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Measurement of the degree of polarization of the spectra from laser-produced Al plasma

Jaehoon Kim*, Dong-Eon Kim

Department of Physics, Pohang University of Science and Technology, San 31, Hyojadong, Namgu, Pohang, KyungBuk 790-784, South Korea

Abstract

Using a polarization-resolved UV–visible spectrometer, the degree of polarization of the spectra from laser-produced Al plasma was measured. To generate the Al plasma, Q-switched Nd/glass laser was used. The pulse duration of the laser is 3 ns and the energy per pulse is 6 mJ. The degree of polarization of Al III 4s $^2S_{1/2}$–4p $^2P^0_{3/2}$ transition was measured at different positions from a target surface using a space and polarization-resolved spectrometer. To resolve the different polarization components of the emission line, a dichroic polarizer was used in front of the entrance slit of the spectrometer. The degree of polarization was observed to be $2.1 \pm 0.13\%$ 220 μm from target surface and decreased as the distance from the target increased, vanishing about 1.3 mm from the target surface. To avoid the possible error due to the shot-to-shot variation of the line intensity, a calcite crystal was used to simultaneously observe the two polarization components. Both measurements yielded the same result. The plasma parameters, such as the electron temperature and density, were estimated by spectroscopic methods. The measured electron temperature was about 3 eV and the density was 2×10^{17} cm^{-3} near the target surface and decreased to 4×10^{16} cm^{-3} 1.3 mm away from the target surface.

Keywords: Laser-produced plasma; Polarization spectroscopy; UV–visible spectrometer

1. Introduction

If there exists a population imbalance among the magnetic sublevels of an excited state, the radiation from this excited state can be polarized [1]. This population imbalance comes from the spatially anisotropic excitation process. In this point of view, the observation of the polarization of emission lines becomes a tool to find out the presence of anisotropy in plasmas [2].

This plasma polarization spectroscopy has been applied to laser-produced plasmas [3–6]. Previous studies dealt with high density and high temperature plasmas produced by high power lasers by means of emission lines in the X-ray and soft X-ray region.

In this work, the degree of polarization of a spectral line from a low-temperature Al plasma produced by a low power laser was measured using a polarization-resolved UV–visible spectrometer. The plasma parameters such as electron temperature and electron density was measured using spectroscopic method.

2. Experimental setup

Fig. 1 shows the experimental setup. To generate Al plasma, a Q-switched Nd/glass laser was used. The

* Corresponding author.
E-mail address: jhoonie@postech.ac.kr (J. Kim).

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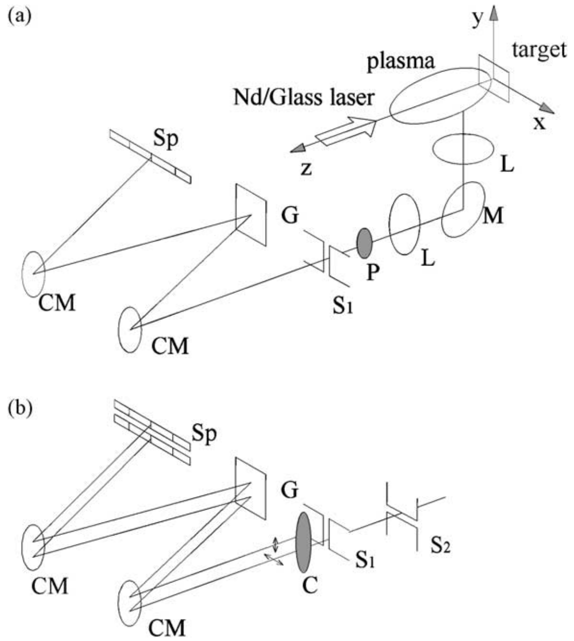

Fig. 1. Experimental setup. When using dichroic polarizer in front of the entrance slit of the spectrometer (a), only one polarization component is taken. Two spectra are needed to measure the degree of polarization. A calcite crystal after the entrance slit of the spectrometer (b), two polarization components of the spectra is taken simultaneously: L, imaging lens; M, turning mirror; P, dichroic polarizer; S_1, spectrometer slit; S_2, auxiliary horizontal slit to limit the viewing area; CM, concave mirror; G, plane diffraction grating; Sp, spectrum; C, calcite crystal.

full width at half maximum of the laser pulse duration was 3 ns and the energy per pulse was 6 mJ. The direction of the laser is z-direction as shown in Fig. 1. This direction is defined as the quantization axis of the magnetic sublevel. This laser beam was focused onto an Al target surface with a focal spot size of 0.260 mm diameter. The power density on the target surface was then about 4×10^9 W/cm^2. The spectrometer sees the plasma along y-direction. Two imaging lenses were used to image the plasma on the entrance slit of UV–visible spectrometer with a focal length of 1 m. Measured spectral resolving power ($=\lambda/\Delta\lambda$) at 300 nm wavelength was 1800 when using 2400 lines/mm grating. This spectrometer was designed in the configuration of near-normal-incidence to the concave mirror to minimize an astigmatism. Hence the overall optical system of the spectrometer and imaging optics could image the plasma in one direction; the imaging direction was the direction of z-axis as shown in Fig. 1. The spatial imaging property of the system was measured using a 0.4 mm diameter wire as a fiducial at the position of the plasma following Ref. [7]. The spatial resolution was measured to be about 0.3 mm. All the spatially resolved data were taken at positions which were at least 0.3 mm apart.

