Dynamics of microbubble generation and trapping by self-focused femtosecond laser pulses

Kun Yang,^{1,2} Yun Zhou,¹ Qiushi Ren,² Jing Yong Ye,³ and Cheri X. Deng^{1,a)}

¹Department of Biomedical Engineering, University of Michigan, 2200 Bonisteel Boulevard, Ann Arbor, Michigan 48109, USA

²Department of Biomedical Engineering, Shanghai Jiaotong University, 800 Dongchuan Road, Shanghai 200240, People's Republic of China

³Center for Ultrafast Optical Science and Michigan Nanotechnology Institute for Medicine and Biological Sciences, University of Michigan, 2200 Bonisteel Boulevard, Ann Arbor, Michigan 48109, USA

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Different from conventional optical tweezers used for trapping high refractive index micron-sized particles, bubble generation and trapping by femtosecond laser offer a unique strategy to manipulate microbubbles. Using high frequency ultrasound imaging and fast-frame optical video microscopy, we obtained results revealing the spatiotemporal characteristics of bubble generation and trapping by self-focused femtosecond laser pulses at multiple locations along the laser beam. We detected distinct acoustic signals associated with the laser focus and measured the trapping force by using acoustic radiation force to detrap the bubble from the laser beam. © 2009 American Institute of Physics. [DOI: 10.1063/1.3187535]

Spatial control of single micron-sized bubbles in a noncontact fashion offers important opportunities for investigating fundamental and applied problems such as sonoluminescence¹ and sonoporation,^{2,3} which employs acoustic cavitation to induce transient disruption of cell membrane for nonviral deliver of drug and genes.^{3,4} Optical tweezers^{5,6} are used to trap particles of high refractive index^{5,7} for various applications including stretching single deoxyribonucleic acid (DNA) molecules⁸ and measuring forces exerted by a single motor proteins.⁷ However, the techniques are not successful for trapping bubbles, which have lower refractive index than host medium and are repulsed from the focus of a Gaussian beam. Although optical vortex beam produced with a TEM₀₁ mode of a laser, Laguerre–Gauss optical trap,^{3,9} or a two-dimensional interference pattern¹⁰ have been tested to trap low-index particles, achieving bubble trapping with a convenient configuration remains challenging.

A recent unexpected observation demonstrated that a single microbubble generated via laser induced optical breakdown (LIOB) can be trapped stably by a self-focused (SF) femtosecond laser in water.¹¹ Although a rigorous theory of the exact trapping mechanism is not currently available, this finding offers a unique scheme for bubble trapping.

LIOB results from tight energy confinement of high intensity femtosecond laser and involves highly localized bubble generation.¹² It has been used for micro- and nanomachining,^{13–15} modification of cells¹⁶ and small living systems.^{17,18} Investigation of LIOB and laser-medium interaction traditionally relied on optical contrast of bubbles in bright field¹⁹ or phase-contrast imaging²⁰ to assess bubble generation and expansion. Since gas bubbles are efficient acoustic targets due to the large acoustic impedance mismatch between gas and surrounding liquid,^{21,22} ultrasound imaging may provide additional useful information of LIOB.

In this study, we investigated the dynamic process of bubble generation and trapping by SF femtosecond laser pulses using high frequency ultrasound imaging and fast-frame video microscopy. We used a 250 kHz regeneratively amplified Ti:sapphire laser (Coherent, RegA) with a pulse duration of 100 fs at a wavelength of 800 nm. The laser beam (Fig. 1) was directed upward and loosely focused (*f*-number 15) into a body of de-ionized water (resistivity = 18.0 MΩ cm). Optical imaging used a high speed camera (Photron Fastcam SA3, Motion Engineering Inc., IN) and high frequency ultrasound imaging employed a Vevo 770 (Visual Sonics Inc., Canada) with imaging probe RMV 708 (15 dB bandwidth 22–82.5 MHz).

LIOB and bubble generation by the SF laser were readily observed in our experiments, as reported previously¹¹ and shown by the example in Fig. 2. A bubble was captured quickly (<0.1 ms) downward and eventually trapped $245.7 \pm 64.9 \mu\text{m}$ ($n=6$) below the LIOB site while other bubbles floated away. The stably trapped bubble immediately ceased further LIOB and bubble generation (removal of the trapped bubble resumed LIOB). It first grew quickly (<100 ms) to 30 μm before decreasing at a slower rate to a

FIG. 1. Schematic of the experimental setup for studying LIOB and bubble trapping by femtosecond laser using ultrasonic and optical imaging.

^{a)}Electronic mail: cxdeng@umich.edu.

FIG. 2. Optical images taken at different time points showing the process of LIOB, bubble generation, trapping, and decreasing in size by upward directing femtosecond laser pulses (enhanced online). [URL: <http://dx.doi.org/10.1063/1.3187535.1>]

stable size of $6.89 \pm 0.71 \mu\text{m}$ ($n=17$) almost indefinitely or for the experimental duration (>20 min) (Fig. 2), in sharp contrast with the short lifetime (~ 140 ms) of a free bubble of this size due to surface tension and gas diffusion.²³

Our time-resolved imaging measurements showed that LIOB occurred 10.4 ± 1.7 s ($n=13$) after the start of laser illumination (700 mW). The delay decreased to 4.7 s at 900 mW and increased to 42 s at 300 mW. These results indicate that the observed LIOB was likely the result of “nucleation” by impurities (e.g., irons, occasional small gas pockets, or dusts) in the water used in experiments. The impurities initiated LIOB at laser intensity levels lower than the intrinsic LIOB threshold in ideal, pure water.

