An Experimental Study on Micro-Bubble Generation by Laser-Induced Breakdown in Water

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This paper reports a detailed experimental investigation of bubbles with various diameters generated by laser-induced breakdown in water, which is an important issue in the field of laser medical care. The bubbles were generated by a pulsed Nd:YAG laser at 266-1064 nm, and the sizes of the bubbles were measured by a CCD camera. A time-resolved measurement with a gated ICCD camera revealed the process of bubble formation after laser breakdown. We were able to achieve manipulation of single bubble generation with desired bubble diameter ranging from 10 to 200 µm. The bubble size could be stably controlled as a function of the injected laser energy into water, which varied between 0.5 mJ and 12 mJ. More interestingly, the injected energy can form either a single bubble or multiple bubbles, with an energy more than 8 mJ, probably due to excess heat injection into the water. These results show the potential for generating nano-bubbles or micro-bubbles of arbitrary size.

Key Words: Micro-Bubble, Nano-Bubble, Laser-Induced Breakdown, LIB, Cavitation

1. Introduction

In recent years, micro-scale and nano-scale bubbles in water have been the subject of significant interest for medical, biological, and environmental applications. ‘Micro-bubbles’ are defined as bubbles having diameters ranging from several tens of µm to several hundreds of nm, while the diameters of nano-bubbles are less than a few 100 nm.[1] Recent studies have suggested that such bubbles can have a significant impact on the growth promotion effects of microbes or fish and shellfish, purification of polluted water, among others.[2, 3] Thus far, as practical methods to generate bubbles, techniques such as rapid mixing of gas and water, fluid flow controlled by pressure, and ultrasound irradiation into water have been conventionally used.[4] However, these techniques may not be able to generate bubbles in a selected portion of water and other aqueous solution such as a physiological saline solution. Furthermore, it has not been feasible to control the generated bubble diameters using these methods.

In order to regulate the bubble diameter, we have demonstrated a method using laser-induced breakdown in a small volume of water, wherein focused laser energy can be delivered to evaporate the liquid. Similar to optical breakdown phenomena, there have been several research studies on laser ablation of various solid materials as a function of a wide range of parameters such as energy/power densities and irradiated laser pulse duration from sub-µs to ~100 fs. Observations of several complicated processes as well as model analyses, including debris and/or fragment ejection after evaporation of the solid materials as well as shock wave propagation in a low ambient pressure, have been actively studied. However, there have been only a few reports on the interaction between water and a laser. Laser-induced breakdown of water has been mainly studied for use in eye surgery and blood vessels by an underwater shock wave to occur in the case and a blood vessel in the field of medical care. Recently, generation of bubbles with ~1-mm size for medical applications has been reported.[5] Since the generated bubble size is strongly related to the absorbed energy in a given volume of liquid, a focused optical geometry for laser breakdown could result in the generation of desired bubble size with excellent reproducibility.

By employing the laser breakdown method, a compact non-contact system can be realized for controlling the generated size and quantity of bubbles. This study is aimed at investigating nano- and micro-bubbles of desired diameters generated by laser-induced breakdown in water. This paper reports the results of observations of micro-bubble generation by laser-induced breakdown.

2. Laser-Induced Bubble Theory

Incident laser energy E_{in} is consumed or is converted through various energy pathways, including shock waves, cavitation bubble generation, dispersion, transmission, and light emission due to the breakdown.[6] This energy can be mainly divided into two categories. Energy lost through scattering, transmission, and reflection phenomena are mostly ineffective to form bubbles. However, energy lost to evaporation, cavitation, plasma radiation, and acoustic radiation can lead to the formation of bubbles. The energy fraction delivered to each process is of significance.

Just after the breakdown plasma is formed, the volume of material can be evaporated. In general, this portion contributes to the formation of a spherical cavitation bubble, expanding very rapidly in diameter to a maximum value. The energy for the generation of a bubble is given by:

$$E_B = \frac{4\pi}{3}(p_0 - p_v)R_{\max}^3 \qquad (1)$$

where R_{max} is the radius at the time of maximum bubble expansion, p_0 is the hydrostatic pressure, and p_v is the vapor pressure inside the formed spherical bubble [6)]. E_B represents the cavitation bubble energy. The diameter then decreases drastically (bubble collapse) due to rapid cooling of the cavitation bubble in a ~40 µs time duration.

To simplify the relationship between laser energy E_{in} and bubble generation, the other spent energies are summarized as E_α. The relationship is then given as:

$$E_{in} = (p_0 - p_v)V_B + E_\alpha \qquad (2)$$

where V_B is the volume of a bubble. In other words, the volume of a bubble is proportional to the laser energy, and this fact can be used to control the generated size of a bubble by controlling the laser energy.

3. Experimental setup

Figure 1 shows a schematic of the experimental setup to determine diameters of cavitation bubbles after sufficient cooling. The setup consists of a laser source, an optical focusing system, a quartz cuvette containing water, and a diagnostic system.

