Report on Visit to Ruhr-University Bochum
by International Training Program

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I have developed a plasma diagnostic system using an extended cavity diode laser (ECDL) at Ruhr University, Bochum. I stayed at Prof. Czarnetzki's laboratory. The duration of visit was one month (February 13 to March 13). Although it was a relatively short duration as a period of development of experimental equipment, the laser light source was assembled and the laser absorption spectroscopy of Ar metastable atoms was performed. I would like to thank the staffs and the students of Prof. Czarnetzki's laboratory for their kind cooperation in our experiment. The summary of the visit is reported below.

Introduction of Bochum and Ruhr University

Bochum is an industrial city, which prospered as a town of coal mines and iron manufacturing industry, in North Rhine-Westphalia, Germany. Although all coal mines were closed by the 1970s, one of them is used as a museum and a situation of those days can be known there. The city has a population of about 400,000. In recent years, the main industry of this region is changing from mining and manufacturing to the automobile industry, etc. Bochum central station is located at the center of the downtown. Ruhr University station adjoins Ruhr University which is in the distance for 10 minutes by subway from Bochum central station. The number of students of Ruhr University is about 34,000 people, and the number of staffs is about 5000 persons. Approximately 10 % of students are international students from 130 countries.

Figure 1 shows the buildings of Ruhr University. The design of these buildings is unified and cannot be distinguished easily. Furthermore, since these buildings were stood on a hill, the each building has slightly-different layered-structure; therefore I often took the wrong way until I got used. The circumference of the university has rich nature and there is a beautiful park on the south of the campus (Fig. 2).

There is the Ruhr in the south of the park. The Ruhr, which is a medium-size river in western Germany, is a right tributary of the Rhine. Many people were enjoying the walk of a riverbank (Fig. 3). Hattingen famous for rows of houses

Fig. 1 Buildings of Ruhr University

Fig. 2 Park in Ruhr University

Fig. 3 Riverbank of the Ruhr

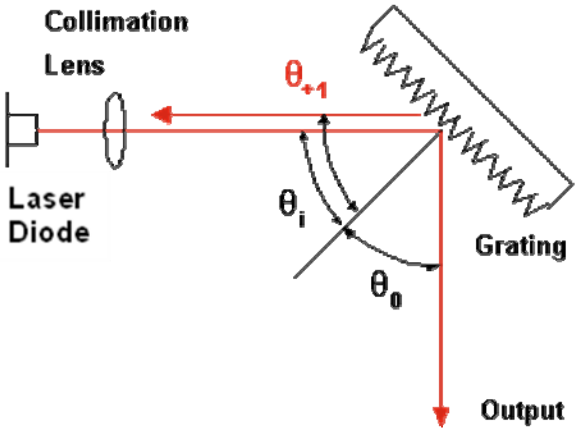

Fig. 4 Schematic diagram of ECDL

in the 16th century is located on the hill on the other side which faced across Ruhr.

Since Ruhr University has separated a few from the downtown, it is very suitable for concentrating on research in a quiet environment.

Introduction of the host laboratory

Professor Czarnetzki's laboratory is getting the remarkable result in the basic research of plasma physics. One of their papers published by Journal of Physics D has been chosen as one of the most-cited articles in Journal of Physics D in 2008 (D O'Connell et al., J. Phys. D: Appl. Phys. 41 (2008) 035208). They are doing the study of low-temperature plasmas with potential for technical applications. Application and development of novel plasma diagnostic methods are also studied in the laboratory.

Development of extended cavity diode laser (ECDL)

In recent years, an understanding of spatial structure formation of plasma and neutral gas in consideration of the interaction of plasma and neutral gas is beginning to attract attention. In condition of low gas pressure and high degrees of ionization, electron pressure can exceeds neutral gas pressure. In this case, the modification of the spatial distribution of neutral gas by electron pressure has been reported. Therefore, in order to realize uniform plasma processing in large area, an understanding the interaction of plasma and neutral gas is needed. In order to evaluate the local pressure of neutral gas, it is necessary to measure the density and temperature of neutral gas. Although the density and temperature of neutral gas are acquired by observing the Doppler spectrum of neutral gas, a tunable laser with narrow line width is needed for the observation of the low-temperature neutral gas. Since the line width of pulsed laser is relatively wide, it is not suitable for observing velocity distribution of low-temperature neutral gas.

