Single-Shot Measurement of Transient Phase Shift Induced by Laser Wake *

Jun Dong(董军), Zhong-Gui Lu(卢宗贵), Bo Zhang(张波), Zhi-Tao Peng(彭志涛)**, Zhi-Hong Sun(孙志红), Yan-Wen Xia(夏彦文), Hao-Yu Yuan(元浩宇), Jun Tang(唐军), De-Yan Zhu(朱德燕), Hua Liu(刘华), Jia-Kun Lv(吕嘉坤)

Research Center of Laser Fusion, China Academy of Engineering Physics, Mianyang 621900

(Received 2 December 2016)

Based on the frequency-to-time mapping relation of the linearly chirped pulse, the temporal phase shift induced by a laser-excited wake in a helium gas jet is measured using a chirped-pulse spectral interferometry with ~140 fs resolution over a temporal region of 1 ps in a single shot. In this measurement, the image of the wake is obtained with one-dimensional spatial resolution and temporal resolution limited only by the bandwidth and chirp of the pulse. The 'bubbles' feature of the wake structure, along with multiple wakes excited by the main lobe and the side lobe of a laser focal-spot, is captured simultaneously.

PACS: 42.25.Hz, 52.38.Kd, 41.75.Jv DOI: 10.1088/0256-307X/34/5/054204

In laser-plasmas interactions, the change in the electron density caused by an intense pump-pulse can lead to a change in the refractive index of plasmas. This change can be directly characterized by the probe-pulse amplitude and phase.[1,2] Hence, the ultrafast transient laser wake induced by the pump in the low-density plasma is often measured by spectral or frequency-domain interferometry (SI), which is a linear technique with a key advantage of weak laser pulse for probing.[3,4] An ultrashort probing pulse was required with a shorter duration than the duration of the wake oscillation in an early measuring work of SI for a laser wake. The temporal evolution of the laser wake is then retrieved via step-by-step scanning of the delay between the pump and probe pulses.[5−7] However, these multi-shot techniques cannot provide rapid or accurate feedback for optimizing experimental parameters which are an average over shot-to-shot variations of the laser-generated plasmas structure. The single-shot spectral interferometry (SSI) was developed and applied for real time measurement.[8−10] The advantage of SSI is that it makes single-shot measurement of optical phase shift with femtosecond resolution over time scales of picoseconds possibly.

In this Letter, the SSI technique and an imaging spectrometer are used for the spatio-temporal measurement of ultrafast phase shift induced by the laser wake created via the SILEX-I: Ti:sapphire laser at CAEP. Single-shot visualization of the laser-wake structure is demonstrated. The evolutions of multiple wake periods are captured.

The SSI scheme utilizes twin linearly chirped Gaussian pulses, $E(t)=E_0\exp(-at^2+i\omega_0 t)\exp(ibt^2)$, with the spectral bandwidth (full width at half maximum, FWHM) $\Delta\omega$ and group delay dispersion (GDD) $\beta_2=\frac{1}{2}[\partial^2\phi(\omega)/\partial\omega^2]_{\omega_0}$, to act as a reference pulse $E_{\rm r}(t)$ and a copropagating probe pulse $E_{\rm pr}(t)$ which is delayed by $\Delta\tau$. Here $b=\beta_2^{-1}[1+(2\ln 2)^2\beta_2^{-2}(\Delta\omega)^{-4}]^{-1}/4$ is the chirp parameter, $\varphi(\omega)$ is the spectral phase, ω_0 is the central frequency, and $a=2\ln 2\times\tau_{\rm chirp}^{-2}$ with $\tau_{\rm chirp}$ being the pulse-duration (FWHM).

