Particle manipulation using an ultrasonic micro-gripper

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We show that ultrasonic micro-grippers, 100 μm high segmented circular structures actuated with piezoelectric elements, can be used to establish a localised resonant pressure field within a fluid droplet, and hence allow effective manipulation of silica microspheres independently from the global boundaries of the fluid volume. We demonstrate through experiments and simulations that despite variations in the fluid shape and location, the method achieves particle clustering in consistent locations at fixed operating frequencies. © *2012 American Institute of Physics*.
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Manipulation of particles suspended in microfluidic volumes has a wide range of important applications including concentration,[1] collection,[2] assembly,[3] sorting,[4] and patterning.[5] Ultrasonic actuation is an appealing way to affect such manipulation as integration of the required piezoelectric transducers into chip-like devices is straightforward. Exposure to an ultrasonic field causes acoustic radiation forces (ARF), which result from time averaged non-linear terms in the Navier-Stokes equation,[6] to act on suspended particles. Whilst it is possible to generate these forces from a travelling (propagating) ultrasonic wave,[7,8] a more common approach is to use standing waves produced under resonant conditions. When standing waves are used, the resultant high pressure amplitudes lead to significantly larger forces being generated, causing particles which are denser and stiffer than the suspending medium to migrate to pressure nodes.[9]

ARF arising in resonant pressure fields have previously been used to collect particles in lines along the length of microfluidic channels,[10,11] to create grids of clumps using two intersecting standing waves across a chamber,[12,13] and to create an ultrasonic cage using three dimensional trapping.[14] These forces have also been used to bring particles into contact with a predetermined surface for detection applications[15,16] and to manipulate particles in a droplet.[17] A common feature of all of these examples of ultrasonic particle manipulation is that the ultrasonic pressure fields were dictated by the geometric shape of the fluid; either the shape prescribed by the enclosure or, in the case of the droplet, by the liquid-air interface.

This letter reports a new method to minimize the dependence of the particle forces on the geometric shape and volume of the fluid. We have developed ultrasonic microgrippers, microfabricated cylindrical structures actuated through piezoelectric elements [Fig. 1(a)], to establish a localised pressure field within the fluid volume. Experiments conducted with fluid droplets, the volume and placement of which were intentionally varied, demonstrated that in the presence of ultrasonic actuation, the grippers could control the resonant frequencies and the position of the particle clumps reliably and consistently for all of the tested cases. Hence, through a combination of microfabricated features and ultrasonic actuation, the localised pressure fields and hence the particle manipulation can gain an independence from the global geometry of the fluid. We have used the microgrippers within droplets, but equally such substructures could be used within enclosed systems for localised excitation.

The specific case presented here finds applications in the concentration of particles in small droplet volumes for subsequent detection, either optically,[18] using Raman spectroscopy[19] or using a biological sensor.[20] For all these applications, accurate control of the clump locations and resonant frequencies ensures effectiveness and ease of operation.

The ultrasonic micro-grippers used in the experiments consisted of 100 μm deep, segmented cylindrical structures. The inner and outer diameters were 1000 μm and 1220 μm, respectively [Fig. 1(a)]. The grippers were etched into a (100) oriented Si wafer using the Bosch process and the wafer was diced into 10×10 mm^2 chips for subsequent testing. Each chip was affixed onto a piezoelectric piece (Pz26, Ferroperm, Denmark) to enable actuation. Prior to assembly, the lower electrode of the piezoelectric was separated into two regions (by a cut of approximately 20 μm depth using a wafer saw) such that a strip of electrode runs down one side of the piezoelectric. Wires were connected to the electrodes using conductive silver paint, the active signal being connected to the strip electrode, and all other parts of the electrodes being grounded.[12] Finally, the silicon chip-piezo assembly [Fig. 1(a)] was affixed to a glass microscope slide (not shown) to allow easy mounting under a microscope (Olympus ZSH, Australia) fitted with a CCD camera (Hitachi HV-D30, USA) connected directly to a PC for image capture.

For the experiments, a 1.00 μl droplet of distilled water containing a 2% concentration of 4.47 μm diameter silica spheres was introduced manually via a micropipette above the micro-grippers. The device was then actuated with a drive signal, produced using a signal generator (Stanford Research DS345) connected to a power amplifier (Amplifier Research 25A250A).

