Ultrasonic particle trapping in microfluidic devices using soft lithography

S. S. Guo,[1,a] L. B. Zhao,[1] K. Zhang,[2] K. H. Lam,[2] S. T. Lau,[2] X. Z. Zhao,[3] Y. Wang,[2] H. L. W. Chan,[2] Y. Chen,[4] and D. Baigl[5]

[1]*Department of Applied Physics, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, People's Republic of China and Department of Physics, Wuhan University, Hubei 430072, People's Republic of China*

[2]*Department of Applied Physics, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, People's Republic of China*

[3]*Department of Physics, Key Laboratory of Acoustic and Photonic Materials and Devices of Ministry of Education, Wuhan University, Hubei 430072, People's Republic of China*

[4]*Department of Applied Physics, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, People's Republic of China and Department of Chemistry, Ecole Normale Supérieure, 24 rue Lhomond, 75005 Paris, France*

[5]*Department of Chemistry, Ecole Normale Supérieure, 24 rue Lhomond, 75005 Paris, France*

(Received 26 March 2008; accepted 12 May 2008; published online 28 May 2008)

We report on the feasible fabrication of microfluidic devices for noncontact particle trapping. A half-wavelength resonator was constructed using standard soft lithography to generate ultrasonic standing waves through a miniature piezoelectric transducer. Microparticles (400 nm to 10 μm in diameter) flowing through polydimethylsiloxane microchannels were efficiently trapped to levitate in the middle depth of a resonance cavity. Such a device could potentially offer a flexible platform for particle-based assays for a large variety of applications. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2937910]

With the growing interest in micro-total-analysis systems, considerable efforts have been devoted in the past few years to the development of acoustic techniques for particle handling such as manipulating, separating, and trapping.[1–3] In the early 1990s, Wu already showed the application of acoustic tweezers to trap latex particles and clusters of frog eggs.[4] More recently, Hu *et al.* reported ultrasonic trapping of small particles using sharp edges vibrating in a flexural mode.[5] While the acoustic radiation forces are particularly strong in standing wave fields, ultrasonic standing wave manipulation constitutes a most efficient noncontact mode for particle handling. In this case, due to the low mechanical stress generated by the applied acoustic forces, the ultrasonic method is well adapted to the integration in microfluidic systems.[6,7] Indeed, Nilsson and co-workers have demonstrated working lab-on-chip systems with integrated ultrasonic elements for the standing wave based trapping of microparticles or cells.[8–10] The key feature of this achievement was the fabrication of the microfluidic channels directly in silicon or glass materials and integration of multilayer piezoelectric transducers.

In this letter, we report on an alternative fabrication method based on standard soft lithography technique that does not require any sophisticated microfabrication procedures. Ultrasonic standing waves were generated by a miniature piezoelectric transducer in a half-wavelength resonator. Polystyrene (PS) particles were trapped in a resonance cavity while continuously flowing through a microchannel. Our setup was evaluated by measuring the trapping efficiency as a function of particle size.

Figure 1 shows the setup for ultrasonic particle trapping in a microfluidic device. It consists of two major components: (a) a base plate of a printed circuit board (PCB) with a single element transducer mounted on it and (b) a glass lid bound to a polydimethylsiloxane (PDMS) block containing fluidic microchannels (placed on the PCB) acting as an acoustic reflector. Piezoelectric active element used in this work was (001)-oriented $0.67(Mg_{1/3}Nb_{2/3})O_3-0.33PbTiO_3$ (PMN-PT) single crystal ($1\times1\times0.44$ mm^3) with excellent electromechanical coefficient k_t (~0.6). It was mounted on the PCB using epoxy backing [Fig. 1(a)]. Standard soft lithography was used to fabricate the mold of upper microfluidic channel. First, a mold was prepared by spin coating a negative photoresist (SU-8 50, thickness: 150 μm) on a silicon wafer prior to patterning by UV photolithography and antisticking treatment by trimethylchlorosilane in vapor phase. Then, PDMS was spin coated on the mold with a 5:1 ratio (A&B, Sylgard 184). The glass substrate was adhered onto the top of the PDMS and cured at 80 °C for 4 h. After curing, PDMS bound to glass was peeled off from the mold and fixed on the PCB. Holes (diameter: 0.7 mm) were drilled through the PCB for fluidic connections. A resonance cavity was formed between the surfaces of piezoelectric PMN-PT transducer and glass reflector. A picture of the assembled device is shown in Fig. 1(b).