After a temporal phase shift $\Delta\Phi(t)$ caused by wake perturbation is imposed on the probe pulse, in which the Taylor series expansion of $\Delta\Phi(t)$, neglecting higher order series, is $\Delta\Phi(t)=\phi_0+\phi_1 t+\phi_2 t^2$, the reference pulse $E_{\rm r}(t)$ and the perturbed probe pulse $E'_{\rm pr}(t)$ are sent to a spectrometer, and interfere in the frequency domain according to

$$I(\omega)=|A_{\rm r0}(\omega)|^2+|A_{\rm pr0}(\omega)|^2+2A_{\rm r0}(\omega)A_{\rm pr0}(\omega)\cdot\cos[\omega_0\Delta\tau+\Delta\varphi(\omega)], \quad (1)$$

where $E_{\rm r}(\omega)=A_{\rm r0}(\omega)e^{i\varphi_{\rm r}(\omega)}$ and $E'_{\rm pr}(\omega)=A_{\rm pr0}(\omega)e^{i\varphi_{\rm pr}(\omega)}$ are the Fourier transforms of $E_{\rm r}(t)$ and $E'_{\rm pr}(t)$, respectively, and $\Delta\varphi(\omega)=\varphi_{\rm pr}(\omega)-\varphi_{\rm r}(\omega)$ is the spectral phase difference between the perturbed probe and reference pulses.

The chirped probe pulse is temporally overlapped onto transient wake evolution, thus the varying phase shift $\Delta\Phi(t)$ is encoded onto the chirped pulse's frequency components. On the basis of the spectral interference, $\Delta\varphi(\omega)$ extracted from a spectral interferogram can be expressed as

$$\begin{aligned}\Delta\varphi(\omega)=&\frac{(b^2+b\phi_2-a^2)}{4(a^2+b^2)[a^2+(b+\phi_2)^2]}\phi_2(\omega-\omega_0)^2\\&+\frac{b+\phi_2}{4[a^2+(b+\phi_2)^2]}2\phi_1(\omega-\omega_0)\\&-\frac{b+\phi_2}{4[a^2+(b+\phi_2)^2]}\phi_1^2+\phi_0.\end{aligned} \quad (2)$$

Substituting the frequency sweep $(\omega-\omega_0)=2bt$ into Eq. (2), $\Delta\varphi(\omega)$ becomes

$$\begin{aligned}\Delta\varphi(\omega)=&\frac{(b^2+b\phi_2-a^2)b^2}{(a^2+b^2)[a^2+(b+\phi_2)^2]}[\phi_2 t^2]\\&+\frac{(b+\phi_2)b}{a^2+(b+\phi_2)^2}[\phi_1 t]+\phi_0\\&-\frac{b+\phi_2}{4[a^2+(b+\phi_2)^2]}\phi_1^2.\end{aligned} \quad (3)$$

*Supported by the National Natural Science Foundation of China under Grant No 61377102, and the Defense Industrial Technology Development Program under Grant No B1520133010.
**Corresponding author. Email: peng_zhitao@163.com

When the conditions

$$|\phi_2|/|b| \ll 1,$$
$$b^2 \gg a^2 \sim \beta_2^2 \Delta\omega^4 \gg 1 \tag{4}$$

could be satisfied, then a wake-induced phase shift $\Delta\Phi(t)$ can be obtained by the following formula

$$\Delta\Phi[t(\omega)] \approx \Delta\varphi[(\omega - \omega_0)/2b]. \tag{5}$$

Equations (4) and (5) indicate that utilizing the time-frequency relation of the linearly chirped pulse, the transient phase shift induced by the laser wake can be obtained through the one-to-one 'directly mapping' approach from frequency-domain to time domain.

With this method, the temporal resolution of extracted transient phase shift is determined by

$$\Delta t \geqslant (8 \ln 2\beta_2)^{1/2}\Big[1 + \frac{2}{\beta_2^2 \Delta\omega^4}\Big]^{1/2}. \tag{6}$$

Combining Eq. (4) with Eq. (6), the resolution is limited to

$$\Delta t \sim 2(\beta_2)^{1/2}. \tag{7}$$

Equations (4) and (7) indicate that a chirped probe pulse with large $\Delta\omega$ and small group delay dispersion β_2 can improve temporal resolution for transient measurement.