It was observed experimentally that collection of the particles within the centre of the gripper occurred at a frequency of 1.480 MHz [Fig. 1(b)]. The height of the collected particles was determined by altering the focal plane of the microscope. Figs. 1(c) and 1(d) show the relatively large focal difference between particles on the top surface of the

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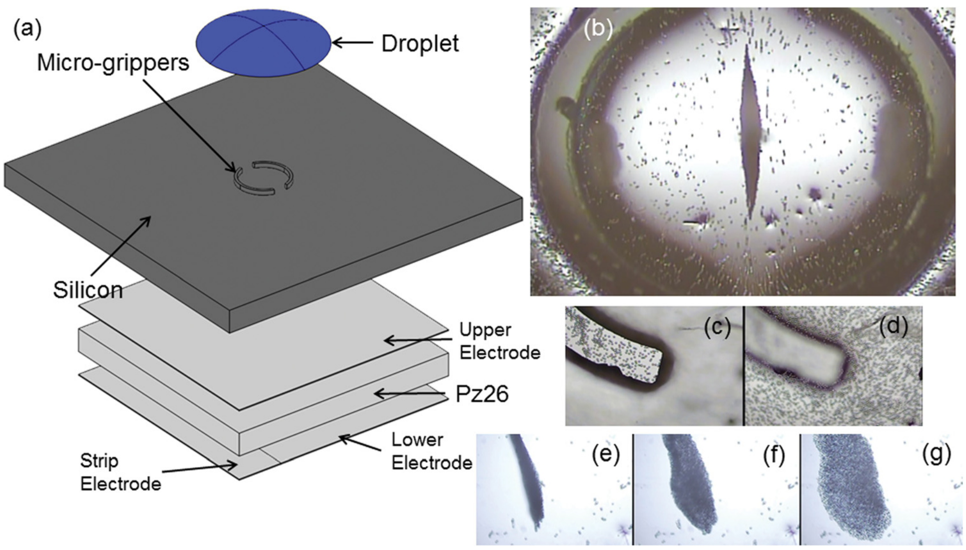

FIG. 1. (a) Exploded view of the device, showing the droplet, micro-grippers, silicon substrate, and piezoelectric transducer. (b) Image of particles collected within the micro-grippers using an actuation frequency of 1.480 MHz. Images showing (c) the focal plane level with the top of the grippers and (d) the substrate (base of the grippers), which are clearly distinguishable. Snapshots over time showing the dispersion of particles from (e) a stacked arrangement to ((f) and (g)) a dispersed arrangement after actuation is turned off. This occurs in the focal plane, which coincides with the substrate.

micro-grippers and those resting at the bottom of the cavity (prior to actuation), respectively. The piezoelectric was then actuated, leading to the formation of a clump, after termination of the excitation the particle clumps were observed to disperse, Figs. 1(e)–1(g), this sequence of images was recorded with the focal plane fixed at the base of the gripper. Initially, once the trapping field was removed, the particles at the centre of the image of the clump are out of focus, whilst those at the periphery of the clump are in focus [Fig. 1(e)]. Subsequently, the particles are observed to slide outwards [Fig. 1(f)] and as they rapidly become focussed this demonstrates that they come to rest on the bottom surface [Fig. 1(g)]. These observations suggest that during ultrasonic actuation the agglomerated particles sit on the substrate, with the force field causing particles to be stacked in layers.

In order to demonstrate that the particle collection shown in Fig. 1(b) was due to a local pressure field induced by the micro-grippers and not a global property of the droplet, a series of experiments were performed in which droplets were placed off centre from the grippers. The respective centroids of the droplets, collected particles, and micro-grippers were determined from image analysis; they are as shown by the square, cross, and diamond markers superimposed on the images in Figs. 2(a) and 2(b). The results of twelve of these tests are summarized in the polar plot of Fig. 2(c). (The circular markers represent the location of the particles relative to the droplets' centroid and the crosses denote the particles relative to the centre of the micro-grippers.) This result shows that the collection of particles within the micro-grippers in a repeatable and stable manner is possible for a wide range of

