Measurement of ultra-intense laser driven shock velocity by frequency domain interferometer using chirped pulse laser

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1. Introduction

Gbar shock waves have important applications for inertial confinement fusion and for studying matter under extreme conditions. In the fast ignition scheme inertial fusion, shock waves driven by ultra-intense lasers are one of candidates for the core heating. However, we have not yet know how much the pressure is driven by the ultra-intense lasers in the dense plasma. Velocity Interferometer System for Any Reflector (VISAR) has been widely used to measure the velocity of shock wave in material to estimate the pressure of shock compression [1]. The frequency domain interferometer with an ultra-short pulse laser can also characterize shock waves in femtosecond time scale [2]. The frequency domain interferometer with a chirped pulse laser provide a single-shot measurement of shock wave in picosecond time scale [3, 4].

To measure the shock wave velocity and pressure, we have developed a frequency domain interferometer using a part of the chirped pulse amplified (CPA) laser of 800 nm wavelength, which we call the probe beam. We irradiate the main part of the CPA laser to a solid zirconia plate and generate shock waves in the sample. By illuminating the probe beam from the rear surface, the frequency domain interferometer measure the motion and reflectivity of the rear surface. From the temporal change of the motion and reflectivity, we estimate the velocity of shock wave.

2. Frequency domain interferometer using a chirped pulse laser

We consider the spectral fringe generated by the interference of two Gaussian chirped pulses. The fields of the reference and the signal beams are represented by

$$E_r(t) = E_{r0} \exp(-\frac{t^2}{\tau^2}) \exp[i(\omega_0 + at)t] \qquad (1)$$

and

$$E_s(t) = E_{s0} \exp(-\frac{t_s^2}{\tau^2}) \exp[i(\omega_0 + at_s)t_s], \qquad (2)$$

respectively. The path-length deference of two beams are Δl. The signal beam is delayed compared with the reference beam, $t_s = t - \Delta l / c$. τ, ω_0, and a denote the pulse width, central angular frequency, and chirp rate, respectively. The spectral fringe is derived as

$$P(k) = P_r(k)[|E_{r0}|^2 + |E_{s0}|^2 + |E_{r0}E_{s0}|\cos(\Delta lk + \arg(E_{r0}E_{s0}))], \qquad (3)$$

Where k and $P_r(k)$ denote the wave number and the power spectrum of the reference light. The angular frequency of spectral fringe is $\Omega_{rest} = \Delta l$.

When the signal beam is reflected by a plane moving at the velocity of v, the pulse width, central angular frequency, and chirp rate are changed to $\tau' = \frac{c}{c-2nv}\tau$, $\omega_0' = \omega_0 \frac{c-2nv}{c}$, $a' = a(\frac{c-2nv}{c})^2$ due to Doppler shift, respectively. Delay time is also changed to $t_s' = t - \frac{2n\Delta l_0}{c-2nv}$.

The frequency of spectral fringe is changed to

$$\Omega_{move} = -2v \frac{a[4c(k-k_0) + 2ck_0]}{4\left[\left(\frac{1}{\tau}\right)^4 + a^2\right]} + \Delta l \approx -v \frac{ack_0}{\left[\left(\frac{1}{\tau}\right)^4 + a^2\right]} + \Delta l. \qquad (4)$$

The frequency change of spectral fringe is proportional to velocity of reflector.

Next we consider the case that the reflectance is temporally changing. The field of signal beams is represented by

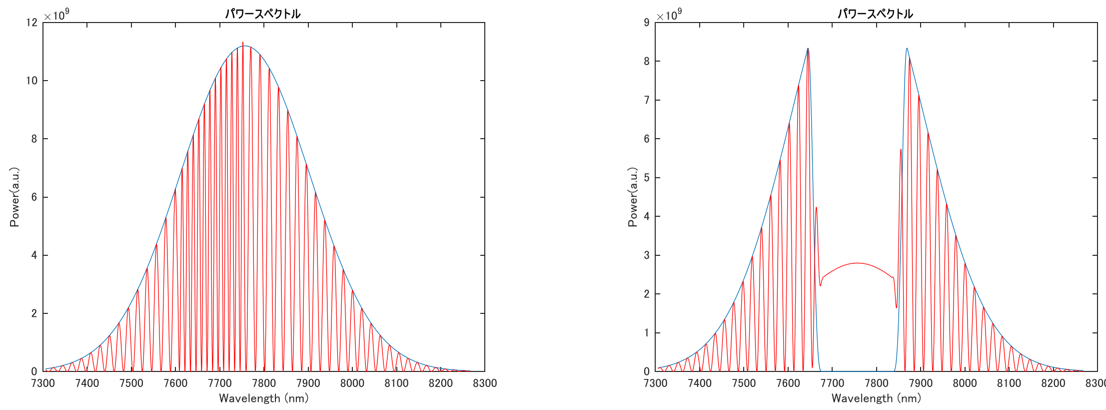
$$E_s(t) = E_{s0}(t) \exp(-\frac{t_s^2}{\tau^2}) \exp[i(\omega_0 + at_s)t_s]. \qquad (5)$$

We assume the reflectance is slowly changing compared with the chirp rate. We can derived the spectral fringe.

$$P(k) \approx P_r(k)\left[|E_{r0}|^2 + |E_{s0}|^2 + \frac{\pi}{a}\left|E_{r0}E_{s0}\left(\frac{k-k_0}{2a}\right)\right|\cos(\Delta lk + \arg(E_{r0}E_{s0}))\right]. \qquad (3)$$

The amplitude of the spectral fringe approximately corresponds to temporal profile of the reflectance.