To measure the degree of polarization of an emission line, two methods were used. The first one is to use a dichroic polarizer in front of the entrance slit of a spectrometer. The spectrometer system sees the wide region of a plasma, a region of about 1.5 mm from a target surface, with a spatial resolution of 0.3 mm. The disadvantage of this setup is that for the measurement of the degree of polarization, we need two spectra obtained independently with a polarizer set for the horizontal and vertical polarization, respectively. The measurement of the degree of polarization can be affected by the shot-to-shot variation.

The second one is to use a calcite crystal after the entrance slit. The birefringent property of properly cut calcite crystal separates two perpendicular polarizations and allows one to observe two polarizations simultaneously. Hence the possible error due to the shot-to-shot variation can be avoided. This method was also employed to check the variation of the line intensity which may introduce an error in the measurement using the dichroic polarizer.

In our experiment, two polarizations were separated by 1.6 mm vertically after a 20 mm calcite crystal, and imaged and dispersed by imaging concave mirrors and a grating of the spectrometer on a CCD detector. On the detector, then we have two horizontal lines, one spectrum per each polarization. Since the optical setup in our experiment does imaging in the vertical direction, without the proper limitation of a viewing area, the two spectra overlap each other. To avoid this, we placed a 1 mm wide slit in front of the entrance slit of the spectrometer.

The direction of polarization is defined as follows: one polarization is parallel to the laser incidence axis (z-axis in Fig. 1) and the other polarization is perpendicular to the laser incidence axis (x-axis in Fig. 1). The degree of polarization is then define by $P = (I_\parallel - I_\perp)/(I_\parallel + I_\perp)$, where, $I_\parallel$ is the intensity of the light whose direction of polarization is parallel to the laser incidence axis, and $I_\perp$ the intensity of perpendicular polarization.

3. Results and discussion

3.1. Electron temperature and density measurement

To measure the electron temperature and density of the plasma, spectroscopic methods were used. Fig. 2 shows the typical spectrum from laser-produced Al plasma emitted from 220 μm from target surface. Assuming the local thermodynamic equilibrium [8], the emissivity and the electron temperature are related by the following equation:

$$\ln\left(\frac{\varepsilon_{mn}}{g_m A_{mn} \nu_{mn}}\right) = \ln\frac{N}{Z} - \frac{E_m}{kT} \qquad (1)$$

Here, ε_{mn} is the emissivity, g_m the statistical weight, A_{mn} the spontaneous transition rate, ν_{mn} the frequency of the emitted light, Z the partition function, E_m the upper level energy, and T the electron temperature. Al III 3d ^{2}S–4p ^{2}P^0 (361.235 nm), 4f ^{2}F^0–5g ^{2}G (447.993 nm), and 4p ^{2}P^0–4d ^{2}D (451.253 nm) lines were used to find the electron temperature. Using these lines, the electron temperature was measured to be about 3 eV. The measured electron temperature and the density range assume that energy levels relevant to the above transitions are in the LTE regime [9], which justifies the usage of Eq. (1).

To find the electron density, the Stark broadening was used. The spectral line was fitted using Voigt profile and the Lorentzian width was used. Electron-impact broadening parameter was taken from Ref. [10]. The averaged electron density was measured to be 2.2×10^{17} cm^{-3} at a place of 220 μm away from the target surface and decreased to 4×10^{16} cm^{-3} at a place of 1300 μm.

3.2. Polarization measurement

The optical system consists of many optical elements such as mirrors, grating, lenses, and window as in Fig. 1. It is important to calibrate the sensitivity of the optical system to different polarization components. In this works, Al III 4s ^{2}S$_{1/2}$–4p ^{2}P$^0_{1/2}$ transition line was selected to calibrate the polarization sensitivity of the system because this line can never be polarized from quantum-mechanical point of view [11]. But near a target surface, a high density plasma exists, the continuum radiation of which contaminates the line emission. This region was hence neglected. The polarization sensitivity were measured for the region of 0.4–1.5 mm away from a target surface. The ratio of intensities of two different polarizations, $R = I_{\parallel}/I_{\perp}$ was measured to be about 0.544 in the above region with a standard deviation of 0.002.