This time, we are aiming for observation of the Doppler spectrum of Ar metastable atoms using a tunable diode laser. As a tunable laser whose line width is narrow enough, ECDL of 696.735 nm which excites $(^2P_{3/2})4s[3/2]^o_2$ state Ar atoms to $(^2P_{1/2})4p'[1/2]_1$ state has been developed. The Hitachi laser diode (HL6738MG) was used for the light source. In order to oscillate HL6738MG at long wavelength, the laser diode was operated at relatively high temperature. Since the difference of the operation temperature and room temperature was large, it developed by considering especially temperature stability.

Figure 4 shows the schematic diagram of an ECDL. The output of the laser diode is collimated by a lens and reflected by the diffraction grating. An oscillation wavelength is synchronized to the wavelength of the 1st order diffracted light by returning it to the laser diode. Incidence angle θ_i needs to fulfill the following conditions.

$$\frac{\lambda}{2} = \delta \sin\theta_i ,$$

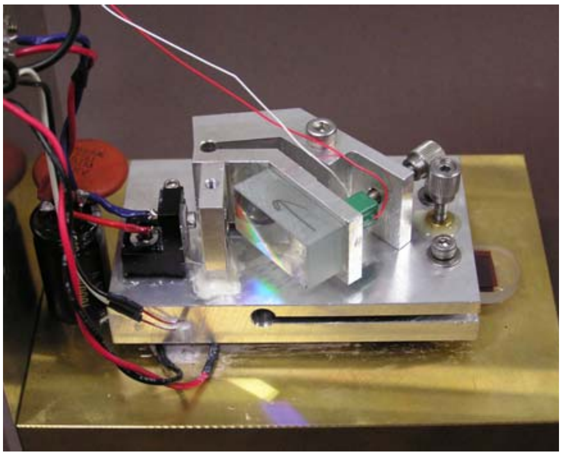

Fig. 5　696.7 nm ECDL

here, λ is the wavelength of laser light, δ is the spacing of the grids. The oscillation wavelength is controlled by adjusting the angle of the diffraction grating.

The ECDL which is tuned at 696.7 nm is shown in Fig. 5. The stabilization and accurate control of the angle of the diffraction grating, temperature, and current of the laser diode are required, since the oscillation wavelength of ECDL is governed by these parameters. The coarse adjustment of the angle of the diffraction grating is performed using a fine screw, and then it is precisely controlled by a piezo-electric device. The wavelength of the ECDL is swept by applying a ramp voltage to the piezo-electric device. Temperature and current were stabilized in the accuracy of about 10 mK and 6 μA, respectively.

Although the feed-forward control of operating current was not performed, the wavelength of the ECDL could be swept in the range of about 5 GHz without mode hop. The laser power was about 10 mW.

Laser absorption spectroscopy of Ar metastable atoms

Laser absorption spectrum measurement was performed for the check of the performance of the newly assembled ECDL. The experimental setup is shown in Fig. 6. Inductive coupled plasma was generated by a spiral antenna. The input RF power was CW 1 kW at 13.56 MHz. The Ar pressure was 0.1 Pa. A part of output of ECDL is sampled by a beam splitter, and it was used for the check of the single mode operation of the ECDL using Fabry-Perot interferometer. The fringes of the Fabry-Perot interferometer are used as a frequency marker when the frequency of the ECDL is swept. Here, the free-spectrum range (FSR) of the Fabry-Perot interferometer is 300 MHz. Laser light was attenuated to 5 μW with ND filter in order to avoid the saturation of

