

Improved Resolution and Stability in a Dispersion Interferometer Using a Modulation Amplitude Ratio

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A dispersion interferometer is immune to mechanical vibrations, which is a great advantage for application to steady-state fusion reactors. This paper describes the performance of a phase-modulated dispersion interferometer with a new phase extraction method using a modulation amplitude ratio.

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On steady-state fusion reactors, reliable electron density measurement is required for fueling control. However, the signal-to-noise ratio (S/N) of conventional interferometers is affected by mechanical vibrations. In addition, fringe jump errors are possible at high densities. One possible approach to these problems is the use of a dispersion interferometer (DI) [1]. The DI is immune to mechanical vibrations, and hence does not need a vibration isolator. A two-color system is also not needed even if short-wavelength lasers (a CO₂ laser and a YAG laser, for example) are used. The fringe jump errors are attributed to 2π ambiguity in the phase shift. If short-wavelength laser light with a phase shift smaller than 2π is selected, the interferometer becomes free from fringe jump errors in principle. However, the S/N is significantly degraded because the phase shift due to vibrations ($\propto 1/\lambda$, λ: wavelength) increases and that due to a plasma ($\propto \lambda$) decreases for conventional interferometers. In contrast, the DI has no issue even if the plasma term is smaller than 2π owing to its immunity to vibrations. Thus, the DI becomes free from fringe jump errors if an appropriate wavelength is selected.

Techniques that improve the resolution of DIs are currently being introduced [2–5]. This paper reports improved resolution and long-time stability in a DI that adopts phase modulation [2] with a photoelastic modulator (PEM) and a new signal processing method that uses a modulation amplitude ratio [4, 5]. Figure 1 shows a schematic view of the present optical and electrical systems used for bench testing. The light source is a CO₂ laser with an output power and wavelength of 8 W and 10.6 μm, respectively. The focused laser light is injected into a nonlinear crystal of AgGaSe₂ to generate the frequency-doubled component (FD1). A mixed beam consisting of the fundamental and frequency-doubled components, whose polarizations are orthogonal, passes through a PEM with a drive frequency

of ω_m to add phase modulation only for the frequency-doubled component. The probe beam then passes through a zinc selenide plate, which simulates the plasma. The following nonlinear crystal generates a frequency-doubled component (FD2) again from the fundamental component. The remaining fundamental component is cut with a sapphire plate, and the interference signal *I* between the two frequency-doubled components is detected. The phases of FD1 and FD2 are shown below,

$$\begin{aligned} \text{phase of FD1} &: 2\omega t + 2\omega\Delta d/c + c_p\bar{n}_e L/(2\omega) + \phi_1, \\ \text{phase of FD2} &: 2(\omega t + \omega\Delta d/c + c_p\bar{n}_e L/\omega + \phi_2), \end{aligned} \quad (1)$$

where $c_p = e^2 2\epsilon_0 m_e c$, ω: angular frequency of the laser light, Δ*d*: change of the optical path length due to vibrations, *c*: light speed, *e*: charge of the electron, ε₀: dielectric constant, *m_e*: mass of the electron, \bar{n}_e : line averaged electron density, *L*: path length in a plasma, and φ₁, φ₂: initial phase.

The phase of the detected interference signal *I* is difference between phases above. Because the phase terms resulting from vibrations, 2ωΔ*d*/*c*, are common, as shown

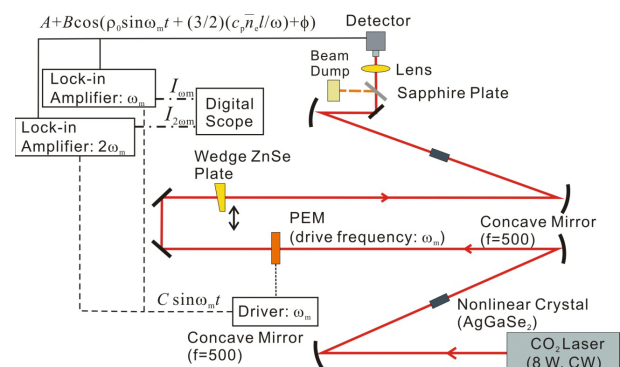


Fig. 1 Optical and electronic systems for bench testing of a dispersion interferometer.

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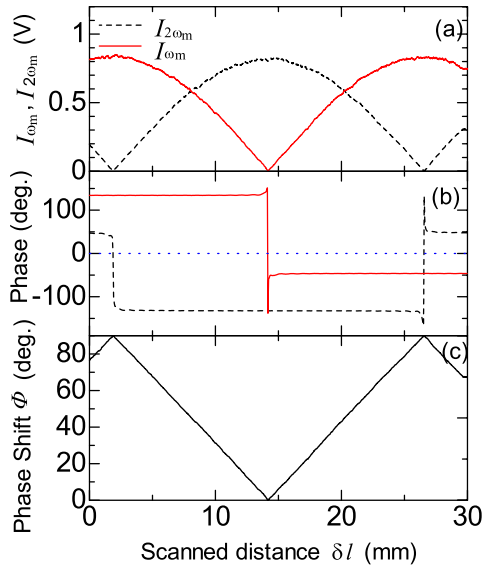


Fig. 2 Scan of a ZnSe plate. (a) Modulation amplitudes of the fundamental (50 kHz) and the second harmonic (100 kHz) of the drive frequency of the PEM. (b) Phases between reference and modulation signals. (c) Phase shift evaluated with Eq. (3) from modulation amplitudes in (a).

in Eq. (1), the vibration term is canceled optically, and the phase shift due to a plasma remains [1]. The interference single I is

$$I = A + B \cos\left(\rho_0 \sin \omega_m t + \frac{3}{2} \frac{c_p \bar{n}_e L}{\omega} + \phi\right), \quad (2)$$

where $A = I_1 + I_2$, $B = 2\sqrt{I_1 I_2}$, I_1, I_2 : intensities of frequency-doubled components, ρ_0 : maximum retardation, and $\phi = \phi_2 - \phi_1$: initial phase.

