Property of Laser-Induced Plasma in Liquid

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The plasma was produced by focusing YAG laser in liquid and the plasma property in liquid was studied. The fundamental wavelength and the second harmonic wavelength of YAG laser were used in this experiment. The ultra pure water dissolved with NaCl was used as a test liquid, and the NaCl concentration was changed up to 24 %. The electron density was measured by using a laser interferometer. The electron density was highest at the focal spot and it reached to the order of 10^{25} m^{-3}. Even if the wavelength, light intensity or NaCl concentration was changed, the electron density at the focal spot was almost constant. The electron temperature at the focal spot was obtained from spectral line intensity ratio of H atoms. The electron temperature of the order of 10^3-10^4 K was obtained.

Keywords: laser induced plasma, Electron density, YAG laser, liquid, NaCl

1. Introduction

Although a large number of studies have been made on laser-induced plasma on solid surface or in gas, [1, 2] little is known about laser-induced plasma in liquid. One of the applications is to improve the quality of water [3] by resolving environmental materials.

The ultra pure water dissolved with NaCl and the concentration was changed. The NaCl was used as a substitution of environmental materials. When a YAG laser beam was focused in liquid, dense plasma was produced. The physical property of plasma produced in liquid by the YAG laser has not been enough study yet. Then, the physical properties of laser-induced plasma in liquid were investigated.

The breakdown threshold is observed at NaCl concentration up to 24%. When NaCl concentration is 0 %, the threshold is about 2×10^{14} W/m^2. It decreases with increasing NaCl concentration. As the laser light illuminated in liquid is attenuated by the absorption and scattering, the accurate light intensity in liquid must be corrected by knowing the loss coefficient. The loss coefficient is about 3 m^{-1}.

The electron density was measured by using a laser interferometer. The electron density was obtained by using the peak time of interferometric signal. It was found that extremely dense plasma with an electron density of the order of 10^{25} m^{-3} at the focal spot was produced. The spatial distribution of the electron density was measured. The electron density was highest at the focal spot and the electron density was decreased away from the focal spot.

2. Experimental arrangement

The experiment arrangement to measure the electron density is shown in Fig. 1. The maximum laser energy of YAG laser was 350 mJ with a wavelength of 1064 nm and a pulse half width of 15 ns. Moreover, the YAG laser was able to drive the second harmonic oscillation with energy of 180 mJ, a wavelength of 532 nm and a pulse half width of 15 ns. The chamber was made of acrylic and had three quarts glass windows of height of 25 mm, width of 30 mm and thickness of 2 mm. The ultra pure water or the ultra pure water dissolved with NaCl was used as a test liquid. The NaCl concentration was changed from 0 % to 24 %. The YAG laser light was focused from the out side of the chamber using the lens of the focal length 60 mm. The diameter of focal spot was 120 μm for 1064 nm and it was 80μm for 532 nm. The laser power was controlled using the optical filter.

The electron density of laser induced plasma was measured by a Mach-Zender interferometer. An Ar-ion laser was used as a probe laser of the Mach-Zender interferometer. Moreover the electron density was measured by using a He-Ne laser. When the electron density distribution was measured, the experiment was carried out adjusting the position of the focusing lens and the chamber on an X-stage with a micrometer.

Additionally, the electron temperature was measured by emission spectrum intensity. The spectrum signal was observed by spectroscope.

3. Electron density

The interferometric signal and the laser pulse are shown in

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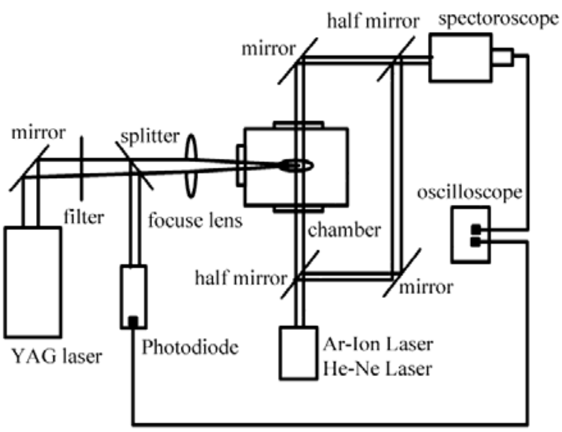

Fig. 1 Experimental arrangement.

