit and a lens with a focal length 500mm, then arrives at detector unit, the other goes through a phase delay unit and the same lens, and then arrives at detector unit, too. First, temporal synchronization is adjusted by temporal delay unit and monitored by a cross-correlation generator in the detector unit. Second, phase synchronization is adjusted by phase delay unit and monitored by a far field interferogram in the detector unit. In our design, temporal resolution is 6.7fs in temporal synchronization, and phase resolution is 0.007π in phase synchronization. Experiment has proved that this diagnostics is useful to realize synchronization between two ultrashort pulses both in temporal and in spatial.

Keywords: ultrafast laser, coherent beam combination, ultrafast measurements, phases measurement.

1. INTRODUCTION

With the development of high-power ultra-short laser, picoseconds petawatt laser facility has been an important tool for fast ignition, advanced radiography capability, and fast proton ignition. Such research requires petawatt laser with high energy, such as 10kJ or even to 200kJ with pulse width <20ps[1] . However, the energy of single petawatt laser is limited because of the size and damage threshold of large grating. In recent years, the maximum output of a single petawatt laser is 2.6kJ at OMEGA EP[2]. To enhance the output energy and achieve higher intensity of the petawatt laser, scientists came up with coherent beam combination. Yan-lei Zuo et al. studied the effect of beam directivity on focal spot distribution using a Gaussian beam by Fourier method[3].Yu-chuan Yang carried out a phase synchronization experimental research on coherent beam combination based on the continuous source[4]. In 2011, D. Homoelle, J. K. Crane et al. investigated the phase compensation of an individual advanced radiographic capability (ARC) aperture with different dispersions at the National Ignition Facility (NIF)[5]. In 2012, Yan-qi Gao et al. simulated the phase requirement for coherent combination of high-power laser[6].

The picoseconds pulse-coherent combination aims to keep both temporal and phase synchronized. The temporal synchronization has recently obtained some achievement, not only the passive synchronization method but also active synchronization can maintain a constant and sync'ed output of two independent lasers of different wavelength and pulse width[7, 8], where as the phase synchronization is still ambiguous. Based on the recent process, picosecond pulse diagnostics for single-petawatt laser could provide parameters, such as energy, pulse width, far-field, and pulse contrast under a single shot. The measurement range of our picosecond auto-correlator for single shot reaches 18ps, with temporal resolution is below 0.1ps[9]. To monitor and analyze coherent combination, a diagnostics scheme is developed for both phase and temporal synchronization with multi-ultrashort pulses.

2. PRINCIPLE OF SYNCHRONIZATION DIAGNOSTICS

This article presents a scheme that initially monitors and adjusts temporal synchronization using correlation method. Phase synchronization is then achieved using a phase delay unit (PDU) with a Soleil-Babinet compensator. All

2015 International Conference on Optical Instruments and Technology: Advanced Lasers and Applications,
edited by Jianqiang Zhu, Chunqing Gao, Proc. of SPIE Vol. 9621, 962106 · © 2015 SPIE
CCC code: 0277-786X/15/$18 · doi: 10.1117/12.2189707

components that fulfill the temporal synchronization requirement form the temporal module. Similarly, the elements that realize phase synchronization requirement constitute the phase module. These two modules utilize time-division multiplexing in monitoring and adjusting temporal and phase synchronization. The principle of this diagnostics is introduced by taking two pulses (A and B) in picoseconds as showed in Fig.1.

