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Research note

Comparison of coherent forward scattering and atomic absorption profiles of O I 844.6-nm and Ar I 842.5-nm lines in the pulsed and continuous radio-frequency glow-discharge plasmas

Hideyuki Matsuta

Institute for Materials Research, Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai 980-8577, Japan

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ABSTRACT

Comparison of the coherent forward scattering (CFS) and atomic absorption (AA) of the O I 844.6- nm and Ar I 842.5 -nm lines was performed in pulsed and continuous radio-frequency glow discharge (GD) plasma. Zeeman splitting of the conventional AA spectra and the self-absorption profile of CFS radiation could be observed for different magnetic fields, above ~50 and ~10 mT, respectively. The calculation of the axial variation of the magnetic field of the GD tube and the magnetic field determined by the measured Zeeman splitting allowed us to determine the locations of the highest and the second highest relative maximum of the number density of excited argon atoms in the lower state of the Ar I 842.5-nm transition.

1. Introduction

The coherent forward scattering (CFS) spectra of the O I 844.6-nm and Ar I 842.5-nm lines in continuous radio-frequency (RF) glow-discharge (GD) plasma have been recorded by a CFS spectrometer in Faraday configuration with permanent double ring magnets and a diode laser source [1,2]. Previous works [1–3] suggested that the excited oxygen and argon atoms showing CFS for the O I 844.6-nm and Ar I 842.5-nm lines are produced by an internal conversion of each metastable oxygen and argon atom via collision with electrons or plasma gas particles and a subsequent non-radiative process similar to quenching in RF-GD plasma [1,3]. Note that the lower level of the measured excited atom is the resonant state connected to the ground state. Collisions of a large number of low-energy (thermalized) electrons and plasma gas particles might be involved in the conversion of the metastable atom to the resonant state-excited atom [3]. In previous research, CFS signals have been recorded with a combination of a chopped probe light beam and a lock-in amplifier [1] (hereinafter referred to as the “continuous RF mode”), to observe CFS of the excited atoms produced by the collisions of both electrons and plasma gas particles with the metastable atoms. If a pulsed RF-GD plasma is adopted, the electron number density is largely modulated, whereas the particle (neutral + ionized plasma gas) remains almost unchanged. Consequently, the contribution of the electron collisions to the CFS signals could be selectively measured by phase-sensitive detection (hereinafter referred to as the “pulsed RF mode”). In this study, a comparison of the CFS and atomic absorption (AA) profiles of the O I 844.6-nm and Ar I 842.5-nm lines in the pulsed and continuous RF-GD plasmas was conducted. In addition, on the basis of the Zeeman splitting of the observed atom profiles and the calculated axial variation of the magnetic field of the GD tube, the locations of the highest and the second highest number density of excited argon atoms in the lower state of the Ar I 842.5-nm transition in the pulsed RF mode were determined.

2. Experimental

In previous research [1], the CFS and AA spectra of the O I 844.6-nm and Ar I 842.5-nm lines in the continuous RF mode are measured by a CFS spectrometer in Faraday configuration with permanent double ring magnets. The experimental layout and details for the continuous RF mode were provided in Figs. 1 and 2 and Table 1 of a previous study [1]. The inter-magnet spacing was 90 mm.

The experimental layout for the pulsed RF mode is shown in Fig. 1. A 13.56 MHz RF power of 5–40 W was supplied to the ring electrode to produce the GD. The pulse repetition rate of the RF was 2–5 kHz. The argon pressure was 2 Torr (266 Pa), and the oxygen pressure was 0.2 Torr (27 Pa). The relatively low O_2 pressure compared with that of Ar was adopted because an increase in the oxygen pressure resulted in the reduction of the O I 844.6-nm CFS and AA signals. In the absorption measurements, the AA signal was obtained with the parallel polarizer setting of the CFS spectrometer [4], whereas the AA signals appeared as self-absorption of the CFS radiation was recorded with the crossed

E-mail address: matsuta@imr.tohoku.ac.jp.

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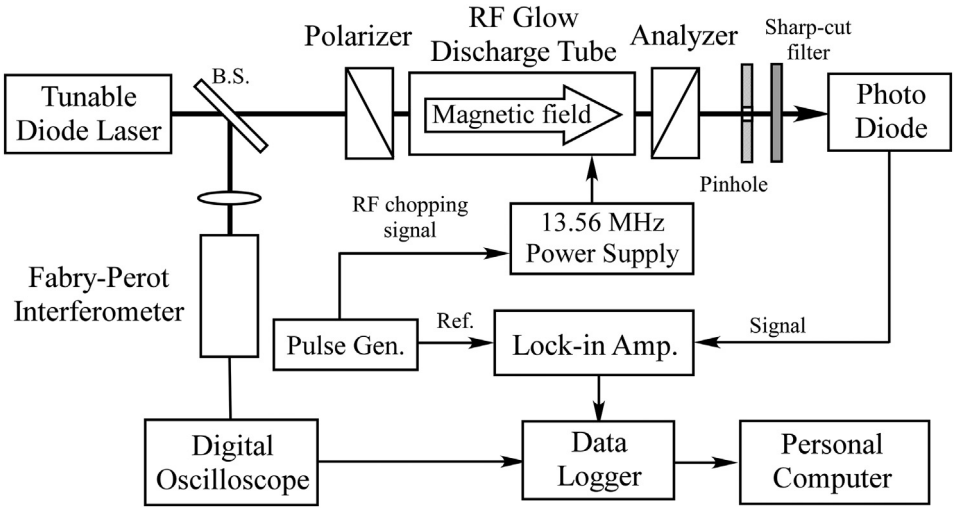

Fig. 1. Schematic of the experimental setup for the pulsed RF mode.

polarizer setting. Emission spectra were measured using an optical fiber-fed spectrograph [5].