To characterize the performance of the fabricated device, trapping of particles was observed using an inverted fluorescence microscope (Olympus IX71) equipped with a charge-

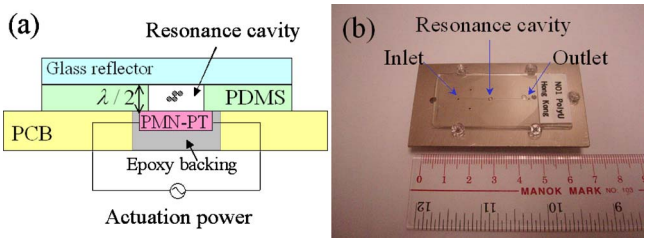

FIG. 1. (Color online) Schematic (a) and photograph (b) of the microfluidic device for ultrasonic trapping of microparticles.

[a]Electronic mail: gssyhx@whu.edu.cn.

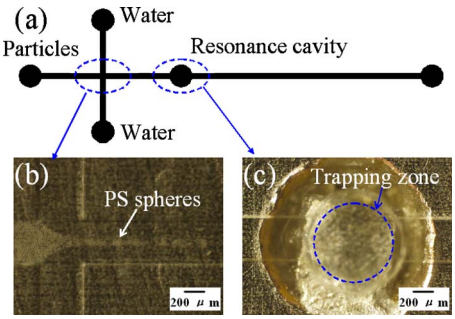

FIG. 2. (Color online) (a) Schematic representation of the microfluidic channels (width: 400 μm, height: 150 μm) used in the device. (b) Focusing region with 10 μm PS particles (0.25 wt %) at a flow rate of 20 μL/h. (c) Resonance cavity.

coupled device (DP71) camera, fluids were flown through device by syringe pumps (TS2-60, Longer, Baoding), a function generator (Model 8116A, HP) through a high frequency amplifier (Model 25A100, Amplifier Research) was used to excite the piezoelectric transducer, and the actuation voltage was recorded using a digital oscilloscope (TDS 210, Tektronix) with a 50 Ω termination.

An aqueous suspension of PS microsphere was injected through the main microchannel (width: 400 μm, height: 150 μm) and focused hydrodynamically using water coming from two side microchannels [Fig. 2(a)]. Figure 2(b) shows a typical image in the focusing zone for 10 μm PS microsphere (0.25 wt. %) at a flow rate of 20 μL/h. Using this way, the suspension of particles was directly focused in the center of the main microchannel, which avoided the widening of the flow profile and reduced the risk of losing some particles that bypass the trapping zone. The cylindrical resonance cavity consisted of a hole (height: 150 μm, diameter: 1 mm) in the PDMS block crossed by the main channel [Figs. 2(a) and 2(c)]. The PMN-PT transducer was driven at the first resonance frequency of 5.2 MHz in thickness mode, giving a half-wavelength of 150 μm (sound speed ~1500 m/s). The trapping zone of this microfluidic device was located at a distance in the near-field region of acoustic waves (distance $<a^2/\lambda$, where a is the piezoelectric transducer radius and λ is the ultrasonic wavelength; in our case, $a \sim 0.5$ mm and $a^2/\lambda \approx 800$ μm).[10]