2.1 Temporal synchronization

For the temporal module, the first test pulse A can be expressed in time domain by

$$I_1(t) = \exp(-4\ln 2\frac{t^2}{\Delta T_1^2}) \tag{1}$$

The another test pulse B can be formulated as

$$I_2(t) = \exp(-4\ln 2\frac{t^2}{\Delta T_2^2}) \tag{2}$$

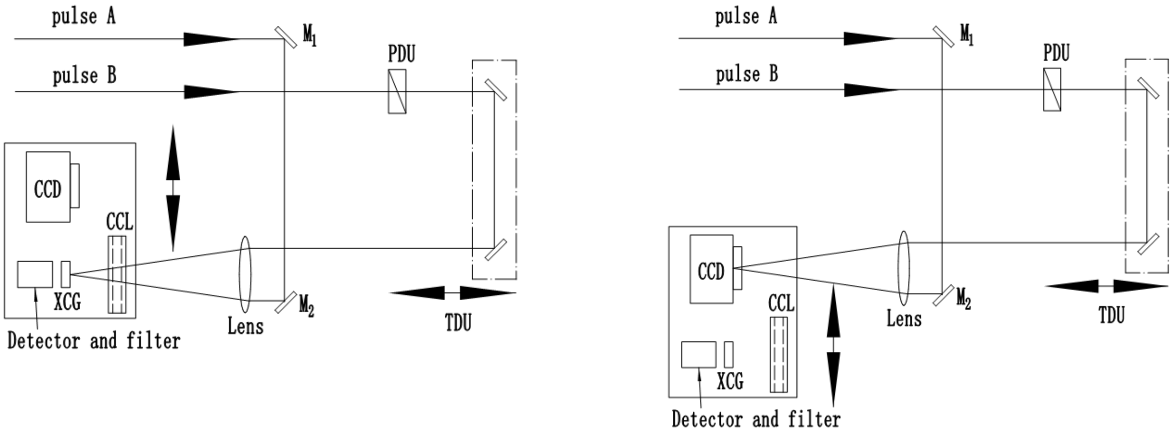
where ΔT_1 and ΔT_2 are pulse widths of test pulses. Because ΔT_1 maybe not equal to ΔT_2, it is cross-correlation in nonlinear crystal. Especially, it is auto-correlation when $\Delta T_1 = \Delta T_2$. So auto-correlation is a kind of cross-correlation. Cross-correlation of these two pulses (A and B) in a nonlinear crystal can be expressed as

$$X(\tau) = \int I_1(t) I_2(t-\tau) dt \tag{3}$$

where $\boldsymbol{\tau}$ is the time delay between pulse A and pulse B. Based on Eqs. (1), (2), and (3), the relationship of cross-correlate signal $X(\tau)$ with $\boldsymbol{\tau}$ can be derived as

$$X(\tau) = \exp(-4\ln 2\frac{\tau^2}{\sqrt{\Delta T_1^2 + \Delta T_2^2}}) \tag{4}$$

If $\boldsymbol{\tau}=0$, $X(\tau)$ is the maximum value. If $\boldsymbol{\tau}\neq 0$, the value of $X(\tau)$ is less than the maximum $X(\boldsymbol{\tau}=0)$. The temporal synchronization of two ultrashort pulses is analyzed by monitoring the intensity of the cross-correlation signal.



(a) (b)

Fig.1 Schematic of synchronization diagnostics for multi-ultrashort pulses. (a) temporal synchronization module, (b) phase synchronization module.

Fig.1(a) shows the schematic of temporal module. The first beam (pulse A) is reflected by M1 and M2 then passes through the lens. The second beam (pulse B) passes through the PDU, temporal delay unit (TDU), and also, at the lens. The TDU consists of a pair of vertical reflectors, which are setup on a travel stage. The temporal synchronization is adjusted by changing the optical path difference between pulse A and pulse B. Focal spots are converted into focal lines by a convex cylinder lens (denoted as CCL in the figure). When pulse A and pulse B reach onto the cross-correlation generator (denoted as XCG in the figure), the two focal lines overlapped on the focal plane. It simplifies adjustment of cross-correlation by comparing the two focal spots.