The experimental setup is shown in Fig. 1. The SILEX-I laser system produced 800 nm ultrashort ultraintense laser pulses by chirped-pulse amplification, using titanium-doped sapphire gain media. The uncompressed beam was split into pump and probe beams which were then independently compressed to 30 fs. In the experiment, the wake was excited by the focusing pump beam, and second-harmonic reference and probe pulses were generated in a common time-delayed line by type I phase matching of two 0.2 mm BBO crystals and a 13.39 mm delay-glass plate for effective separation between the pump pulse with the reference and probe pulses. Firstly, the 800 nm probe beam converted to 400 nm in a BBO crystal, and the remaining, nearly undepleted 800 and 400 nm pulses then passed through a delay-glass plate, in which they separated temporally by group-velocity dispersion. The temporally advanced 800 nm pulse converted in an identical BBO crystal, generating a second 400 nm pulse collinear with the first, and advanced in time by $\Delta\tau = 3$ ps. After these pulses recombined collinearly with the pump through a 59-mm-thick high reflector BS for 800 nm with high transmission at 400 nm, which chirped and stretched 400 nm pulses to ~1 ps duration by linear dispersion, all pulses were focused into a jet of helium gas through an off-axis parabola. The leading pulse (central wavelength $\lambda_{\rm ref} = 400$ nm) arrived at the jet before the pump, and acted as a reference. The trailing pulse (central wavelength $\lambda_{\rm pr} = 400$ nm) rode with the pump, overlapping its co-propagating wake and ionization front, which introduced temporal/spectral phase perturbation to it. By imaging the interaction plane onto the slit of an imaging spectrometer, two-dimensional single shot spectral interferogram of period $2\pi/\Delta\tau$ with one-dimensional spatial resolution could be read. Longitudinal phase perturbations along the wavelength axis and transverse spatial phase variations along the orthogonal (slit) axis were recorded simultaneously.

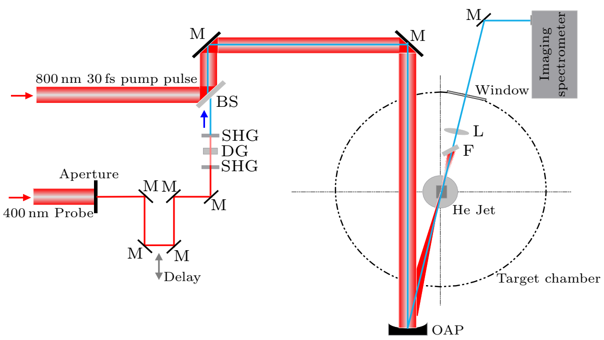

Fig. 1. Experimental setup, showing SHG: 0.2 mm BBO crystal, DG: delay glass plate with 13.39-mm thick, BS: beam-splitter and stretcher, OAP: off-axis parabola, He-jet: a jet of helium gas, F: filter with high reflection for 800 nm and high transmission at 400 nm, and L: imaging lens.

The time-dependent wake was generated by a 100 mJ, 800 nm, 30 fs pump pulse focused by an $f/8$ off-axis parabola into a supersonic He gas jet with a focal-spot region of $\sim$ 180 µm. The reference and probe chirped pulses were collinearly focused with the pump to an FWHM spot size of $\sim$ 450 µm overfilling the pump spot region. Thus a time/frequency- and space-dependent phase variation of the probe pulse was generated due to the pump-induced wake. The pump was removed from the beam path by a filter with a ~50-nm-bandwidth high reflectivity coating at 800 nm. The leaving reference and probe pulses were imaged with 9×magnification onto an imaging spectrometer slit, which produced a spectral interferogram on the spectrometer's focal plane CCD with one-dimensional (1D) space resolution along the slit.