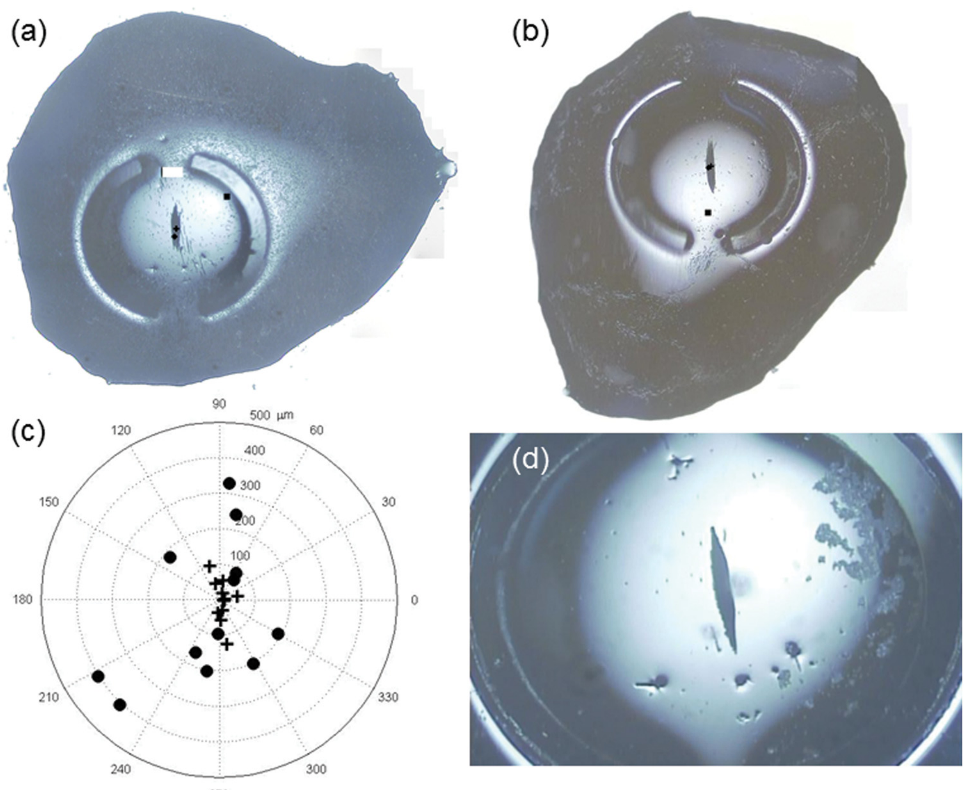

FIG. 2. (a) and (b) Images of the whole droplets placed on top of the micro-grippers. It can be seen that despite the different shapes of the droplets, particle collection still occurs within the centre of the micro-grippers. The centre of droplet is marked with a black square, the gripper centre with a diamond, and the centroid of the particles with a cross. (c) The comparison of the various centres is shown for multiple experiments. Here, the crosses show the offset of the particle centre and the circles the offset of the droplet centre, both offsets being with respect to the gripper centre. (d) Particle collection at the same frequency within a droplet, which is 5% larger in volume.