2.2 Phase synchronization parallel to the optical axis

Phase synchronization parallel to the optical axis is also called piston phase. In a phase module, only the phase difference is considered, and the phase of pulse A is assumed to be 0. The optical field analytical expression of pulse A can be written as

$$u_A(x,y,\omega)=\exp\{-(\frac{x}{R_0})^2+(\frac{y}{R_0})^2\} \tag{5}$$

That of pulse B can be expressed as

$$u_B(x,y,\omega)=\exp\{-(\frac{x}{R_0})^2+(\frac{y}{R_0})^2\}\exp[-j\varphi(x,y,\omega)] \tag{6}$$

$\varphi(x,y,\omega)$ can be expanded in Taylor series

$$\varphi(x_0,y_0,\omega)=\varphi(x_0,y_0,\omega_0)+\varphi'(x_0,y_0,\omega_0)(\omega-\omega_0)+\frac{1}{2}\varphi''(x_0,y_0,\omega_0)(\omega-\omega_0)^2+$$

$$\frac{1}{6}\varphi'''(x_0,y_0,\omega_0)(\omega-\omega_0)^3+\cdots \tag{7}$$

The first item $\varphi(x_0,y_0,\omega_0)$ affects the spatial coherent combination of these pulses and can be adjusted by the phase delay unit concerned in this paper, whereas other items, φ' affects the temporal coherent combination which can be equalized by adjusting the TDU. φ'' and φ''' are known as the group velocity dispersion(GVD) and third-order dispersion(TOD) which can be balanced in analysis[5] so that the peak intensity of combined beam will not degrade significantly with these high-order dispersion. A typical phase distortion of pulses in a petawatt source mainly is wavefront distortion. The wavefront distortion caused in transmission progress could be corrected by adaptive optical system at first, then utilizing this scheme to realize the phase synchronization. More complex distortion will be researched in the future.

Based on the principle of Fraunhofer diffraction, the optical field distribution on the focal plane can be expressed as

$$\widetilde{E}(x,y)=\frac{CA_m}{f}\exp(ikf)\exp(ik\frac{x^2+y^2}{2f})\iint\widetilde{E}(x_1,y_1)\exp(ik\frac{xx_1+yy_1}{z_1})dx_1dy_1 \tag{8}$$

C is a constant, and A_m is amplitude of optical field. Light intensity is expressed by：$I=|\widetilde{E}(x,y)|^2$.

Fig.1(b) presents the schematic of the phase module. Moving the platform to CCD (comparing Fig.1(a) and Fig.1(b)), the diffraction pattern of these two pulses is recorded by a CCD camera. Adjusting the PDU alters the phase difference between A and B. Focal spot splitting caused by the interaction of two beams can be observed on the CCD camera. If no division is observed in the far-field after fine adjusting of the PDU, phase synchronization of these two pulses is accomplished.

When these two pulses (A and B) are in phase, the focal spot has its optimal energy focus ability. If they are out of phase by π/2 and 3π/2, respectively, the focal spot splits into two parts having different sizes. However, the large spot and the small spot exchange positions. If the pulses are out of phase by π, the focal spot is divided into two parts having the same sizes and intensities.

2.3 Phase synchronization perpendicular to the optical axis

In a phase module, CCD camera is adopted to monitor the intensity of the focal spot. For convenience, aperture of pulse A and pulse B is considered rectangular, whose sizes are 4 mm×8mm, such that a=4mm and b=8mm. The distance between the two beams is defined as ***d***, and phase difference is defined as $\Delta\varphi$. This design is similar to the aperture of a beam in ARC of NIF[5,10], which is shown in Fig. 2.

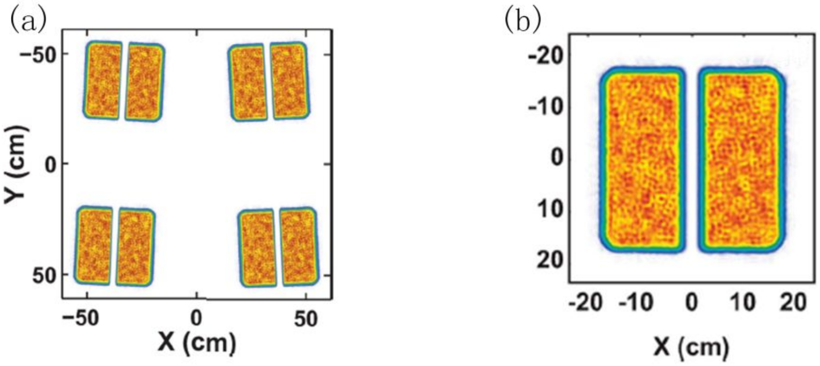


Fig.2 (a) ARC near-field intensity of NIF (National Ignition Facility) and (b) ARC aperture near-field intensity