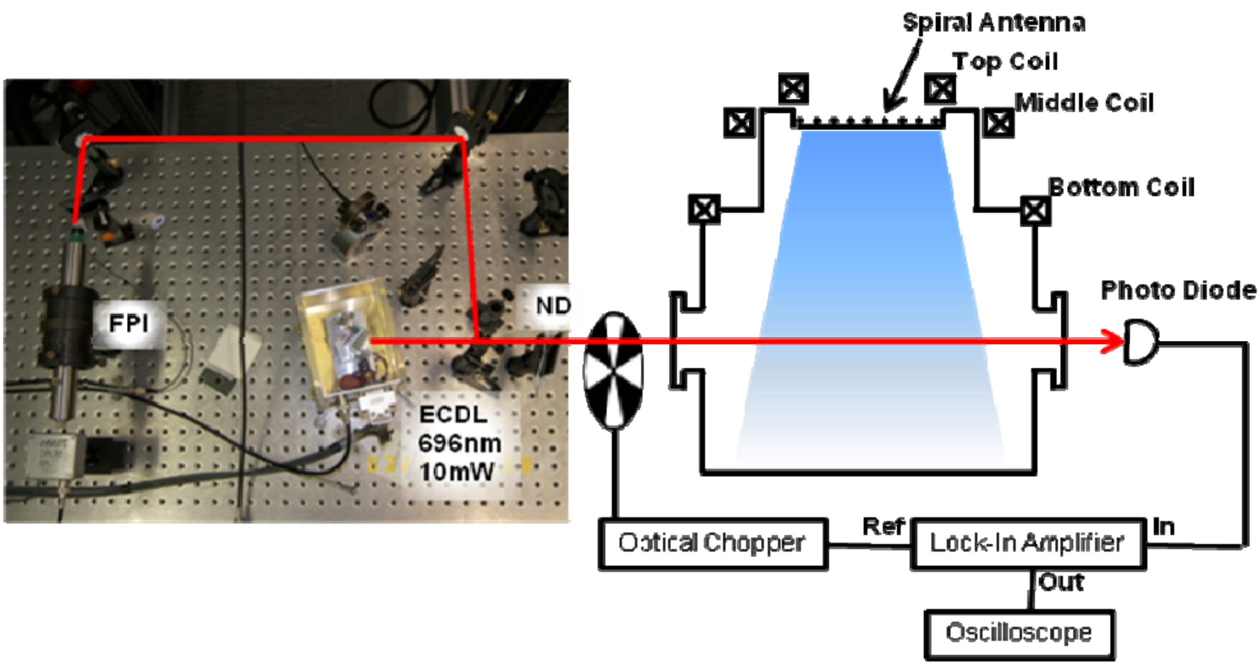

Fig. 6 Experimental setup

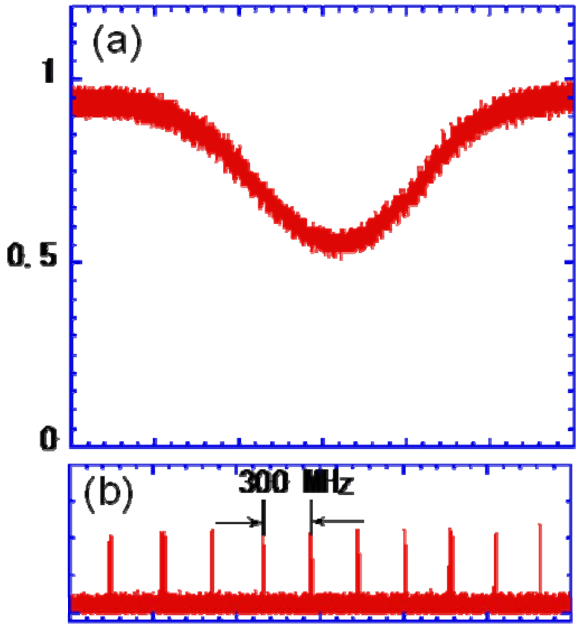

Fig. 7 (a) absorption spectrum, (b) fringes of the Fabry-Perot interferometer

absorption. The laser light was modulated at 900 Hz by using an optical chopper, and then introduced from the side-view port of the vacuum vessel. Transmitted laser light is detected by a photo-diode, and the modulated component is detected by a lock-in amplifier. The output of the lock-in amplifier is recorded by an oscilloscope.

The absorption spectrum of Argon metastable atoms and the fringes of the Fabry-Perot interferometer are shown in Fig, 7. By calibrating the tuning frequency using the fringes, the width of the Doppler spectrum was estimated at about 1 GHz. The temperature of Ar metastable atoms was estimated at 420 K from the Doppler width. It was shown that the performance of the ECDL was sufficient for the application of the plasma diagnostics by the tentative experiment. It was also confirmed that the sufficient quantity of Ar metastable atom existed in the target plasma.

The detailed laser absorption spectroscopy will be performed as the next experiment. The observation of the spatial distribution of Ar metastable atoms using a laser induced fluorescence method will be also performed.