Bubbles are generated through breakdown in water by a pulsed Nd:YAG laser at 532 nm with a pulse width of 8 ns and a repetition rate of 10 Hz (Surelite I-10, Continuum). 266, 532, and 1064 nm in wavelengths are investigated in these bubble formation experiments. The laser pulse energy was varied between 0.5 mJ and 25 mJ. The laser beam is focused with a 25 mm plano-concave lens into the quartz cuvette filled with distilled water (height: 45 mm, width: 10 mm, length: 40 mm, thickness: 1 mm). The distance between the focal point and the cell wall is 20 mm.

To determine the diameters of the cavitation bubbles, a CCD camera with an electronic shutter is used. After the laser pulse is passed through the water, an expanded image of the inside the cuvette is captured. White light was used as a back-light to illuminate the narrow portion of the cuvette. The minimum spatial resolution of this diagnostic system is ~15 µm.

Figure 2 shows the experimental schematic to observe time-resolved images of cavitation bubbles. A time-resolved image of the cavitation bubble is captured with a gated image intensified CCD (ICCD) camera. Instead of an LED, as a back light for this particular experiment not to surpass the breakdown plasma emission, another pulsed Nd:YAG laser at 532 nm (Powerlite 8000, Continuum) with a pulse width of 6 ns and a repetition rate of 10Hz is synchronously operated through a trigger delay generator (Stanford Research Systems DG-535). The breakdown point was observed using an ICCD camera with appropriate optical filters. The system can capture images in increments of 10 ns.

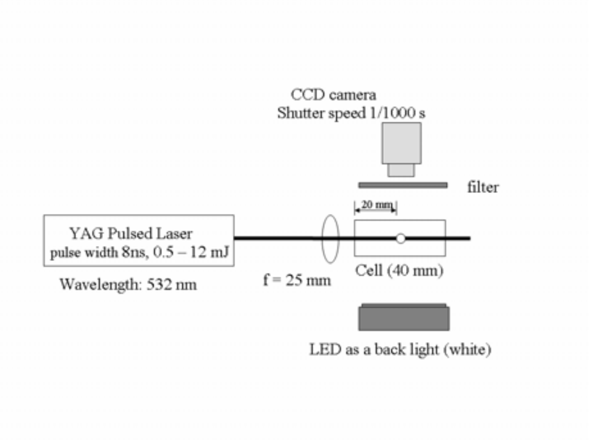


Fig.1 Schematic of the experimental setup. The bubbles generated by the laser (266 -1064 nm) were observed by a CCD camera.

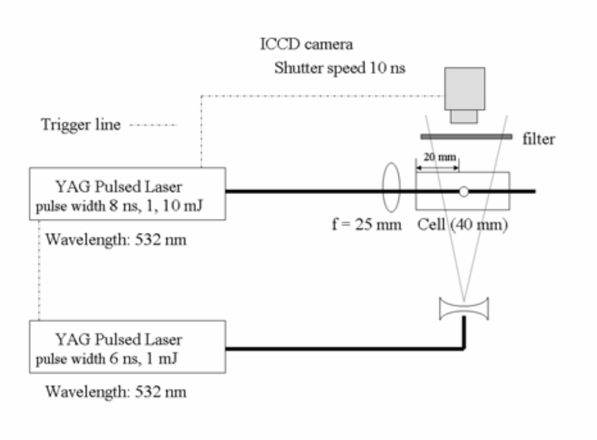


Fig. 2 Schematic of the experimental setup for observing time-resolved images of cavitation bubbles. The breakdown point was detected by an ICCD camera with appropriate optical filters.

4. Results and Discussion

4.1 Observations with the CCD camera

A single bubble was generated when the pulse energy was less than 8 mJ, while a few bubbles were generated when the pulse energy was more than about 10 mJ. The generated bubble size was measured to be in a range from ~10 to 200 µm in diameter. The bubble diameter as a function of the laser pulse energy from 1 mJ to 25 mJ at 266 nm, 532 nm, and 1064 nm are plotted in Fig. 3.

Figure 4 shows the relationship between the bubble volume, calculated from the diameter, and the laser pulse energy. The volume of bubbles was found to be proportional to the laser pulse energy (Fig. 4). To generate the desired sized bubbles in a desired space, the best wavelength is found to be the visible

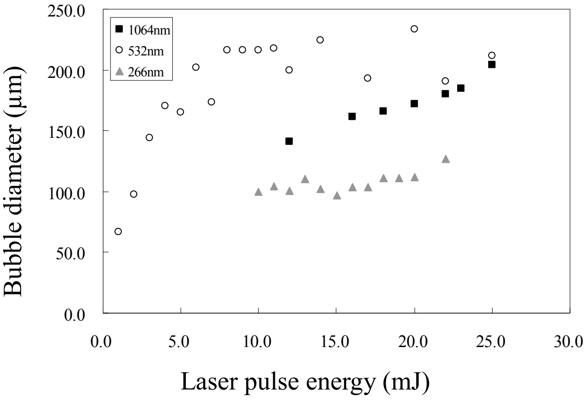


Fig. 3 Relationship between the bubble diameter and laser pulse energy between 1 mJ and 25 mJ at 266-1064 nm.