The effect of beam distance ***d*** is also considered during phase synchronization. It causes phase difference that is perpendicular to the optical axis. If no phase difference exists along the optical axis between pulse A and pulse B, the main factor that influence the focal spot is the ratio of beam distance to beam aperture (***d/a***), which is always >1.

For example, in multi-slit diffraction, the expression of the coherent intensity I can be expressed as single-slit diffraction factor multiplied by interference factor, which is based on Fraunhofer diffraction theory.

$$I = I_0\left(\frac{\sin\alpha}{\alpha}\right)^2\left[\frac{\sin(N\varphi/2)}{\sin(\varphi/2)}\right]^2 \tag{9}$$

where N is the number of slits, $(\frac{\sin\alpha}{\alpha})^2$ is the single slit diffraction factor, and $[\frac{\sin(N\varphi/2)}{\sin(\varphi/2)}]^2$ is the interference factor that represents N bunch of iso-amplitude, iso-phase difference and beam interference.

The number of bright fringes on focal spot is affected by the interference factor. These bright fringes are interference fringes, which are located at zero order of the diffraction area, and their intensities are modulated using a single-slit diffraction factor. According to theoretical calculation, the modulation is based on the ratio of beam distance to beam aperture. The number of bright fringes increases and the width of fringes gradually narrow as the ratio increases.

If the temporal synchronization is fulfilled, the brightest spot of focal plane is an Airy disk such that ***d*** is 0, and the near field is an 8mm×8mm square distribution. It has 86% of the total energy. But there is ***d***>***a*** in engineering design. So the brightest spot is selected based on the intensity of the coherent signal. When the energy of the coherent signal is greater than 90% of energy of Airy disk, the phase synchronization perpendicular to the optical axis is obtained, and the focal spot is in a proper state.

Given the effect of ***d*** on focal spot, the intensity expression can be derived as

$$I = C'(2+2\cos(k\delta-\frac{kxd}{f}))\sin c^2(\frac{ax}{f\lambda})\sin c^2(\frac{by}{f\lambda}) \tag{10}$$

where C' is a constant factor, $\sin c(x)=\frac{\sin\pi x}{\pi x}$, $k=2\pi/\lambda$, and $k\delta$ is the phase difference. The relationship between ***d/a*** and focus can be analyzed to improve intensity of focus.

