Diode-laser heterodyne interferometer for measurement of electron and gas number densities in microplasmas

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1. Introduction

“Microplasmas” are small-scale (below mm) plasmas generally generated near and at atmospheric pressures, which have been widely applied to such material and biomedical processes in recent years. [1] Measurement of electron density and gas temperature in the microplasmas is very important to understand and control these plasmas for further improvement of their fundamental and application studies.

Measurement of electron density in microplasmas
- Laser Thomson scattering spectroscopy [2]
- Measurement of Stark broadening in hydrogen atomic emission [3]
- CO2 laser heterodyne interferometry [4]
- Millimeter-wave transmission measurement (microplasma arrays) [5]

Measurement of gas temperature in microplasmas
- Rotational distribution of molecular (nitrogen...) emission (Raman scattering, Laser induced fluorescence spectroscopy)
- Doppler broadening in laser absorption spectroscopy

In this study, we tried to measure these parameters using near-infrared (NIR) diode-laser heterodyne interferometer.

Heterodyne interferometer measures temporal change of refractive index in the plasmas including information of both electron density and gas temperature, and it can measure without any attention to gas species. The NIR interferometer is being developed for diagnostics of microplasmas generated in pressures (densities) higher than atmospheric air.

References:

2. Laser heterodyne interferometer

Conditions of gas pressure and electron density in phase shift measurement for electron density diagnostics

Refractive index of plasma $N$ is written by the Drude model as following:

$$N^2 = 1 - \frac{1}{1 + \frac{\lambda_{\text{Dr}}}{\lambda}}$$

where $\lambda$ is the probing light frequency, $\lambda_{\text{Dr}}$ is the electron collision frequency. In further calculation of the interferometer theory, there is a assumption that $\lambda_{\text{Dr}}$ can be ignored ($\lambda \gg \lambda_{\text{Dr}}$). Therefore, we need to consider the $\lambda_{\text{Dr}}$ assumption when we choose the probing light frequency especially high-pressure plasma sources. (Fig. 1)

Also, for the electron density measurement, we usually simplify the relationship between phase shift of probing light and electron density as follows [8]

$$\Delta \theta_{\text{electron}} = \int \frac{k_B T_{\text{plasma}}}{k_B T_{\text{gas}}} \frac{\lambda^2}{4 \pi c} \frac{1}{l} rd\lambda$$

where $k_B$ and $l$ are the wavenumbers, $c$ is the speed of light, and $l$ is the length of plasma along the laser path. Here, we use an approximate expansion assuming a condition of $\lambda \gg \lambda_{\text{Dr}}$. Therefore, we need to consider the limitation of electron density of tested plasma source as shown in Fig. 2.

For atmospheric and higher pressure plasmas, we have high measurement electron density over $10^8$ cm$^{-3}$, near-IR range is appropriate.

3. Experiments

3.1. Diode-laser heterodyne interferometer

- Diode-laser wavelength: 981 nm
- Bandwidth of laser freq.: <1 MHz (1 ms)
- Detector: Si amplifiers, <100 MHz
- AOM modulation freq.: 110 MHz
- Bandwidth of phase measurement module: <10 MHz
- Response delay of phase measurement module: <150 ns

Pulsed DC microplasma

- Pulse modulation: 500 Hz, duty 5%
- Current in steady state: 250 mA
- Gas flow: Argon, 10 sccm

Gas temperature increase

- When the DC discharge is ignited, the phase rapidly decreased and becomes steady state. It goes back to zero after the current pulse is stopped.
- The phase change in this range can be categorized into the gas temperature component due to the change of gas number density as following [9]
- From the phase shift at 27.5 degree, the peak gas temperature in the plasma is calculated at $T_{\text{gas}} \approx 507 K$.

4. Conclusions

- We chose near-infrared 890 nm of the laser wavelength in heterodyne interferometer constructed for refractive index measurement of microplasmas generated at atmospheric and higher pressures for the diagnostics of electron density and gas temperature variations.
- From the experimental results of pulsed DC discharge measurement, temporal resolution of our NIR laser heterodyne interferometer is ~100 ns, and the phase resolution is ~0.5 degree at this moment.
- Now, it can be utilized to fast sensitive gas-density measurement for diagnostics of microplasmas such as plasma actuators and electron density measurement in relatively high power discharge over $10^8$ cm$^{-3}$.

References:

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Fig. 1: Relationship between probing light wavelength (frequency) and measurable range of argon gas pressure for laser heterodyne interferometer: Electron collision frequency $\lambda_{\text{Dr}}$ was calculated using a coefficient shown in [8].

Fig. 2: Relationship between probing light wavelength (frequency) and measurable range of electron density for laser heterodyne interferometer. Phase shift by electron density is calculated with an assumption of 1 mm plasma length along the laser path. (7)

Fig. 3: Experimental setup of NIR diode-lase heterodyne interferometer. AOM is acousto-optical modulator.

Fig. 4: Schematic and photographs of pulsed DC discharge microplasma operated in atmospheric-pressure argon gas flow in ambient air.

Fig. 5: Temporal evolutions of phase shift and discharge current measured by NIR interferometer. Lower figure is enlarged graph around discharge ignition to investigate electron-density signal.