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Accuracy evaluation of atomic oxygen number density measurement by high sensitive laser absorption spectroscopy using microwave discharge oxygen plasma

マイクロ波酸素プラズマを用いた高感度レーザー吸収分光法における酸素原子数密度測定の精度評価

Ryo Morita, Makoto Matsui

森田　陵, 松井　信

Shizuoka University

3-5-1, Johoku, Naka-ku, Hamamatsu, Shizuoka prefecture 432-8561, Japan

静岡大学　〒432-8561　静岡県浜松市中区城北3-5-1

Laser absorption spectroscopy (LAS) using a forbidden line enables the ground state atomic oxygen number density measurement with a visible diode laser. However its small transition probability requires more than four orders of magnitude higher sensitivity than conventional LAS. For this purpose, we proposed high sensitive LAS combined wavelength modulation spectroscopy (WMS) with integrated cavity output spectroscopy (ICOS). In this study, the sensitivity of LAS was enhanced about 575 times only by ICOS. The signal to noise ratio of ICOS was improved about 26 times by a combination with WMS.

1. Back ground

During re-entry of space planes and spacecrafts into the earth's atmosphere, entry velocity reaches several km/s, resulting in that the shock layer is formed in front of vehicles. These vehicles are thermally damaged by convection and radiation heating from the shock layer. Thermal protection system (TPS) has been developed to protect vehicles from these heating condition. Although the atomic oxygen and nitrogen number density are important factors for TPS developments regarding to the surface catalytic effect or passive/active oxidation, their measurement method has not been established yet.

Since their resonance lines from the ground states belong to the vacuum ultraviolet region, two-photon absorption laser induced fluorescence spectroscopy (TALIF) and vacuum ultraviolet absorption spectroscopy (VUVAS) has been used to measure the ground state number density. However, these methods are difficult to diagnose optically thick plasma such as the surface region of the test material in the shock layer.

In this study, laser absorption spectroscopy (LAS) using a forbidden transition at OI 636 nm is proposed to measure the ground state number density. The LAS can not only access inside the shock layer by a visible diode laser but also give the absolute number density without calibration. The problem is that the absorption coefficient of the forbidden transition line is about nine to ten orders of magnitude smaller than the resonance line. The relationship between fractional absorption at OI 636nm and pressure is shown in Fig.1. It is found that fractional absorption of OI 636 nm is about 8.5×10^{-7} at which the pressure is 1kPa. On the other hand, the measurement limit of LAS is about 1×10^{-2}. The sensitivity of LAS is necessary to be enhanced from four to five orders of magnitude.

To solve this problem, two kinds of sensitive methods such as wavelength modulation spectroscopy (WMS) and integrated cavity output spectroscopy (ICOS) are combined. This method is called WM-ICOS. The sensitivity of LAS will be enhanced about five orders by WM-ICOS. In this study, the effective mirror reflectance is measured by cavity ring-down spectroscopy. The measured number density by ICOS and LAS are compared using ArI 826 nm of microwave discharge argon plasma, and the sensitivity enhancement and adequacy of ICOS is demonstrated. Additionally, the signal to noise ratio of ICOS is enhanced using wavelength modulation.

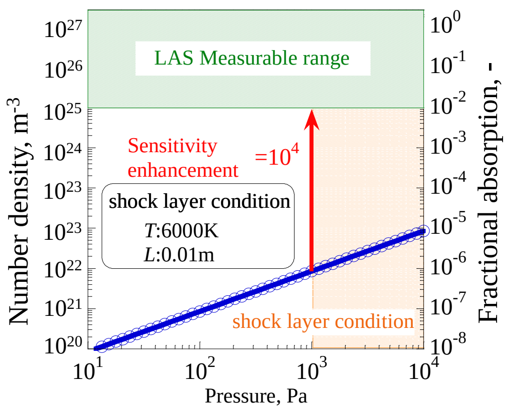

Fig.1. Fractional absorption of OI 636 nm

2. Principle

2.1 *Laser absorption spectroscopy* (*LAS*)

