Electron density measurement for plasmas by Terahertz time-domain spectroscopy

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Abstract. A new plasma diagnostic tool of terahertz time-domain spectroscopy (THz-TDS) has been developed. The THz-TDS system allows one to obtain the electron density and collision frequency of a plasma simultaneously from the phase shift and absorption rate of THz waves that are transmitted through the plasma. The line-averaged electron densities of Ar inductively coupled plasmas (ICPs) and CH₄/Ar capacitively coupled plasmas (CCPs) were evaluated by the system and found to be 10¹⁷-10¹⁸ m⁻³ for Ar ICPs and 10¹⁵-10¹⁶ m⁻³ for CH₄/Ar CCPs, depending on the discharge conditions. These results have demonstrated the feasibility of electron density measurements by THz-TDS for reactive plasmas.

1. Introduction

Terahertz time-domain spectroscopy (THz-TDS) has been applied to the measurement of electron densities in steady-state inductively coupled plasmas (ICPs) and capacitively coupled plasmas (CCPs). The ultimate goal of this study is to develop a new electron density diagnostic system that is appropriate for high-density plasmas, to which commonly used Langmuir probe or microwave interferometry techniques for plasma density measurement cannot be applied. Especially of our interest is to apply THz-TDS to low-gas-temperature atmospheric-pressure plasmas, which have recently employed for a wide range of applications in nonconventional plasma processing (For example, [1].)

Since plasma frequencies of high-density plasmas may lie in a sub THz region, the electron density and the collision frequency in such a plasma can be estimated from the phase shift and the transmissivity of THz waves that is transmitted through the plasma. In THz-TDS, both absorption and phase spectra of THz waves are obtained from Fast Fourier transformation of the time-dependent signals of an electromagnetic (EM) wave that is transmitted through a medium. Jamison et al. estimated time dependent electron densities and collision frequencies of transient pulsed helium discharges by THz-TDS [2]. In our study, on the other hand, we have demonstrated for the first time that THz-TDS can be applied also to the electron density measurement of steady-state discharges generated by inductively coupled plasma (ICP) or capacitively coupled plasma (CCP) systems.
The phase of an electromagnetic wave shifts when it passes through a plasma. The phase shift of a THz wave passing through a plasma may be evaluated from the following expression:

\[
\Delta \Phi = \frac{\omega L}{c} \left( 1 - \left( 1 - \frac{\omega^2}{\omega_p^2 + \nu^2} \right)^{\frac{1}{2}} \right)
\]

with \( \omega_p = \left( \frac{n_e e^2}{\varepsilon_0 m_e} \right) \),

where \( \omega \) is the frequency of the THz wave, \( L \) is the length of the plasma that transmits the THz wave, \( \omega_p \) is the electron plasma frequency, \( n_e \) is the electron number density and \( m_e \) is the electron mass. Equation (1) shows that the electron density of a plasma averaged along the light path length can be estimated from the phase shift obtained by the transmission measurement of a THz wave. In THz-TDS, the electron density can be obtained without the information on the electron temperature unlike the probe method.

2. Experimental apparatus

2.1. Terahertz time-domain spectroscopy (THz-TDS)

We have used a THz-TDS system at Institute of Laser Engineering of Osaka University [3]. A schematic layout of the THz-TDS system used in this study is shown in figure 1. A laser beam emitted from the femtosecond laser (Tsunami, New Port/ Spectra Physics Inc.) is polarized by a half-wave plate and split by a beam splitter into the pump beam and the probe beam. Average power of the pump beam at the emitter is reduced to 12mW by a variable neutral density (ND) filter. The probe beam is then delayed by an optical time delay mirror and reaches the detector. The pump beam is focused to the gap of a dipole-type photoconductive antenna, which is installed on the emitter and biased at a 60 V (peak-to-peak) 10 kHz alternating voltage. THz waves radiated from the emitter are collimated to an about 1 inch diameter and directed to the plasma chamber by an off-axis parabolic mirror. THz waves passing through the plasma chamber are then directed to the detector by another off-axis parabolic mirror. When the THz wave and the pump beam arrive at the detector simultaneously, the magnitude of the instantaneous electric field of the THz wave is recorded.

![Figure 1. The schematic layout of THz time-domain spectroscopic system.](image_url)
13.56 MHz radio frequency (RF) power is applied to the electrode of each system through an impedance matching network. The plasma chamber is set in an aluminium box that prevents RF noise generated by the plasma formation system from affecting the measurement system. The polyethylene windows or the high resistivity Si windows, through which THz waves can pass with little loss, are attached to the both ends of the plasma chamber.

3. Experimental results

The electron densities of Ar ICP plasmas and CH$_4$/Ar CCP plasmas have been measured by the THz-TDS system described above. The operating pressures were 25 Pa and 100 Pa and the operating power was in the range from 20 W to 100 W for Ar ICP plasma. Figure 4 shows the phase shift of a THz wave pulse transmitted into an Ar ICP plasma at 25 Pa and 40 W. The phase shift of the THz wave was evaluated from the difference between the phases of THz wave transmitted into the plasma and that into the gas (without a plasma). The electron densities of the Ar ICP plasmas were estimated by fitting the equation (1) to the phase shift, as shown in figure 4. The line averaged electron densities of the Ar ICP plasmas for different RF powers at 25 Pa and 100 Pa are plotted in figure 5. Since it is expected that the collision frequency $\nu$ is lower than the THz wave frequency $\omega$ for the Ar ICP plasmas, $\nu$ was neglected when equation (1) was used for fitting. The plasma length $L$ in equation (1) was assumed to be 40 mm, which was consistent with the independently performed density distribution measurement by a Langmuir probe [4]. Since the measurement error of the phase shift per se in a typical THz-TDS system is less than 1%, the main source of electron-density measurement errors is the uncertainty of the plasma length $L$, as easily seen in equation (1). Although the error bars are not given in figure 5, it should be construed that the (line averaged) electron density given in figure 5 may contain errors of about ±10% arising from the difficulty of evaluating the plasma length $L$ exactly.

The phase shift of THz pulses that are transmitted into a CH$_4$/Ar CCP plasma is shown in figure 6. CH$_4$/Ar CCP plasmas were generated with the flow rates of 6 sccm for CH$_4$ and 12 sccm for Ar at the total pressure of 28 Pa. The RF input power was 100 W. The plasma length $L$ in equation (1) was estimated to be about 180 mm. The electron density obtained from the phase shift given in figure 6 is $4.4 \times 10^{15}$ m$^{-3}$ [5].

4. Conclusions

THz-TDS has been applied to the measurements of electron densities of Ar ICP plasmas and CH$_4$/Ar CCP plasmas. Unlike probe measurement, THz-TDS is a non-intrusive method for electron density measurement. Compared with microwave interferometry, which is another non-intrusive method for electron density measurement in plasmas, THz-TDS uses much higher frequencies and shorter
wavelengths. This suggests that THz-TDS is a useful non-intrusive method for electron density measurement for high-density small plasmas.

**Figure 4.** Phase shift of THz pulses through an Ar ICP plasma at 25Pa and 40W.

**Figure 5.** Electron densities of Ar ICP plasmas measured by THz-TDS as function of RF power at 25Pa and 100Pa.

**Figure 6.** Phase shift of THz pulses through a CH$_4$/Ar CCP plasma.

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