Fig. 2. As the electron density is high, it is difficult to find out a turning point in the fringe pattern because probe laser beam for measurement is absorbed or scattered by the plasma. Thus, the peak time of the interferometric signals plots to time and the maximum fringe number is obtained by extrapolating the fringe number until the end of laser pulse from the time that the interferometric signal is not varied. An example of the extrapolation is shown in Fig.3, when the Ar-ion laser was used as a probe laser of the Mach-Zender interferometer. The maximum electron density was estimated from the following equation by maximum fringe number F_L. The electron density is written by

$$n_e = 2.18\times 10^{15}\frac{F_L}{L\lambda}, \tag{1}$$

where n_e is electron density, L is optical length of the probe laser and λ is wavelength of the probe laser. The optical length L necessary to estimate electron density from the fringe number is calculated from theoretical optical path of Gaussian beam of YAG laser.

The electron density distribution on optical axis is shown Fig. 4. The electron density using Ar-ion laser was always lager than that using He-Ne laser. Thus, the influence of refractive index of neutral atoms was removed by taking the difference of refractive index from two results as written by [4]

$$n_e = \frac{n_{(Ar)} - n_{(He-Ne)}}{4.5\times 10^{-16}(\lambda^2_{(He-Ne)} - \lambda^2_{(Ar)})}. \tag{2}$$

Where $n_{(Ar)}$ is refractive index for Ar-ion laser, $n_{(He\text{-}Ne)}$ is refractive index for He-Ne laser, $\lambda_{(Ar)}$ is wavelength of the Ar-ion laser, and $\lambda_{(He\text{-}Ne)}$ is wavelength of the He-Ne laser.

The spatial distributions on optical axis of the electron density calculated by Eq. (2) are shown in Fig. 5. When the laser intensity was 1.3×10^{15} W/m^2 at the focal spot, the electron density of the order of 10^{25} m^{-3} was obtained. At first, the laser induced plasma in the liquid was produced at the focal spot. After that, the plasma developed backward. Since the laser intensity was highest at the focal spot, the electron density was highest there. The forward electron density might show diffusion from backward plasma.

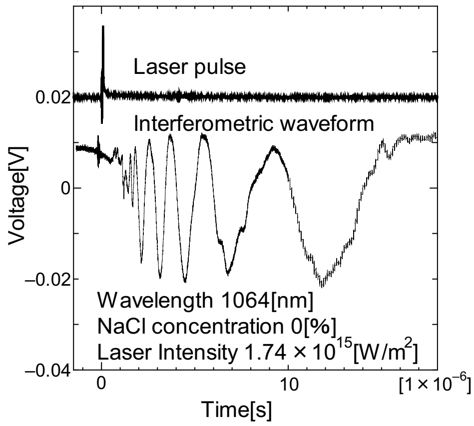

Fig. 2 Interferometric waveform and laser pulse.

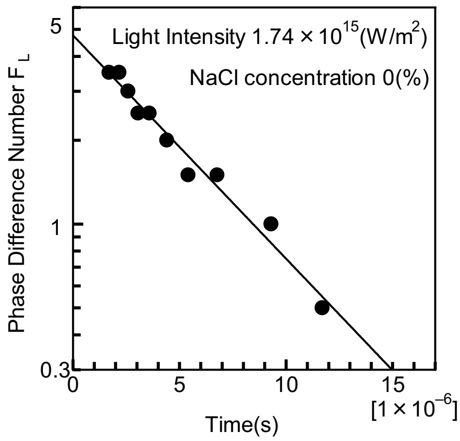

Fig. 3 Example of extrapolation.

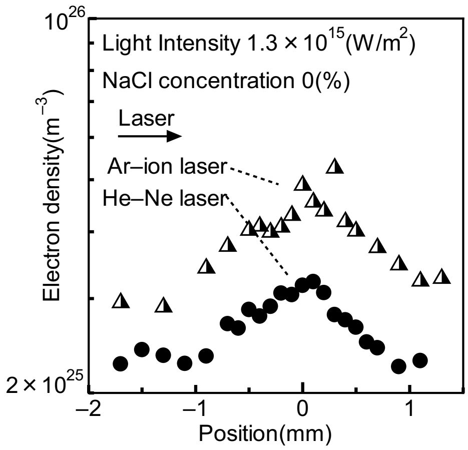

Fig.4, Comparison of electron density using Ar-ion laser and He-Ne laser.

