Non-Invasive Detection of Laser-Induced Breakdown Using Optical Interferometer

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1. Introduction

Laser-induced breakdown can be defined as the generation of an ionized gas (plasma) by irradiation of short pulse laser beam to the target. In the research field of actinide chemistry, these plasmas are of interest because of their wide range of applications, such as in multi-element analysis of highly radioactive material [1] and monitoring of aquatic colloid migration [2]. Recently, special interest was focused on the generation of breakdown events of the colloidal particles, called laser-induced breakdown detection (LIBD), to study a carrier role of it for the migration of radionuclides in a given aquifer [3].

Several LIBD methods were reported for the direct detection of colloids. Photoacoustic (PA) detection method using a piezo-electric transducer (PZT) was developed to obtain the information on the number density of a colloid dispersion [4]. PA detection can provide high sensitivity, but the direct contact measurements cannot be used for strongly corrosive or reactive media. To overcome these limitations, non-invasive optical detection method, which adopted the observation of a flash image in the focal region using CCD camera, was developed [5]. This method is capable of determining the colloidal size as well as the number density of a colloid dispersion, but does not provide the information on time response and spatial propagation of the shock or acoustic waves.

In the present work, another optical detection method using optical probe beam from the heterodyne interferometer was adopted for LIBD. In addition to the non-invasive characteristics, this method is suitable for the direct detection of the shock waves which are generated by a plasma ignition. We show the capability of point detection of shock wave with high spatial resolution and fast time response.

2. Experimental

The experimental apparatus is shown in Fig. 1. A Q-switched Nd:YAG laser was used to produce plasma in the samples (gas, solid and liquid). The pulse width of laser beam is approximately 10 ns at 532 nm. The pulse energy was adjusted from 3 to 20 mJ using variable attenuator. The laser beam was focused by a 75 mm focal lens and the beam waist in air was about 0.2 mm.

Laser-induced breakdown signal was detected by means of optical heterodyne interferometer system. The system consisted of an optical head and an electronic signal processing unit. The optical head consisted of a He-Ne laser source, an interferometer, a Bragg cell and a photo-detector. The probe laser beam reflected by mirror was detected using a photo-detector in the optical head. The electronic signal processor delivered a response proportional to the displacement of the sample. The waveform of detector signal was recorded by a digitizing oscilloscope. Translational stage was used to change the distance from plasma to probe beam position. As an auxiliary tool, a microphone was installed near the plasma to detect the acoustic signal.

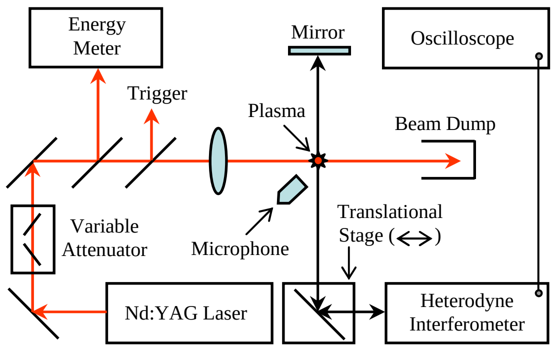

Fig. 1. Experimental set-up.

3. Results and Discussion

Figure 2 shows typical signals detected using an interferometer for an acoustic and a shock wave in gas sample. Five traces are presented that correspond to different distances from the plasma to the probe beam position ranging from 1 to 10 mm. The signals begin at a well-defined delay time after the peak of the laser pulse, which is placed at zero point in X-axis. Waveforms of these traces except trace (a) resemble those of sound waves measured by microphone, as shown in Fig. 3. We measured the delay time of wave from the plasma source to the probe beam position at several distances. Results are illustrated in Fig. 4. As expected, the delay time is linearly dependent on the distances, showing an R^2 coefficient better than 0.9995 ranging from 5-10 mm. The propagation speed of acoustic wave was estimated from the slope of the fitted line. The value obtained, ~370 m/s, is not well agreed with that obtained from the microphone signals, ~346 m/s. We speculate that this disagreement may be due to the shock wave generated from the plasma.

