Electronic Supplementary Information (ESI) for Lab on a Chip

Theory and experiment on particle trapping and manipulation via optothermally generated bubbles

Chenglong Zhao,†[a] Yuliang Xie,†[a,b] Zhangming Mao,[a] Yanhui Zhao,[a] Joseph Rufo,[a] Shikuan Yang,[a] Feng Guo,[a] John D. Mai,[c] and Tony Jun Huang*[a,b]

[a]Department of Engineering Science and Mechanics, The Pennsylvania State University, University Park, PA 16802, USA. Fax: 814-865-9974; Tel: 814-863-4209; E-mail: junhuang@psu.edu
[b]Department of Chemical Engineering, The Pennsylvania State University, University Park, Pennsylvania 16802, USA

[c] Department of Mechanical Engineering and Biomedical Engineering, City University of Hong Kong

† The authors contributed equally to this work.

1. Changes in bubble diameter with laser power and time

The bubble-generating process was further quantified by analyzing bubble diameters using ImageJ software. Figure S1 shows the change in bubble diameter with time when the laser power, measured on the sample plane, was 31, 37, and 45 mW, respectively. The bubble diameter increased rapidly in the first 100 ms and grew at a slower rate afterwards, as shown in Figure S1. Meanwhile, a higher power resulted in a surface bubble with a larger diameter. The minimum power that was required to generate a bubble was 31 mW in this experiment. No bubble formation was observed when the laser power was below 31 mW.

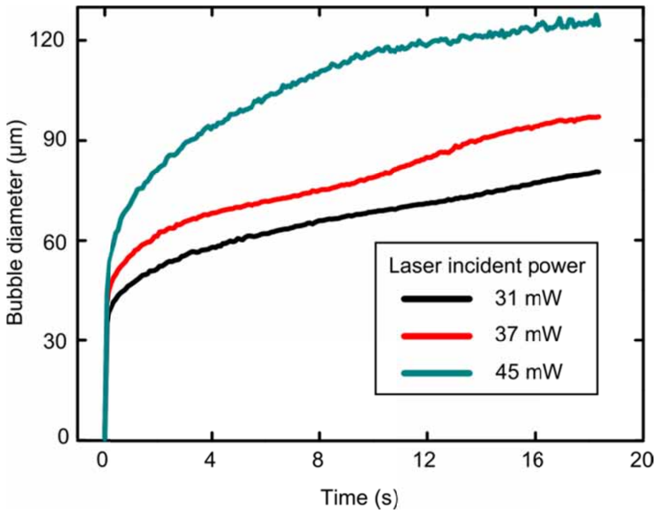

Figure S1: Change in the bubble diameter with time, at three different power levels (31, 37, and 45 mW, measured at the sample plane).

2. Controlling the position of two particles on a bubble

Not only can a single particle be manipulated on the bubble surface with this method, but multiple particles can also be manipulated simultaneously. Figure S2 demonstrates the manipulation of two particles on the bubble's surface. The white dashed circle indicates the laser spot, which moves along the inner periphery of the bubble and the motion trajectory is marked by a red arrow. As discussed in the main text, the particle's position followed the focused laser spot well. These results indicate that multiple particles can be controlled simutaneously using one bubble.

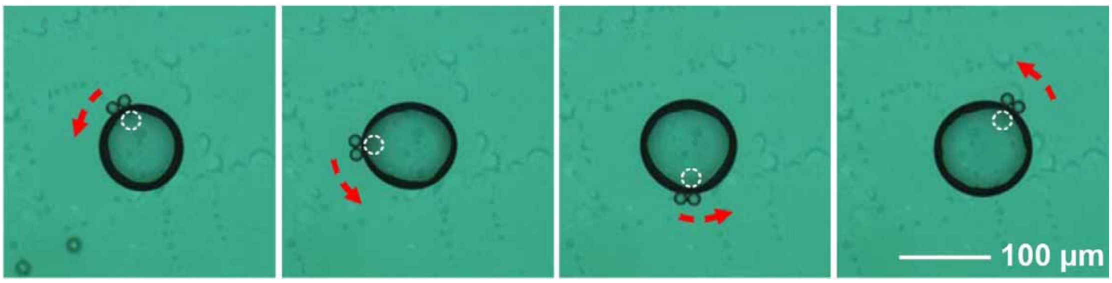

Figure S2: Manipulating two particles simultaneously on a bubble surface.