The trapping performance of the device has been evaluated using 10 μm PS particles. Figure 3 shows typical images obtained before, during, and after application of voltage. First, there was no accumulation of particles before applying actuation voltage [Fig. 3(a)]. When an actuation voltage of 18 V_{pp} (peak to peak) was applied, particles were trapped almost immediately in the center of resonance cavity [Fig. 3(b)] and particles were accumulated very rapidly (less than 200 ms). Then, trapped particles retained in the cavity to form clusters [Fig. 3(c)] and the clusters became larger as new particle brought by the flow stacked layer by layer [Fig. 3(d)]. Finally, when the actuation voltage was removed, trapped particles were released rapidly [Fig. 3(e)] and the flow resumed stable within a few minutes [Fig. 3(f)].

In acoustic applications, the trapping efficiency is essentially given by the percentage of injected particles collected in the acoustic trap.[10] The number of particles passing the acoustic resonator was manually counted (approximately 1500 particles/min). Nearly all the passing particles were captured within the resonance cavity and the trapping efficiency was very high (>90%) while almost no particles were lost.

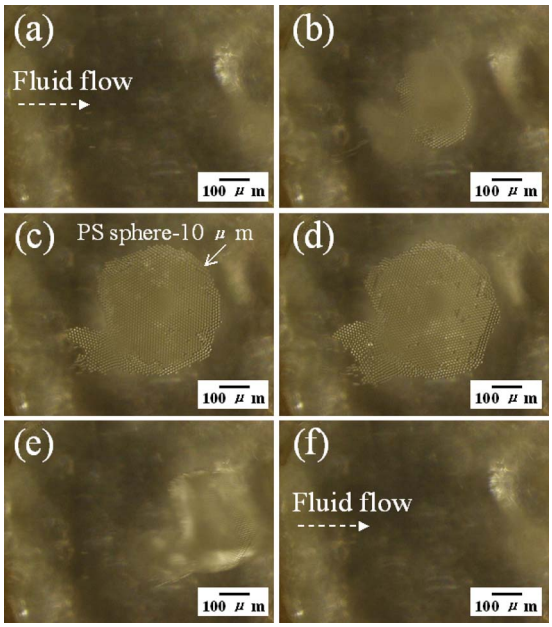

FIG. 3. (Color online) Typical trapping response for 10 μm PS particles (0.25 wt %) at a focusing rate of 20 μL/h. (a) Before applying actuation voltage (b) After applying an actuation voltage of 18 V_{pp}. [(c)–(d)] Particle clusters formed after 15 and 60 s actuation, respectively. (e) Release of the particles when the actuation voltage was removed. (f) A stable flow was obtained 120 s after the release.

According to the acoustic theory, the primary radiation force acting on a compressible sphere in an acoustic standing wave field is given by[11,12]

$$F = \frac{-\pi P_0^2 V \beta_0}{2\lambda} \sin\left(\frac{4\pi z}{\lambda}\right)\left(\frac{5\rho_P - 2\rho_0}{2\rho_P + \rho_0} - \frac{\beta_P}{\beta_0}\right), \quad (1)$$

where P_0 is the pressure amplitude and z is the distance from a pressure node. The spherical particle with volume V, compressibility β_P, and density ρ_P is suspended in a fluid with compressibility β_0 and density ρ_0. According to Eq. (1), microparticles with a larger volume experience a larger force when placed in an ultrasonic standing wave at the first thickness resonance frequency. Because the acoustic force depends on both the particle density and its compressibility, most particles can be affected by acoustic forces as long as their properties differ from those of the surrounding medium.

Finally, we investigated the trapping efficiency of our device using PS particles of 1 μm and 400 nm, respectively (Fig. 4). Compared to the 10 μm particles, the trapping was weaker for those particles and an increase in the number of lost particles was observed [1 μm in Fig. 4(b) and 400 nm in Fig. 4(e)]. Particles in the focused flow were partially retained and levitated in the resonance cavity while some of them were dispersed around the trapping zone, especially for 400 nm particles [Fig. 4(e)]. This can be explained by the strong decrease of the acoustic force with a decrease in particle size. In contrast, the acoustic force on 10 μm particles was large enough to obtain a very efficient trapping. The largest particle diameter possible to handle by the device is practically defined by the ultrasonic wavelength as well as the dimensions of the resonance cavity.