Figure 2(a) shows that a complete two-dimensional frequency-domain interferogram was recorded by a CCD at the detection plane of an imaging spectrometer, which encoded temporal phase variations imposed on the probe by wake perturbations along the wavelength axis and transverse spatial variations along the orthogonal axis (slit). Figure 2(b) shows another 'null' spectral interferogram which was generated by an unperturbed probe pulse and a reference pulse.

Firstly, the Fourier-transform method of fringe-pattern analysis[11] was used to extract directly the spectral phase shifts $\Delta\varphi_1(\omega)$ and $\Delta\varphi_2(\omega)$ as indicated by Eq. (2) from interferograms in Figs. 2(a)and 2(b), respectively. Then the spectral phase shift $\Delta\varphi(\omega) = \Delta\varphi_1(\omega) - \Delta\varphi_2(\omega)$ induced by the wake was obtained. Compared with the inherent phase of the 1 ps chirped probe, the phase change of the probe introduced by the wake is a microscale, thus inequality $|\phi_2|/|b| \ll 1$ of Eq. (4) can be satisfied. The chirped phase $\varphi_{\rm pr}(\omega)$ and spectral bandwidth $\Delta\omega$ of the 400 nm probe were measured independently and respectively. In Fig. 2(b), $\beta_2 = 1/2[\partial^2\varphi_{\rm pr}(\omega)/\partial\omega^2] = 5.02 \times 10^3\,{\rm fs}^2$, and $\Delta\omega = 6.9 \times 10^{13}$ rad/s, thus inequality $\beta_2^2\Delta\omega^4 = 571 \gg 1$ of Eq. (4) can be satisfied as well. Hence, the 'directly mapping' approach of Eq. (5) can be used here. In Figs. 2(a) and 2(b), the wavelength coordinate can link to the time coordinate through $(\omega - \omega_0) = 2bt$ $(\omega = 2\pi c/\lambda)$, and the spectral phase shift $\Delta\varphi(\omega)$ induced by the laser wake directly mapped to transient phase shift $\Delta\Phi[t]$ by Eq. (5) with 140 fs temporal resolution. The results are illustrated in Figs. 2(c) and 2(d).

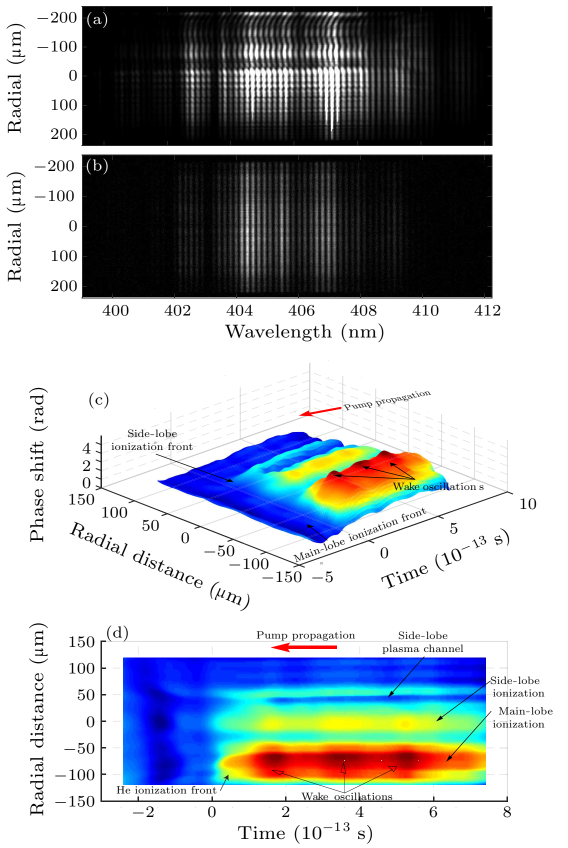

Fig. 2. (a) Recorded signal spectral interferogram by an imaging spectrometer with a pump. (b) Recorded null spectral interferogram by an imaging spectrometer without a pump. (c) The 3D probe phase shift produced by a $\sim$3 TW, 30 fs pump, electron density $\bar{n}_e = 4\times10^{17}\,\mathrm{cm}^{-3}$ in the main-lobe region of the focal-spot. (d) The 2D probe phase-shift image.