3. Dropping off a particle at high speed

The drag force on the particle increases when the bubble moves at high speed. The increased drag force broke the balance between the surface tension force and the pressure force. Therefore, the motion of particles on the bubble's surface was affected. Figure S3 shows that one particle (indicated by a red arrow in Fig. S3) was dragged off the surface bubble by the drag force at high (bubble) speeds (greater than 500 μm/s), indicating that the drag force had increased sufficiently to break the force balance and detached the particle from the bubble. This was also the maximum velocity for particle manipulation that we achieved in our experiments.

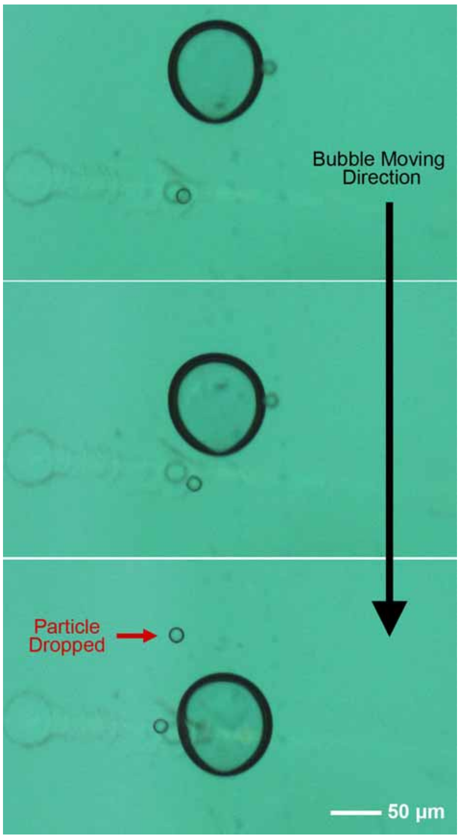

Figure S3: A particle drops off the bubble when the bubble moves at high speed.

4. Simulation of the drag force on a particle when the particle is located near the top of the chamber

In this simulation, a circle with diameter of 15 μm which represents the micro-particle was fixed near the top of the chamber (at a 10 μm distance to the top surface of the chamber). All other experimental parameters were the same as in the simulations in Figure 3 in the main text. The direction of the calculated drag force is marked by a black arrow in Figure S4. This drag force finally pushed the particle to the bottom of the chamber and the particle was recaptured by the convective flow along the bottom surface.

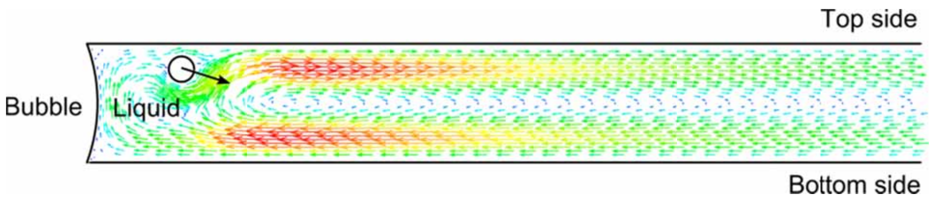

Figure S4: Simulation results of the drag force on the particle when it is located near the top surface of the chamber.

5. Control experiments to exclude the "optical tweezers" effect

In order to check whether there is a net optical tweezering effect when the particle touched the optical field, we conducted the following control experiment and determined that we do not need to take into consideration the optical tweezering effect.

A chamber consisting of two cover glasses without a gold coating was filled with 15 μm PS beads. We focused the laser on one PS bead and found the PS bead cannot be trapped with the laser beam. It did not follow the movement of the laser. In our optothermal trapping experiment, the laser power was further decreased by the gold film on the cover glass. Therefore we do not need to consider the optical tweezering effect. This was expected since the laser was loosely focused in our experiment. Hence, there was no enough force to trap a particle. In order to generate enough trapping force, the laser beam needed to be focused by an objective with a higher numerical aperture, as is typically used in an optical tweezer setup.

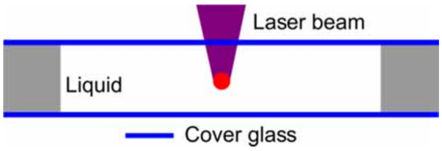

Figure S5: Diagram of the control experiment for testing the "optical tweezers" effect.