In summary, we have proposed a simple method for the fabrication of microfluidic device for microparticles trapping

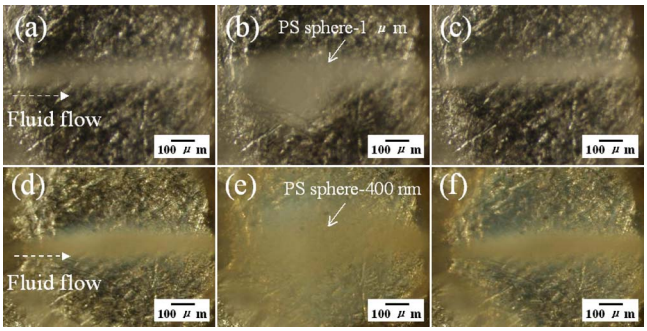

FIG. 4. (Color online) Trapping response for 1 μm [(a)–(c)] and 400 nm [(d)–(f)] PS particles. (a) Injection of 1 μm particles (0.25 wt %) at a focusing flow of 10 μL/h (b) after application an actuation voltage of 13 V_{pp} and (c) after removal of the actuation voltage. (d) Injection of 400 nm particles (0.97 wt %) at a focusing flow of 20 μL/h (e) after application an actuation voltage of 14 V_{pp} and (f) after removal of the actuation voltage.

with ultrasonic standing waves. The fabrication based on standard soft lithography is straightforward and does not require any sophisticated or costly microfabrication protocols. Simple fabrication of the device together associated with high trapping efficiency make it compatible to the general requirements of fast prototyping and device evaluation. This method shall be useful for a variety of application such as microfluidic-based cell handling, bioassays, and high throughput screening technologies.

This work is supported by the Centre for Smart Materials of the Hong Kong Polytechnic University. Financial support from PolyU internal Grant No. 1-ZV46 is acknowledged.

[1]E. H. Brandt, Nature (London) **413**, 474 (2001).
[2]R. H. Liu, J. Yang, M. Z. Pindera, M. Athavale, and P. Grodzinski, Lab Chip **2**, 151 (2002).
[3]M. Wiklund, J. Toivonen, M. Tirri, P. Hanninen, and H. M. Hertz, J. Appl. Phys. **96**, 1242 (2004).
[4]J. Wu, J. Acoust. Soc. Am. **89**, 2140 (1991).
[5]J. Hu, C. Tay, Y. Cai, and J. Du, Appl. Phys. Lett. **87**, 094104 (2005).
[6]M. Wiklund, P. Spegel, S. Nilsson, and H. M. Hertz, Ultrasonics **41**, 329 (2003).
[7]J. J. Hawkes and W. T. Coakley, Sens. Actuators B **75**, 213 (2001).
[8]T. Lilliehorn, U. Simu, M. Nilsson, M. Almqvist, T. Stepinski, T. Laurell, J. Nilsson, and S. Johansson, Ultrasonics **43**, 293 (2005).
[9]T. Laurell, F. Petersson, and A. Nilsson, Chem. Soc. Rev. **36**, 492 (2007).
[10]M. Evander, L. Johansson, T. Lilliehorn, J. Piskur, M. Lindvall, S. Johansson, M. Almqvist, T. Laurell, and J. Nilsson, Anal. Chem. **79**, 2984 (2007).
[11]K. Yosioka and Y. Kawasima, Acustica **5**, 167 (1955).
[12]G. Whitworth and W. T. Coakley, J. Acoust. Soc. Am. **91**, 79 (1992).