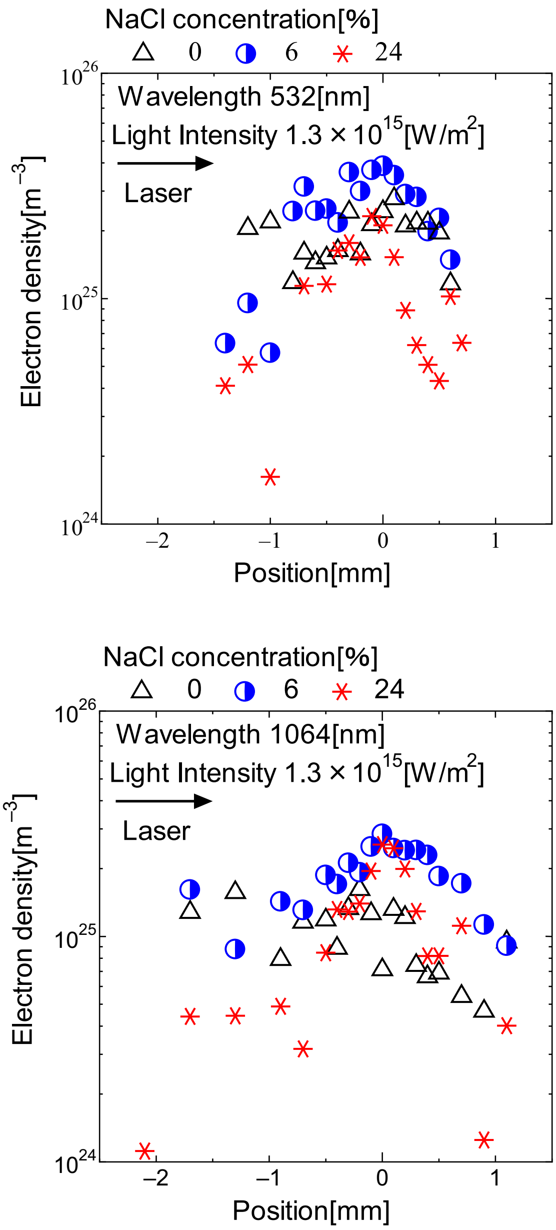

Fig. 5 Spatial distribution of electron density.

The gradients of the electron density distribution are shown in Fig 6. When the NaCl concentration and laser intensity were changed, the electron density was almost constant at the focal spot. The laser transmittance did not depend on the NaCl concentration and was almost constant. The gradient of the backward and the forward increased when the NaCl concentration exceeded 6 %. The collision of electron with Na ions increased with increasing the NaCl concentration. As the results, the electron density increased up to 6 %. However the NaCl concentration exceeded 6%, the plasma was cooled since the collision was increasing with surrounding material, especially Na ions.

4. Electron temperature

Since the plasma generated under the present experimental conditions is in local thermal equilibrium, the temporal behavior of the plasma temperature can be obtained from the spectral intensity. The spectrum signal and laser pulse are shown in Fig. 7. The spectral signal from plasma rose after about 20 ns from laser pulse, and its full-width at half maximum was about 80 ns. The spectrum distribution obtained by observing the peak value of the spectral signal in all ranges from 240 nm to 850 nm is shown in Fig. 8. The spectrum line from the every atoms (H, O, Na, Cl) included in liquid was observed. Especially, H atom had particular lines in range from visible region to near-ultraviolet. The electron temperature at the focal spot was calculated using the spectrum intensity line ratio of H lines shown in Table 1. The equation to calculate the electron temperature was written by

$$\ln \frac{I_{21}\lambda_{21}}{A_{21}g_2} = -\frac{E_2}{kT_e} + \ln C. \qquad (3)$$

Where I_{21} is emission intensity, A_{21} is transition probability, g_2 is statistical weight, E_2 is upper level energy, T_e is electron temperature, k is Boltzmann constant, C is constant. The electron temperature of the order of 10^3 - 10^4 K was obtained.