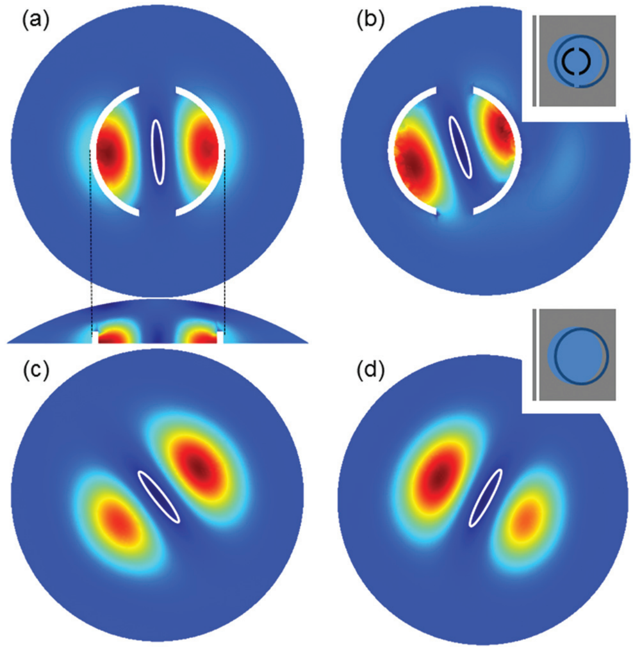

FIG. 3. Slice plots of the time averaged force potential field $\langle U \rangle$ from top view are shown for (a) no-offset and (b) 10% (256 μm) offset droplets in the x direction with micro-grippers, and the absence of micro-grippers for (c) no-offset and (d) 10% (256 μm) offset droplets in the x direction. The locations of predicted particle collection are outlined with white ovals. The insets depict the location of the piezoelectric transducer (grey), the micro-grippers (black), and the centralised (filled) and offset (outline) droplets. A side view of $\langle U \rangle$ is also shown in (a). All the top view slices were taken at 50 μm above the silicon surface (half the micro-gripper height). The piezoelectric transducer was driven at (a) 1.57 MHz, (b) 1.56 MHz, and (c) and (d) 1.59 MHz.

droplet locations. Additionally, variations in droplet volume were tested with Fig. 2(d) showing the collection within a 1.05 μl droplet at the same actuation frequency. Since the collection is not finely tuned to the position or volume of the droplet, it is evident that a localised pressure field attributable to the micro-grippers is responsible for the particle collection.

To further illustrate the effect of the grippers for particle collection, a series of finite element simulations were performed using COMSOL MULTIPHYSICS. An exploded view of the modelled geometry is presented in Fig. 1(a). The acoustics module of COMSOL was applied to the droplet, to solve the Helmholtz equation

$$(\nabla^2 + k^2)p = 0, \tag{1}$$

where k is the wavenumber and p the acoustic pressure. The Helmholtz equation is widely used for ultrasonic application where the fluid can be considered inviscid and compressible. It determines the pressure field from which the force field on the suspended particles can be found for specified boundary conditions.

A model of the system, including the droplet, silicon substrate, and piezoelectric transducer, was constructed. Due to computational limitations, the glass slide used to hold the device was not included in the analysis. Instead, only a section of the full silicon substrate ($7 \times 7 \times 0.5$ mm^3) was modelled with the trapping jaws centred in this region and the piezoelectric transducer ($5 \times 5 \times 0.5$ mm^3) attached to the flat underside of the silicon. It should be noted that due to this approximation in the boundary conditions, predicted and experimental frequencies are expected to differ slightly while the pressure field patterns are captured accurately as discussed below. The air-liquid interface of the droplet was set as a pressure release boundary condition. The water droplet had a volume of 1.00 μl in all models, with a wetted area radius of 1.28 mm (the average measured from 12 experimental results) and a contact angle of 33°, as calculated using[21]

$$R^3 = \frac{3V}{\pi} \frac{\sin^3\theta}{2 - 3\cos\theta + \cos^3\theta}, \tag{2}$$

where R is the radius of the wetted area, V the droplet volume, and θ the contact angle.

In order to predict the behaviour of particles suspended within the droplet, the forces resulting from the acoustic pressure field, as predicted by the finite element model, were determined using the expression derived by Gor'kov,[9] given by