Interestingly, ultrasound imaging detected distinct acoustic signals associated with the laser focus during this quiescent period before LIOB. *B*-mode imaging show the laser focus [arrow in Fig. 3(b)] accompanied by distributed small spots within a narrow zone across the field of view near the focus. The pulse-echo image of the laser focus indicated local acoustic inhomogeneity, which may be associated with the focal change of optical refractive index induced by the ultrafast laser pulses. The duration of the signal was $\sim 0.02 \mu\text{s}$, comparable with the incident imaging pulse itself, indicating that the size of the inhomogeneity is below the axial imaging resolution ($\sim 30 \mu\text{m}$). The signal amplitude was 0.17 mV, equivalent to that of a $2.6 \mu\text{m}$ (diameter)

FIG. 3. Acoustic signals associated with the laser focus. (a) Ultrasound *B*-mode image showing no signals before laser illumination. (b) *B*-mode image of the laser focus (arrow) and distributed small dots within a narrow band zone across the focus. (c) Acoustic signals at the new laser focal location (top arrow) and a stably trapped bubble (bottom arrow). (d) *M*-mode ultrasound image showing the pulse-echo signals of the laser focus, from the laser illumination to the occurrence of LIOB, and the short pulses with interval of $4 \mu\text{s}$.

FIG. 4. Trapping of multiple bubbles by a vertically directed SF femtosecond laser. (a) Optical image of four trapped bubbles. (b) *B*-mode ultrasound image of the same bubbles (enhanced online). [URL: <http://dx.doi.org/10.1063/1.3187535.2>] [URL: <http://dx.doi.org/10.1063/1.3187535.3>]

gas bubble, if compared with the 0.77 mV measured from a $9.3 \mu\text{m}$ bubble with the same detection setting and assuming Rayleigh scattering.^{24,25} The distributed small dots were train of short pulses ($\sim 0.02 \mu\text{s}$) arriving at a uniform time interval of $4 \mu\text{s}$, which corresponded exactly to the pulse repetition frequency (PRF) of the 250 kHz laser. Unlikely the pulse-echo signals from actual physical objects in water, these short pulses could be from the laser energy scattered off the optical inhomogeneity at the focus and passively received by the ultrasound transducer.

These acoustic signals disappeared once LIOB occurred. Interestingly, after a bubble was stably trapped and LIOB stopped, similar acoustic signals reappeared, although at a different location. Figure 3(c) shows an isolated region (top arrow) with a horizontal zone of distributed small dots above a trapped bubble (bottom arrow), indicating a new location of the laser focus. The ultrasound echo signal from a trapped bubble is prominent (bottom arrow), although the imaging resolution is insufficient to depict the actual shape of the bubble. LIOB would occur once again at the new focal location and the acoustic signals associated with the focus disappeared again, followed by trapping of another bubble. *M*-mode imaging, where the vertical axis represents depth along the imaging pulse direction and the horizontal axis the (slow) time, also show the spatiotemporal evolution of these acoustic signals [Fig. 3(d)]. The laser focus was detected from the start of laser illumination ($t=0$ s) until LIOB/bubble generation ($t=10.4 \pm 1.7$ s), which produced a much stronger signal. The signals with $4 \mu\text{s}$ interval were clearly seen as the regularly appearing dots in the image.

The above process repeated, eventually resulting in a series of bubbles each trapped at a location anterior to their respective LIOB site along the laser direction (Fig. 4). The first to fourth trapped bubbles (laser power of 1 W) had a diameter of 6.89 ± 0.71 , 7.32 ± 0.78 , 7.50 ± 1.46 , and $7.93 \pm 0.80 \mu\text{m}$ ($n=17$), respectively. These observations re-

vealed a progressive process of LIOB and bubble trapping by a SF laser beam. The trapped bubble reduced the laser intensity posteriorly, resulting in the laser focus to move upward to a new location by self-focusing in the presence of a trapped bubble.

Although a full theory is not yet available, the observed bubble trapping was attributed to refraction and scattering of the SF laser pulses by the bubble.¹¹ For an upward directed laser, the refraction of the laser beam generates in a downward force, pushing the bubble below the focus to a position where it is balanced with the upward buoyant and the laser radiation force. The transverse restoring force arises from radiation pressure on the side of the bubble.

To measure the transverse trapping force on the bubble, we utilized the acoustic radiation force from a transversely applied plane ultrasound beam (7 MHz) to displace a trapped bubble off the laser beam axis. The acoustic radiation force is determined by the acoustic pressure of the ultrasound beam and the size of bubble.²⁶ At laser power of 700 mW, the trapping force was 411 pN for bubble of a diameter of 9.1 μm , higher than the 87 pN obtained at 210 mW by sweeping the laser beam.¹¹

Despite the failure of bubble trapping with a downward laser beam,¹¹ we achieved bubble trapping with a horizontally directed femtosecond laser beam. Here, a bubble was pulled back horizontally from the LIOB site, opposite to the laser direction, and eventually trapped $\sim 200 \mu\text{m}$ anterior to the laser focus. The axial gradient force repels the bubble in the opposite direction of the laser toward a position where it was balanced only by optical radiation pressure forces. The buoyancy force was now balanced by the transverse trapping force, now in vertical direction. The horizontal configuration can provide additional versatility for bubble trapping.

In summary, this study revealed spatiotemporal details of LIOB and bubble trapping by a SF femtosecond laser beam. Such knowledge may help the development of new opportunities to utilize the unique bubble manipulating mechanism.

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