3. FEASIBILITY ANALYSIS

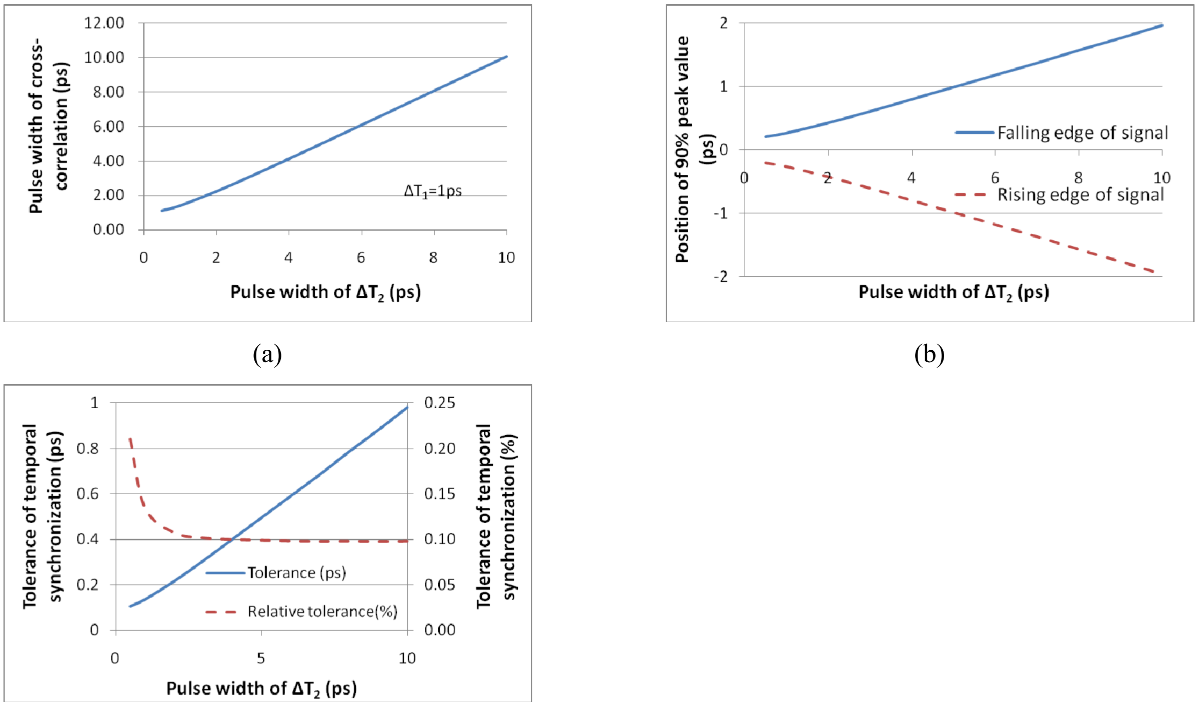
3.1 Error from temporal synchronization

In temporal module, a detector is used in monitoring the intensity of cross-correlation signals. A 90% of the peak value is accepted in cross-correlation because of the measuring error (2%) of common detectors and the output stability error (5%) of lasers. If the signal intensity $\leq$90% of the peak intensity, it is considered as a mismatch.

If pulse width of pulse A does not coincide with that of pulse B, the width of cross-correlation signal is varied. It also changes the position of 90% of the peak value. Meanwhile, the sensitivity for temporal synchronization also differs. All these factors constitute a dominating systemic error.

In Eq. (4), the following assumptions are made: ΔT_1=1ps and ΔT_2=0.5~10ps. As ΔT_2 increases from 0.5ps to 10ps, the width of cross-correlation signal moves from 1.12ps to 10.05ps (Fig.3(a)) and δT_{peak}, which represented 90% of the peak intensity, changes from ±0.21ps to ±1.96ps (Fig. 3(b)). Temporal resolution is decided by movement of TDU. It is 6.7fs when a travel stage with differential drive is used, which has a resolution of 1um for optical path delay. The pulse width of a petawatt ranges from 1~20 ps[1]. Auto-correlation and cross-correlation measurements satisfy the requirement of temporal synchronization. The limiting factor is the sensitivity of the detector.

When pulse width of pulse B changes, tolerance of temporal synchronization is increased from 0.11ps to 0.98ps, where as the relative tolerance is decreased from 21% to 10% (Fig.3(c)). In addition, if pulse width of pulse B is 3 times larger than that of pulse A, the relative tolerance does not change (Fig.3(c)). When these two pulses are both equal to 1ps, the absolute value of tolerance of temporal synchronization is 0.27ps, and the relative tolerance is 14%. The current resolution of a single-shot picoseconds auto-correlator is 0.1ps. It is enough to fulfill the requirement of temporal synchronization in diagnostics. When the auto-correlator is operated under repetition pulses, temporal resolution will improve to 6.7fs.