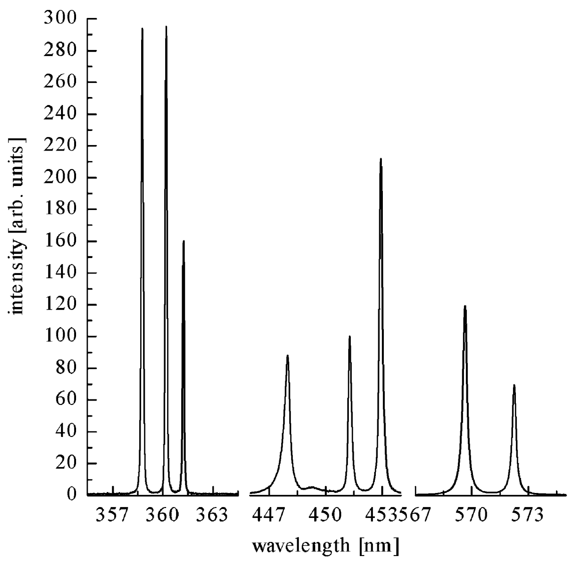

Fig. 2. Typical spectra from laser-produced Al plasma.

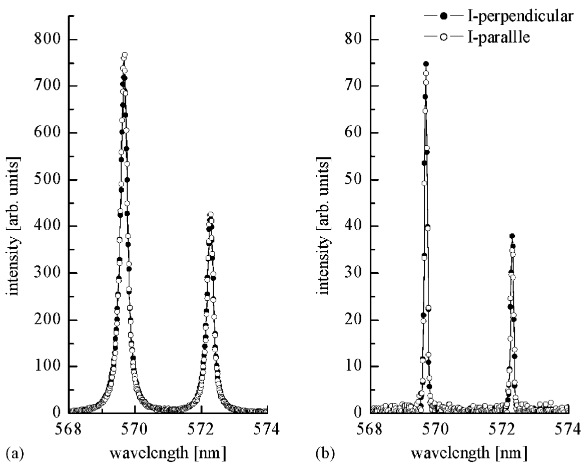

Fig. 3. Polarization-resolved spectra of Al III 4s ^{2}S$_{1/2}$–4p ^{2}P$^0_{1/2,3/2}$ transition using dichroic polarizer. Laser energy is 6 mJ. (a) is taken 220 μm from the target surface and (b) is taken 1.3 mm from the target surface. Open circle is the spectra of parallel to the laser incidence axis and dot is perpendicular.

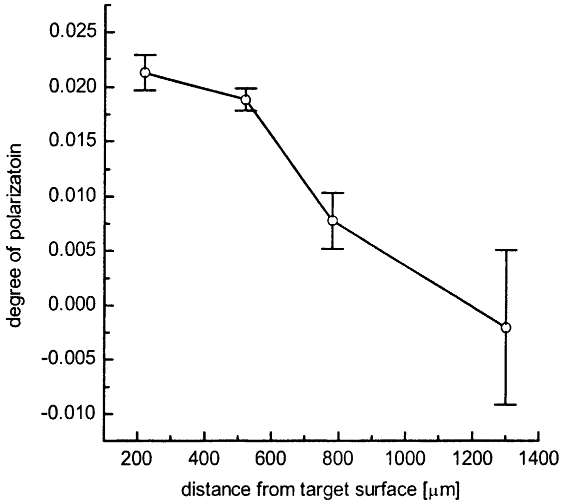

Fig. 4. Degree of polarization as a function of the distance from the target surface.

Fig. 3 shows the polarization-resolved Al III 4s $^2S_{1/2}$–4p $^2P^0_{1/2,3/2}$ lines obtained with a dichroic polarizer. The transition lines were fitted by Voigt profile to find the intensities. Using the calibration of the polarization sensitivity, all the intensities were calibrated. Fig. 4 shows the variation of the degree of polarization with respect to the distance from a target surface. The degree of polarization was measured to be $2.1 \pm 0.13\%$ 220 μm from the target surface, decreased with the distance, vanishing at 1.3 mm.

Another series of experiments were performed with a calcite crystal to check the effect of the shot-to-shot variation of intensity on the polarization measurement. The spectrum was taken at a place of about 400 μm from the target surface. The degree of the polarization was about $2.5 \pm 0.05\%$, confirming that the measured polarization was not affected by the shot-to-shot variation of the plasma.

The electron density and temperature are too low for collisional excitation to be the dominant process to the upper level population. Saha equation indicates that Al IV ion is more abundant than Al III ions. This means that the population of the upper level of transition may be populated by recombination process from Al IV ion. For this case, as in Ref. [12], the origin of the polarization of the emission line may be different from that in the case of dominant collisional process. Quantitative calculations including the recombination processes are needed and under progress.

4. Conclusion

The degree of polarization of Al III 4s $^2S_{1/2}$–4p $^2P^0_{3/2}$ transition from laser-produced Al plasma was measured using a polarization-resolved UV–visible spectrometer. The measured degree of polarization was about 2.1% near the target surface and decreased to zero far from target surface. The electron temperature and density estimated by the spectroscopic method indicates that our plasma is in the recombination phase. Further study is needed to understand the behavior of polarization characteristics of emission lines in a recombining plasma.

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