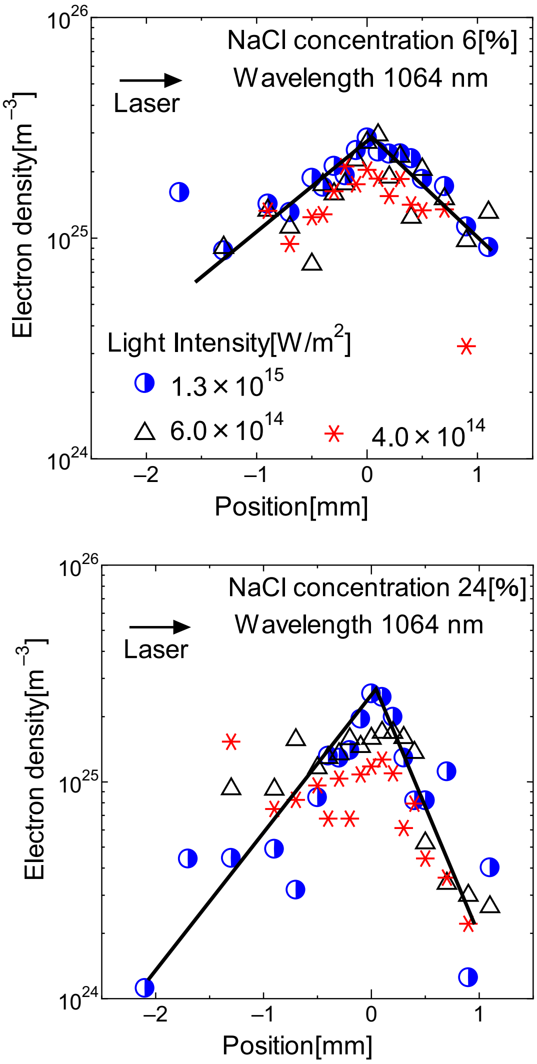

Fig. 6 Gradient of electron density.

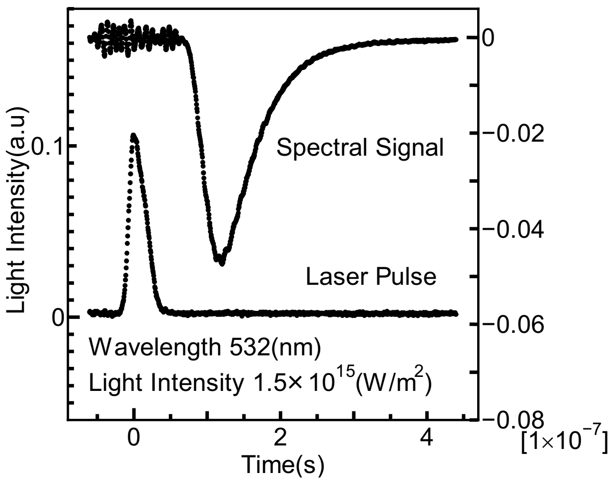

Fig. 7 Spectral signal and laser pulse.

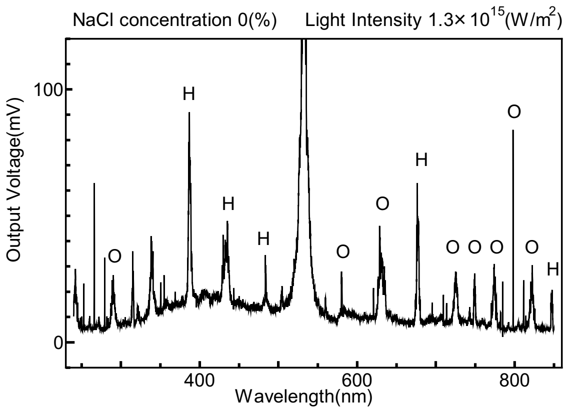

Fig. 8 Spectral distribution.

Table. 1 Spectral lines of H.

λ_{21}[nm]	E_1[eV]	E_2[eV]	g_2	A_{21}[sec^{-1}]
386.9	10.20	13.39	128	2.22E+05
435.1	10.20	13.06	50	2.53E+06
483.4	10.20	12.75	32	8.42E+06
676.3	10.20	12.09	18	4.41E+07
845.0	12.09	13.55	578	3.44E+03

5. Conclusion

When YAG laser beam was focused in liquid, the physical properties of the plasma in liquid was studied. The interferometric measurement was carried out to estimate the electron density distributions of plasma in the liquid. The electron density of the order of 10^{25} m^{-3} was obtained at the focal spot. The electron density was highest at the focal spot and the electron density was decreased away from the focal spot. Even if the wavelength, light intensity or NaCl concentration was changed, electron density at the focal spot was almost constant. The electron temperature was calculated using the spectrum line intensity ratio of H atom. The electron temperature of the order of 10^3-10^4 K was obtained.

6. References

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