Figures 1 show the numerically calculated power spectrum. We assume $\tau = 390ps$, $\lambda_0 = 810nm$, and $a = 25.6ps/nm$. Figure 1(a) show the case that the reflector is start to move at the velocity of 10^6cm/s and stop after 200ps. It is confirmed that the frequency of the spectral



(a) (b)

Fig. 1 Numerically calculated power spectrum.

fringe change due to the motion of the sample. In fig. 1(b), the signal beam vanish during 300ps. The spectral fringe is disappear in the corresponding spectral range.

3. Laser driven shock wave generation and shock velocity measurement

Figure 2 shows the experimental setup. A part of amplified chirped pulse is used as a probe beam. Main part of amplified chirped pulse is compressed and irradiate the sample from the front surface. The peak intensity and the pulse width of the main beam are $5x10^{16}$ W / cm^2 and 180 fs, respectively. The probe beam is illuminate to the rear surface of the sample via the optical delay line. The pulse width and the chirp rate of the probe beam are 640 ps and 25.6 ps /nm. The reflected light from the rear surface and the reference light are fed to the spectrometer and the spectral fringes are recorded.

Figure 3(a) shows spectral fringes. The top interferogram is recorded 10s before the laser irradiation and the middle one 400ps after the laser irradiation, and the bottom one 10 s after the laser irradiation. The horizontal axis denotes the wavelength and the vertical axis corresponds to the position of the sample. In the interferogram before the laser irradiation, the fringes curves due to the surface profile of the sample. The spectral fringes of the middle interferogram differ from the top and bottom interferograms around x position of 320 where the main beam was irradiated. Figure 3(b) shows the intensity profile along the x position of 300 and 320. The horizontal axis denotes the elapsed

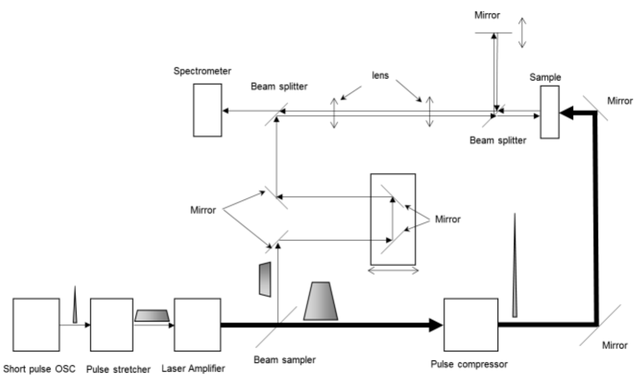
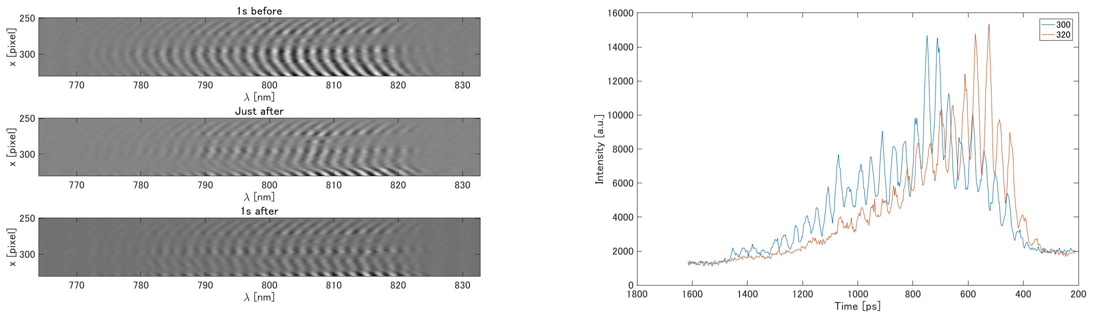


Fig. 2 A schematic diagram of the experimental setup



(a) (b)

Fig. 3 spectral fringes measured using frequency domain interferometer using chirped pulse laser

time from the laser irradiation which is calculated from the delay time and the chirp rate of the probe beam. The intensity profile along the x position of 300 does not change before and after the laser irradiation. The frequency of the fringes along the x position of 320 is changed by the influence of the laser irradiation, which indicates that the rear surface is moving. We confirmed that frequency change occurs immediately after the laser irradiation by changing the delay of the probe beam. We think the movement of the rear surface results from the fast electron. 1100ps after the laser irradiation, the fringes along the x position of 320 disappears. We think it is attributed to the shock wave. By arriving the shock wave at the rear surface, reflectivity of the rear surface is significantly reduces. Considered that1100ns after the laser irradiation the shock wave arrived at rear surface of sample with the thickness of 150 μm, the mean velocity of the shock wave is estimated to be 1.37x10^7 cm/s. If the rear surface is broken before arriving the shock wave, the mean velocity is less than the estimated speed.

4 Summary

We developed a frequency domain interferometer using a part of the chirped pulse amplified (CPA) laser to measure the shock wave velocity. By illuminating the probe beam from the rear surface, we observe the motion and reflectivity of the rear surface. We find that the interference fringes disappear 1100ns after the laser irradiation. Considered that the shock wave arrived at rear surface at this time, the mean velocity of the shock wave is estimated to be 1.37x10^7 cm/s.

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