In LAS, laser beam is passed through the target plasma, and the number density is obtained from the fractional absorption. The relationship between the fractional absorption I_t/I_0 and the integrated absorption coefficient K is expressed by the Beer-Lambert law as,

$$\frac{I_t}{I_0} = \exp\{-K\phi(\lambda)L\}. \qquad (1)$$

Where, λ, L and ϕ are wavelength of laser, effective optical length and line shape function, respectively. The relationship between integrated absorption coefficient and the number density n is expressed as,

$$n = \frac{8\pi}{\lambda^2}\frac{g_i}{g_j}\frac{1}{A}K. \qquad (2)$$

2. 2 *Wavelength modulation spectroscopy* (*WMS*)

WMS with second harmonic detection is a type of absorption spectroscopy for its ability to make sensitive measurement and decaying noise. In this method, laser beam is passed through the target plasma as the wavelength λ is modulated with the frequency *f*. The target plasma absorbs some of the laser beam and the remaining intensity is measured. The detector signal is passed through a lock-in amplifier turn to the second harmonic of the original modulation frequency, and the second harmonic signal is obtained. The second harmonic signal is proportional to the number density.

2.3 *Integrated cavity output spectroscopy* (*ICOS*)

The fractional absorption of LAS depends on the effective optical length *L*. In ICOS, the fractional absorption is increased using two high reflective mirrors. The fractional absorption of ICOS depends on the reflectance of mirrors R_{eff}, is expressed as,

$$\frac{I_t}{I_0} = \frac{(1-R_{eff}{}^2)\exp(-kL)}{1-R_{eff}{}^2\cdot\exp(-2kL)}. \qquad (6)$$

In ICOS, the sensitivity is enhanced about $R_{\mathrm{eff}}/(1-R_{\mathrm{eff}})$ times. In this study, cavity ring down spectroscopy is used to estimate the effective mirror reflectance.

3. Results

3.1 *The sensitivity enhancement by ICOS*

In this experiment, the number density measured by ICOS and LAS are compared using ArI 826nm of microwave discharge argon plasma. To prove the adequacy of ICOS, the low reflective mirrors (*R*=0.985) and high reflective mirrors (*R*=0.99943) are used. The experimental results are shown in Fig.2. The results of 3 kinds of method are agreed, and the adequacy of ICOS was proved. In addition to, the number density obtained by ICOS and LAS are about $1.86\times10^{11}\mathrm{m}^{-3}$ and $1.07\times10^{14}\mathrm{m}^{-3}$, respectively. Therefore, the sensitivity is enhanced about 575 times.

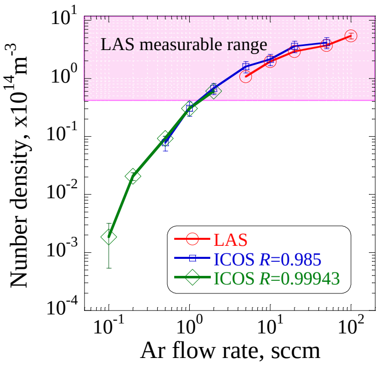

Fig.2. Obtained number density by ICOS and LAS

3.2 *The SNR improvement by WM-ICOS*

For improvement of signal to noise ratio (SNR) of ICOS, wavelength modulation is combined with ICOS. The obtained signal is shown in Fig.3. As a result, the SNR is enhanced about 26 times.

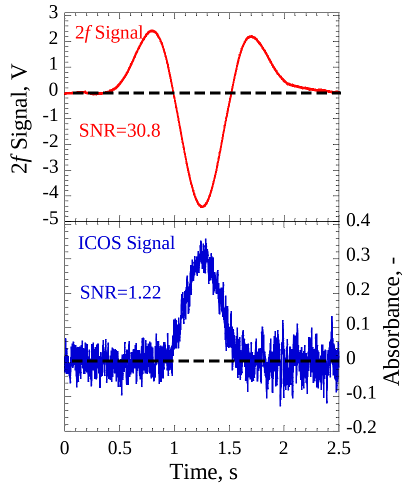

Fig.3. WM-ICOS signal (upper) and ICOS signal (lower).

References

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