(a)

(b)

(c)

Fig.3 Influence from pulse width of pulse B. (a) pulse width of cross-correlation signal, (b) position of 90% peak value, (c) tolerance of temporal synchronization

3.2 Error from phase synchronization parallel to the optical axis

The focal spot splitting caused by phase difference along optical axis is initially discussed. It is compensated by PDU. The distribution of the focal spot in far-field, including phase difference, is shown in Fig. 4. When the phase difference is in multiples of 2π, it has the best energy focal spot concentration. When pulse A and pulse B are out of phase by π/2 and 3π/2, respectively, the focal spot splits into two, which have different sizes. However, the large spot and the small spot exchange positions. If the spot is out of phase by π, the focal spot is divided into two pulses with the same sizes and intensities.

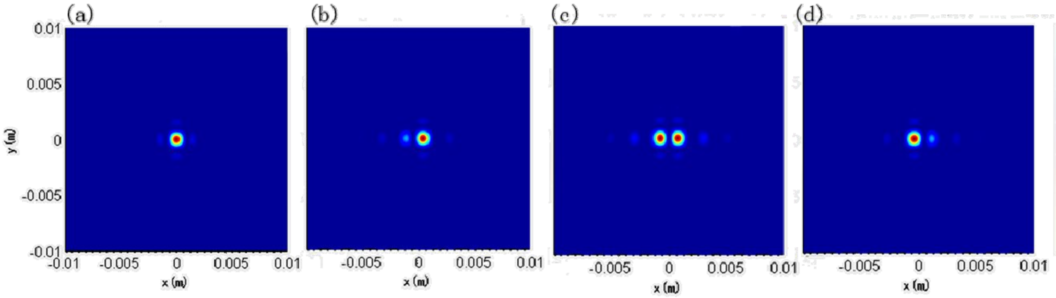


Fig.4 Distribution of the focal spot with phase difference in simulaiton: (a) in phase, (b) π/2 out of phase, (c) π out of phase, and (d) 3π/2 out of phase

After temporal synchronization, the Airy disk is used as a standard, and the brightest spot is used as the basis of a coherent signal. When the energy of coherent signal is ≥90% of the Airy disk energy, the beams are considered in phase. If the beams are in phase, the energy ratio of the brightest spot to Airy disk is 95.35% using simulation calculations. When the phase difference is π/2 or 3π/2, the energy ratio is 80.96%. When the phase difference is π, the energy ratio is 48.9%. As the phase difference during adjustment is increased, the energy ratio of the brightest spot to Airy disk gradually decreases (Fig.5). To assure that the energy of the brightest spot in the coherent signal is higher than 90% of Airy disk energy, the phase difference should be 9π/32 or less, and the precision of PDU needs to be π/4 (0.25π) or less. In this scheme, the PDU product model used is SBC-IR of Thorlabs.Inc.. During the calibration experiment, the phase changes by 2π when the PDU's micrometer travels at 285um under 1053nm laser (the precision of micrometer is 1 um). The phase precision is 2π/285=0.007π. Thus, the PDU satisfies the requirement of phase synchronization.

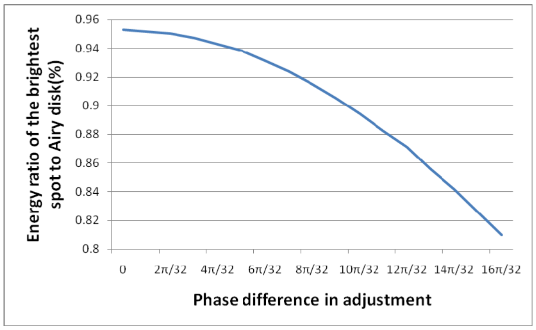


Fig.5 Energy ratio of the brightest spot to Airy disk with adjusted phase difference

The ratios of brightest spot to Airy disk during phase adjustment are shown in Table 1 with data from Fig. 5.

Table 1. Ratio of the brightest spot to Airy disk during phase adjustment

	Phase difference	The energy ratio of brightest spot to Airy disk	Relative error
1)	9π/32+0.14π	85%	5.56%
2)	9π/32	90%	/
3)	9π/32-0.14π	94%	4.44%

It is showed in Table 1 that the relative error is not greater than 5.56% during phase synchronous adjustment along the optical axis.