Figure 2(c) shows that the reconstructed three-dimensional image of the laser wake produced in a jet with a backing pressure of 130 kPa by the pump pulse of peak power $\sim$3 TW and vacuum-focused intensity $\sim 10^{17}\,\mathrm{Wcm}^{-2}$. In a wake 3D image, sharp ionization fronts were observed in the leading edge of the pump. Two transverse ionization steps He^+ respectively excited by the main lobe and side lobe of the focal-spot of the pump were identified by a sharp discontinuity in n_e at their boundary, where the pump intensity dropped to the field ionization threshold[12] ($\sim 10^{16}\,\mathrm{Wcm}^{-2}$) for He^+. As the wake oscillates at plasma frequency $\omega_p = (4\pi n_e q^2/\rho m_e)^{1/2}$ behind the pump, $T_{\rm wake} = 2\pi/\omega_p$ is expected,[13] where $\rho = (1 - \nu^2/c^2)^{1/2}$ is the relativistic Lorentz factor, and n_e, q, m_e and ν are the electron density, electron charge, rest mass, and oscillation velocity, respectively. In the ionization-region core of the main lobe, three periods of sinusoidal oscillations of wavelength $\lambda_p = 54\,\mu$m were clearly observed. These wake 'bubbles' had characteristics of a nearly flat wavefront. The plasma channel in the ionization-region of the side-lobe and the wake oscillations in the ionization-region of the main lobe are observed as well in the wake 2D image as illustrated in Fig. 2(d).

In conclusion, based on the frequency-to-time mapping relation of the linearly chirped pulse, single shot measurement of transient phase shift has been investigated theoretically. According to this method, we construct a single-shot transiently diagnostic technique at the SILEX-I: Ti:sapphire laser to capture 'bubble' structures of laser-induced wake with the time resolution in real time, which is an essential step towards controlling them.

References

[1] Zuo Y L, Wei X F, Zhou K N, Zen X M, Su J Q, Jiao Z H, Xie N and Wu Z H 2016 *Chin. Phys.* B **25** 035203
[2] Zhou L, Li X Y, Zhu W J, Wang J X and Tang C J 2016 *Acta Phys. Sin.* **65** 085201 (in Chinese)
[3] Marques J R, Geinder J P, Amiranoff F, Audebert P, Gauthier J C, Antonetti A and Grillon G 1996 *Phys. Rev. Lett.* **76** 3566
[4] Siders C W, Le Blanc S P, Fisher D, Tajima T and Downer M C 1996 *Phys. Rev. Lett.* **76** 3570
[5] Froehly C, Lacourt A and Viénot C J 1973 *Nouv. Rev. Optique* **4** 183
[6] Reynaud F, Salin F and Barthelemy A 1989 *Opt. Lett.* **14** 275
[7] Hideyuki K, Masaki K, Takatsugu O, Shinichi M, James K K, Shuji K, Shuhei K, Takashi Y, Toru M and Kazuhisa N 2002 *Phys. Plasmas* **9** 1392
[8] Chien C Y, La Fontaine B, Desparois A, Jiang Z, Johston T W, Kieffer J C, Pepin H and Vidal F 2000 *Opt. Lett.* **25** 578
[9] Geindre J P, Audebert P, Rebibo S and Gauthier J C 2001 *Opt. Lett.* **26** 1612
[10] Kim K Y, Alexeev I and Milchberg H M 2002 *Appl. Phys. Lett.* **81** 4124
[11] Takeda M, Ina H and Kobayashi S 1982 *J. Opt. Soc. Am.* **72** 156
[12] Augst S, Meyerhofer D D, Strickland D and Chin S L 1991 *J. Opt. Soc. Am.* B **8** 858
[13] Tajima T and Dawson J M 1979 *Phys. Rev. Lett.* **43** 267