

## Electron density and electron temperature of laser-induced plasma in liquid

N. TSUDA<sup>1</sup>, T. YAMAGUCHI<sup>2</sup>, J. YAMADA<sup>1</sup>

<sup>1</sup> Aichi Institute of Technology, Toyota, Japan

<sup>2</sup> Nagoya University, Nagoya, Japan

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  $10^{25} \text{ m}^{-3}$ . 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.

### 1. Introduction

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

### 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 quartz glass windows of height of 25 mm, width of 30 mm and thickness of 2 mm. 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 outside of the chamber using the lens of the focal length 60 mm. The diameter of focal spot was 120  $\mu\text{m}$  for 1064 nm and it was 80 $\mu\text{m}$  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. 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 spectroscopie.

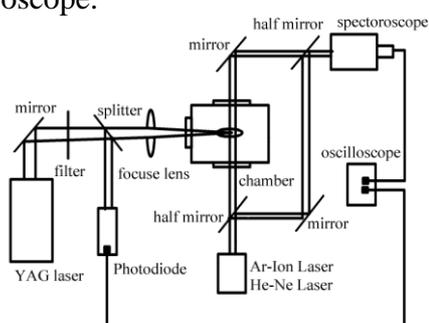


Fig. 1 Experimental arrangement.

### 3. Electron density

The interferometric signal and the laser pulse are shown in 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

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

where  $n_e$  is electron density,  $L$  is optical length of the probe laser and  $\lambda$  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 larger 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]. The maximum electron density was estimated from the following equation by maximum fringe number.

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

Where  $n_{(Ar)}$  is refractive index for Ar-ion laser,  $n_{(He-Ne)}$  is refractive index for He-Ne laser,  $\lambda_{(Ar)}$  is wavelength of the Ar-ion laser, and  $\lambda_{(He-Ne)}$  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  $1.3 \times 10^{15} \text{ W/m}^2$  at the focal spot, the electron density of the order of  $10^{25} \text{ m}^{-3}$  was obtained. At first, the laser induced plasma in liquid was produced at

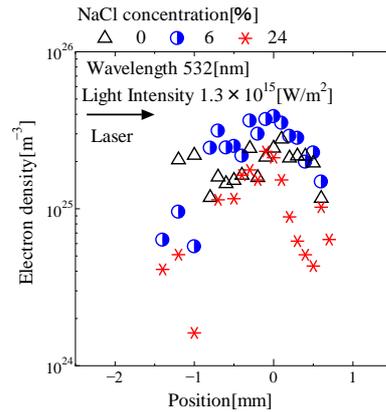


Fig. 5 Spatial distribution of electron density.

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.

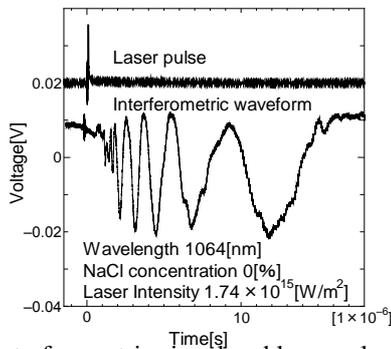


Fig. 2 Interferometric signal and laser pulse.

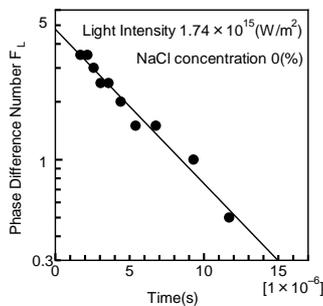


Fig. 3 Example of extrapolation.

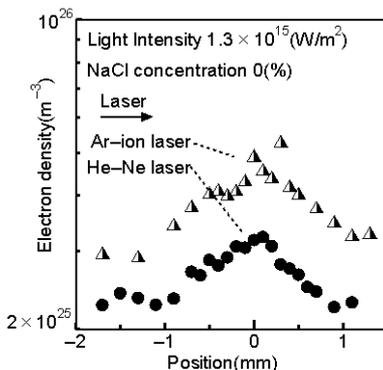


Fig.4, Comparison of electron density using Ar-ion laser and He-Ne laser.

#### 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. 6. The spectral signal from plasma raised 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. 7. 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

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

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.

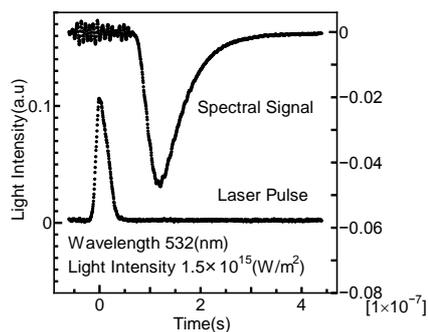


Fig. 6 Spectral signal and laser pulse.

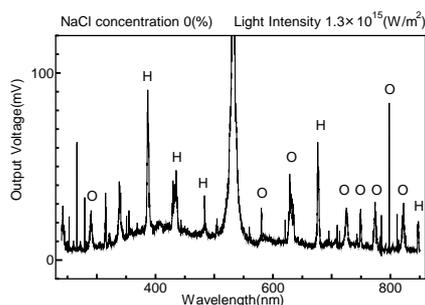


Fig. 7 Spectral distribution.

Table. 1 Spectral lines of H.

$\lambda_{21}$ [nm]	$E_1$ [eV]	$E_2$ [eV]	$g_2$	$A_{21}$ [sec <sup>-1</sup> ]
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 liquid. The electron density of the order of  $10^{25}$  m<sup>-3</sup> was obtained at the focal spot. 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

- [1] Yu. P. Raizer, Sov. Phys. JETP 21, (1965) 1009.
- [2] N. Tsuda and J. Yamada: J. App. Phys, 81 (1997) 582.
- [3] K. Imamura, Y. Tada, H. Tanaka, T. Sakiyama, K. Nakanishi: Journal of Colloid and Interface Science. , 250 (2002) 409.
- [4] S. Takeda: Purazuma no kiso (fundament of plasma) (Asakurasyoten, Tokyo,1966) p. 186 [in Japanese]