3.3 Error from phase synchronization perpendicular to the optical axis

Relationship between ***d/a*** and focus is simulated and showed in Fig.6. Based on the curves, the increase of ***d/a***, causes the decrease in the encircled energy of the brightest spot, as well as in the energy ratio of the brightest spot to Airy disk. In addition, the energy ratio of brightest spot to Airy disk is above 90% if ***d/a***<1.12. Thus, the influence of ***d/a*** to the focal spot is negligible.

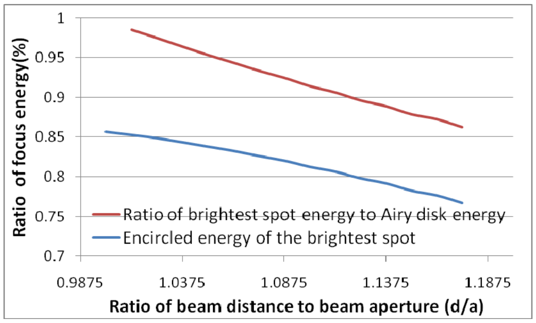


Fig.6 Energy-concentration degree with ratio of beam distance to beam aperture

If there are ***d***=4.2mm and ***d/a***=1.05, the energy ratio of brightest spot to Airy disk is 95.35%. Hence, the tolerance of the focal spot energy caused by ***d*** is 1-95.35%=4.65%.

It can be concluded that error from phase synchronization is $\sqrt{5.56\%^2 + 4.65\%^2}$ =7.25%.

4. EXPERIMENT OF SYNCHRONIZATION DIAGNOSTICS

In our experiment, a 10ps laser pulse is divided into two pulses. Reflection part is used as pulse A, and transmission part is pulse B. Distribution of the focal spot in experiment is showed in Fig.7. It is found that focal distribution of experiment is very similar with that of simulation as showed in Fig.4. And this diagnostics works well in coherent beam combination on ultrashort pulse. When temporal synchronization is realized, focus distribution is influenced by phase synchronization. Tiny fluctuation will change phase and focus distribution. It can also be found that encircled energy will not change. Energy is re-distributed only in neighbor area because of coherent condition. But the brightest spot is divided at different position with different phase. So phase fluctuation will change maximum intensity of the brightest spot. This phenomenon will be researched in the future.

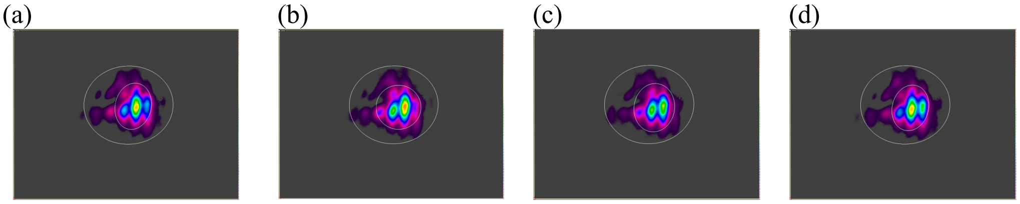


Fig.7 Distribution of the focal spot with phase difference in experiment: (a) in phase, (b) π/2 out of phase, (c) π out of phase, and (d) 3π/2 out of phase

5. CONCLUSION

A method is provided in this article to diagnose synchronization of ultrashort pulses. Theoretical simulation and experiment is taken on in case of two pulses. First, temporal synchronization is adjusted by temporal delay unit and monitored by a cross-correlation generator in the detector unit. Temporal resolution is 6.7fs when the cross-correlator or auto-correlator is in repetition mode with a fine travel stage. Error of temporal synchronization is 14%, which is mainly from detector unit. Second, phase synchronization is adjusted by phase delay unit and monitored by a far field interferogram in the detector unit. Phase resolution is 0.007π when a Soleil-Babinet compensator is used in phase synchronization. Error of phase synchronization is 7.25% after considering both parallel and perpendicular phase difference to the optical axis. Phase fluctuation will be researched in the future.

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