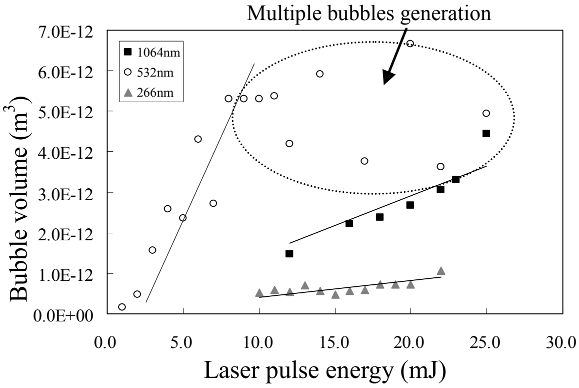
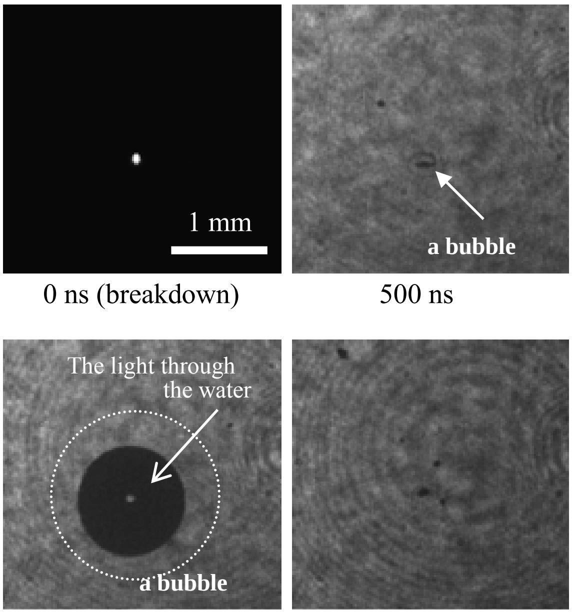


Fig. 4 Relationship between the bubble volume and laser pulse energy. We achieved desired single bubble generation with diameters from 10 to 200 µm. The volume at each energy was calculated from the mean value of 10 radius data analyzed from the CCD images. When the energy was more than about 10 mJ, multiple bubbles were generated.

wavelength because of its high transmittance in water. At 532 nm, it was observed that a single bubble was generated when the pulse energy was less than 8 mJ, while undesirable multiple bubbles were generated when the pulse energy was more than about 10 mJ.

4.2 Investigation of micro-bubble formation with the ICCD camera

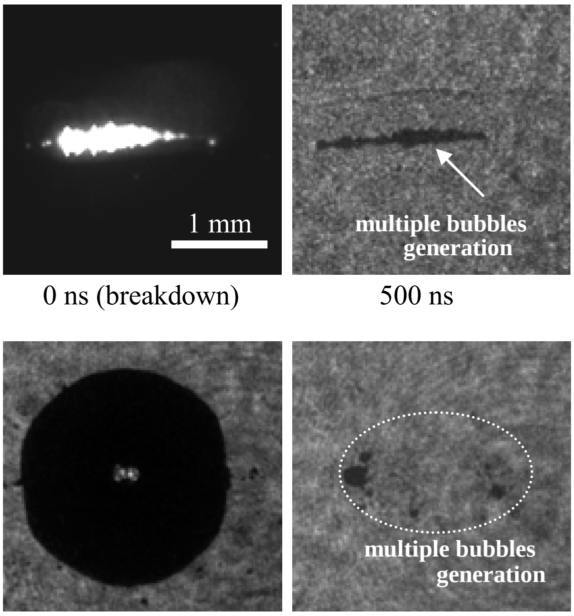
Figures 5 and 6 show breakdown point photographs detected by the ICCD camera for 8 ns after the breakdown at 532 nm in Fig. 5 (1 mJ) and Fig. 6 (10 mJ). It was observed that multiple breakdown points occurred and multiple bubbles formed when the laser energy was more than about 10 mJ. This is the cause of multiple bubbles being generated at 532 nm when the pulse energy was more than about 10 mJ.



0 ns (breakdown) 500 ns

40 µs 120 µs

Fig. 5 ICCD camera images at the breakdown point. The laser energy is 1 mJ at 532 nm.



0 ns (breakdown) 500 ns

40 µs 120 µs

Fig. 6 ICCD camera images at the breakdown point. Laser energy is 10 mJ at 532 nm. This is the cause of undesirable multiple bubble generation.

5. Conclusions

Micro-bubbles were generated by laser-induced breakdown in water. It was observed that a single bubble was generated when the laser pulse energy was less than 8 mJ, while a few bubbles were generated when the pulse energy was more than about 10 mJ. The generated bubble size was measured to range from ~10 to 200 µm in diameter. The volume of the bubbles was found to be proportional to the laser pulse energy. To generate the desired sized bubbles in a desired space, the best wavelength is found to be the visible light wavelength because of its high transmittance in water. Multiple breakdown points and multiple bubbles were observed using the ICCD camera when the laser energy was more than about 10 mJ. Multiple breakdown points generated with excess energy of laser pulse cause undesirable multiple bubble generation.

The results suggest that the laser-induced breakdown generation method could be used to generate micro-bubbles with specific desired diameters.

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