The detected signal is fed into two lock-in amplifiers with reference frequencies of ω_m and $2\omega_m$, respectively. From the ratio of the modulation amplitudes of the fundamental $I_{\omega_m} \propto \sin(3c_p \bar{n}_e L / 2\omega + \phi)$ and the second harmonic $I_{2\omega_m} \propto \cos(3c_p \bar{n}_e L / 2\omega + \phi)$ of I , the line-integrated density can be evaluated as

$$\bar{n}_e L = \frac{2}{3} \frac{\omega}{c_p} \tan^{-1}(I_{\omega_m} / I_{2\omega_m}). \quad (3)$$

In the previous optical system, which adopted an optical configuration with a back and forth beam, a small fraction of the return beam to the laser caused significant instabilities in laser oscillation [5]. Hence, the system is changed to the configuration with a one-way beam not the laser beam to go back. As a result, the instability problems of the laser are completely resolved, and the resolution and long-time stability are improved, as discussed below.

To simulate the phase shift due to a plasma, a zinc selenide plate with a wedge angle of 0.25 ± 0.05 deg is scanned by δl perpendicularly to the beam path. As shown in Fig. 2 (a), the amplitudes of I_{ω_m} and $I_{2\omega_m}$ change. The wedge angle evaluated from the gradient of the evaluated

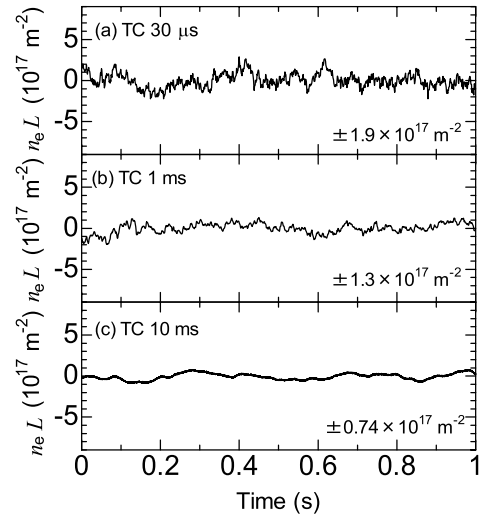


Fig. 3 Variation in baseline with several time constants of lock-in amplifier.

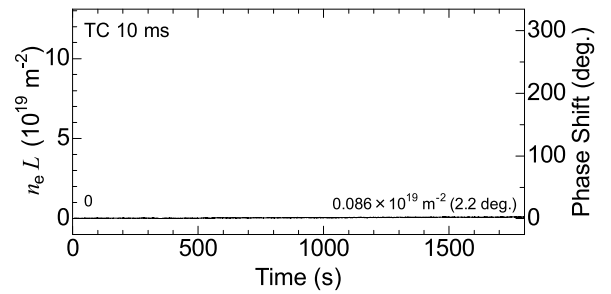


Fig. 4 Baseline of line-integrated density with a time constant of 10 ms for 30 min.

phase shift (Fig. 2 (c)) is 0.24 deg, which agrees well with the actual angle. Because the phases between the reference and modulation amplitudes change by π as shown in Fig. 2 (b), the dynamic range of the phase shift without phase ambiguity becomes 2π when the phase signals are used in addition to the amplitudes. This method is similar to quadrature detection. For a CO_2 laser, a phase shift of 2π corresponds to a line-integrated density of $1.4 \times 10^{20} \text{ m}^{-2}$.

Variations in the baseline with time constants (TCs) of the lock-in amplifier of 30 μs , 1 ms, and 10 ms are shown in Figs. 3 (a)–(c). The TC required for line-averaged density measurement on ITER is 1 ms. Typically, the width of the variations is approximately $\pm 1 \times 10^{17} \text{ m}^{-2}$ with a TC of 1 ms for 1 s. Even when the TC is 30 μs , the typical variation in the baseline is approximately $\pm 2 \times 10^{17} \text{ m}^{-2}$. Because the typical time constant of the density increase by a pellet injection is about 1 ms, a time constant of 30 μs is sufficient for density monitoring of this rapid phenomenon. The noise frequencies are mostly less than 100 Hz. In the previous configuration, phase noise with the same frequency as the modulation of the laser cavity length (510 Hz) was significant. This is because the return

beam enhanced the cavity modulation. The phase noise almost disappears in the new configuration. For faster measurement, with a TC of $10\mu\text{s}$, the S/N becomes five times worse than that with a TC of $30\mu\text{s}$.

Considering the large helical device (LHD), ITER, and future DEMO reactors, which aim for steady-state operation, density measurement should be stable for a long period. Figure 4 shows a long-time measurement of 30 min. The baseline drifted by about $9 \times 10^{17} \text{ m}^{-2}$ with a TC of 10 ms. Although the cause of the drift is not clear yet, one candidate is the change in room temperature. Because the nonlinear crystal is only air cooled with fans, a slight change in the room temperature will cause a change in its refractive index, which could cause the drift in the detected phase. Active control of the temperature of the air or the nonlinear crystal might improve the long-time stability.

In conclusion, we modified the optical configuration of a phase-modulated DI with a PEM. We suppressed a variation of the line-integrated electron density to $\pm 1 \times 10^{17} \text{ m}^{-2}$ with a TC of 1 ms. The variation in the base-

line is reduced to within approximately $9 \times 10^{17} \text{ m}^{-2}$ for 30 min.

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