3. Results and discussion

3.1. O I 844.6-nm AA and CFS radiation self-absorption spectra in the pulsed RF mode

The AA and CFS spectra of *the* O I 844.6-nm line were measured in pulsed RF mode as shown in Fig. 2. Because the absolute lasing frequency of the diode laser could not be measured in this study, the relative frequency was used. The oxygen pressure was 0.2 Torr (27 Pa). The RF power was set at 40 W (reading value of the directional wattmeter), and the pulse repetition rate of the RF was 2 kHz. In the CFS spectrum, the AA profile appeared as self-absorption of the CFS radiation, and a Zeeman splitting of ~500 MHz was observed on it, whereas no Zeeman splitting was observed for the conventional AA spectrum, for which a linearly polarized light source was used. To explain the different appearance of the two O I 844.6-nm spectra, simulation of the absorption profile was performed for linearly polarized and CFS radiation. Fig. 3 shows that the linearly polarized radiation equals the sum of left-handed (σ^+) and right-handed (σ^-) circularly polarized ones. The CFS radiation is assumed to consist of left-handed circularly polarized radiation at high off-resonance frequencies and of right-handed circularly polarized radiation for low ones. Furthermore, the polarization state of CFS radiation is assumed to change clearly at zero off-resonance frequency. In this simulation, the σ^+ and σ^- profiles were calculated by using the imaginary part of the plasma dispersion function because it corresponds to the Voigt absorption profile [6]. Detailed calculations of the plasma dispersion function, and the used parameters, e.g., temperature, Doppler-broadening parameter, Lorentzian width of the upper state, and Larmor frequencies, have been described in previous research [2]. The number density of the excited atoms giving the O I 844.6-nm line is assumed to be high at the region near the ring RF electrode of the discharge tube (see Fig. 8; magnetic field: ~10 mT), and the AA occurs mainly at this region. Zeeman splitting of both σ^+ and σ^- lines at 10 mT, ± ~250 MHz in off-resonance frequency $(\omega - \omega_0)/2\pi$ (ω_0: resonance frequency (rad/s) of the atom, ω: lasing frequency). When the σ^+ and σ^- profiles are simply superimposed as shown in Fig. 3(a), no Zeeman splitting peaks appear on the calculated AA profile. But when the σ^+ and σ^- Zeeman components absorb the CFS radiation, a ± ~250 MHz Zeeman splitting similar to the observed self-absorption profile can be reproduced as shown in Fig. 3(b).

In the previous papers, when adopting the continuous RF mode, no Zeeman splitting was observed on the self-absorption profile of the CFS radiation (see Fig. 7 of Ref. [1] and Fig. 2 of Ref. [2]). This discrepancy might be explained as follows: The excited atoms in the lower state of

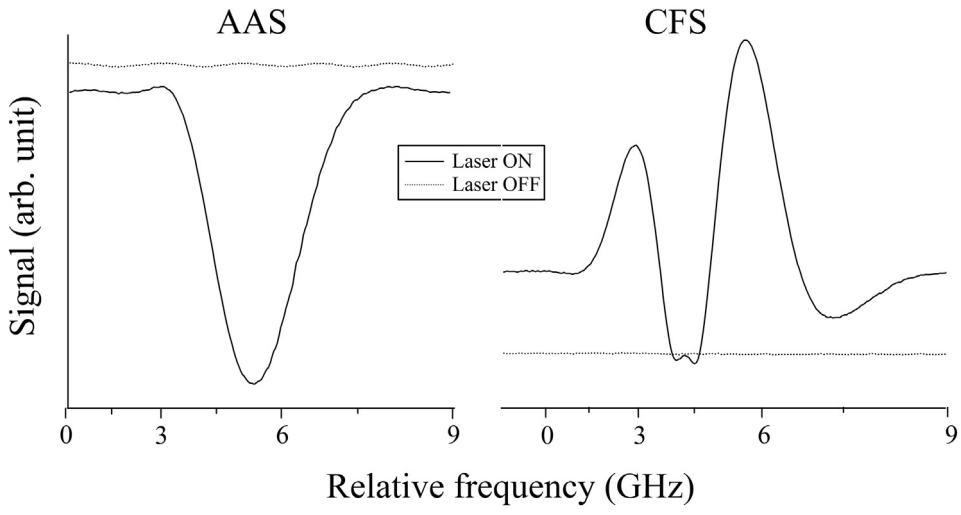

Fig. 2. AA and CFS spectra of O I 844.6-nm line in the pulsed RF mode. O_2 pressure: 0.2 Torr (27 Pa), RF power: 40 W, and pulse repetition rate: 2 kHz.