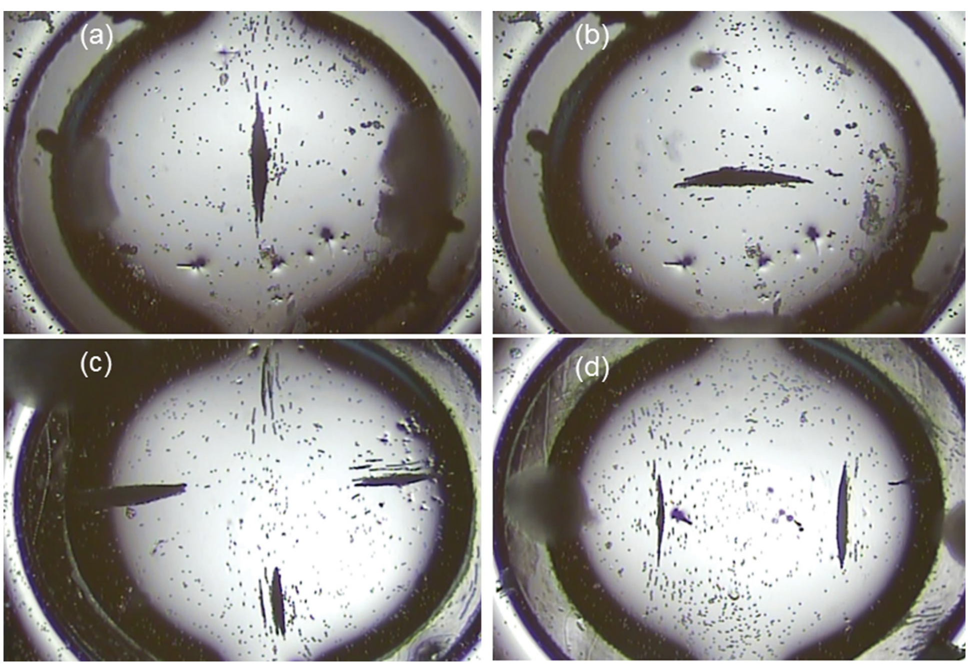

FIG. 4. Images of particles collected at driving frequencies of (a) 1.480 MHz, (b) 1.550 MHz, (c) 1.920 MHz, and (d) 2.050 MHz.

$$\langle U\rangle = 2\pi r^3 \rho_f\left(\frac{f_1}{3\rho_f^2 c_f^2}\langle p^2\rangle - \frac{f_2}{2}\langle v^2\rangle\right), \quad (3)$$

where $\langle\cdot\rangle$ represents a time average, r the radius of the particle, $\langle U\rangle$ the time averaged radiation force potential (note that $F = -\nabla\langle U\rangle$, where F is the average radiation force experienced by the particle), $v = \nabla p/i\omega\rho_f$ is the fluid particle velocity (as distinct from the velocity of the microparticles), the compressibility factor $f_1 = 1 - (\rho_f c_f^2/\rho_p c_p^2)$, the density factor $f_2 = 2(\rho_p - \rho_f)/(2\rho_p + \rho_f)$, ρ is density, c is the speed of sound, and the subscripts p and f refer to particle and fluid properties, respectively. Equation (3) assumes that the particle radius is small compared to the acoustic wavelength, and the radius of the particle is larger than the displacement of fluid particles.[22] The use of silica particles ($\rho = 2000$ kg m^{-3}, $c = 5968$ m s^{-1}) led to values of the compressibility and density factors of 0.9693 and 0.4010, respectively.

Fig. 3(a) shows the resultant modelled radiation force potential field when the droplet was symmetrically located over the gripper and the piezoelectric was actuated at 1.57 MHz (the resonant frequency within the grippers, as defined by the finite element model). It can be seen that the micro-grippers localized the U field in the 1 mm diameter region prescribed by the gripper. The particles are expected to cluster in the location of minimum force potential (dark blue) and as such, for this case, with sufficient particle concentration the line shape seen in Fig. 1(b) would be produced. At lower concentrations, the particle cluster will become more circular in shape, conforming to contours in the radiation force potential. When the droplet was offset by 10% of its diameter in the x direction [Fig. 3(b)], a similar (slightly rotated) outcome resulted at 1.56 MHz, with the particles again collected at the centre of the gripper. (It should be noted that this small frequency shift was not observed in the experiments.) From the predicted force potential field patterns and required driving frequencies, we can confirm that the grippers were acting to create a localised field, which lessens the effect of the fluid geometry. In contrast, when the grippers were removed [Figs. 3(c) and 3(d)] the resonant fields were centred by the droplet and as such moved when the position of the droplet changed. Hence, in the absence of the micro-grippers, the particles would be collected at the highly variable locations shown by the black circles in Fig. 2(c). In addition to this location effect, complex and changing droplet shapes can be expected to cause variations in the required resonant frequency. The experiments show that in the presence of the micro-gripper this effect is also removed.

The cylindrical geometry of the micro-grippers permits the possibility of more complex higher modes of operation. Several of these modes were found by sweeping the frequency with which the micro-grippers were actuated. Fig. 4 shows four of these modes: vertical clumping at 1.480 MHz, horizontal clumping at 1.550 MHz, four regularly spaced outer clumps at 1.920 MHz, and two vertical separated clumps at 2.050 MHz. These various modes of operation would allow for applications that are more complicated. For instance, one could imagine treating separate specimens in configurations (c) or (d), then switching to (a) or (b) and observing the ensuing interaction. In addition, simultaneous excitation of (a) and (b) would be expected to result in circular clumps.[12]

This work shows increased reliability in particle collection location and device operating frequencies by use of microfabricated structures within a fluid volume from examining droplet offsets and volumes. Such localised structures could prove highly beneficial for gaining more control over manipulation strategies in both open and enclosed microfluidic volumes.

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