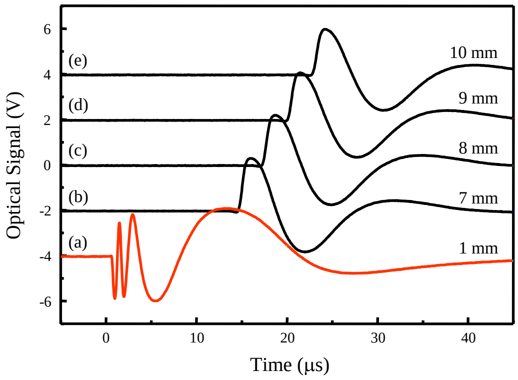

Fig. 2. Detection of shock and acoustic waves using interferometer at several distances from laser-induced plasma.

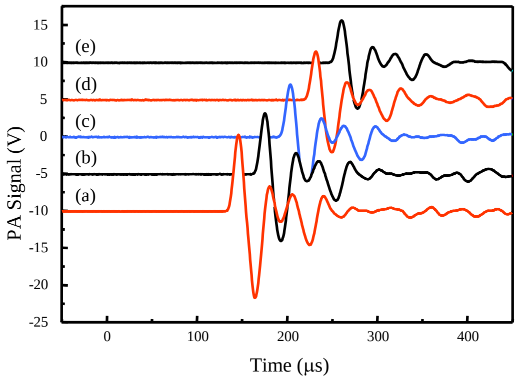

Fig. 3. Detection of sound wave using microphone at several distances (10 mm steps) from laser-induced plasma.

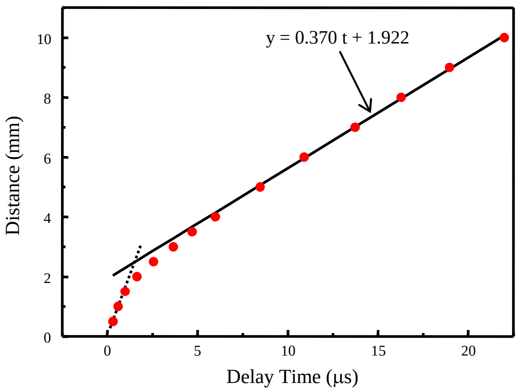

Fig. 4. Propagation of acoustic wave measured by probe beam.

Depending upon the type of interaction of laser radiation with matter, the generated waves can be either acoustic waves or shock waves. The latter, high-pressure waves propagating at supersonic speed appear when the absorption of laser beam is followed by formation of plasma. The waveform detected at very short distance, as shown in trace (a) of Fig. 2, is different from other waveforms. This behavior is also tentatively assigned as due to the shock wave generation. Nonlinear behavior of the delay time at short distances ranging from 1-3 mm is clearly observed in Fig. 4. The slope designated as dotted line is steeper than the solid line because of the supersonic speed of shock waves.

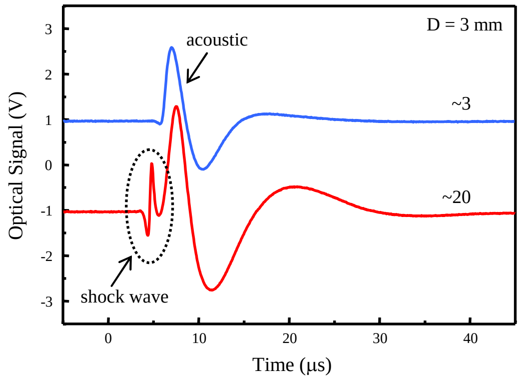

Fig. 5. Shock wave generation with higher laser beam energy.

To distinguish the waveform of shock wave from that of nominal acoustic wave, the dependence of waveform on the laser beam energy was examined. The upper trace in Fig. 5 shows the waveform detected at the distance of 3 mm from the plasma source with laser beam energy of ~3 mJ. When the beam energy increased from ~3 mJ to ~20 mJ at the same distance, the other waveform, indicated in the dotted circle of lower trace, appeared since the breakdown effect was enhanced.

4. Conclusion

Non-invasive optical detection using optical heterodyne interferometer has been performed for LIBD.

We identified the waveform of shock wave which is different from that of acoustic wave. The method adopted in this work has a capability of point detection with high spatial resolution and fast time response.

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