Surface acoustic wave (SAW) directed droplet flow in microfluidics for PDMS devices†

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We direct the motion of droplets in microfluidic channels using a surface acoustic wave device. This method allows individual drops to be directed along separate microchannel paths at high volume flow rates, which is useful for droplet sorting.

Soft lithography using the elastomer polydimethylsiloxane (PDMS) enables fabrication of simple and low cost complex microfluidic channel structures. However, to control micro flow and gain functionality of a microfluidic device, other components such as valves or pumps must be added. Techniques to manipulate flow in microfluidic devices exploit various physical effects, such as hydrodynamic pressure gradients, capillarity, magnetic forces, dielectrophoresis and electrohydrodynamics.1 In fluorescence activated cell sorters (FACS machines) droplets are sorted at high speed in an electric field after selectively charging objects of interest. Similarly, magnetic manipulation requires the attachment of some magnetic particles while dielectrophoretic techniques exploit a contrast in dielectric constant between the objects and bulk. All these techniques exploit some specific property of the object as compared to the bulk carrier fluid.

Our novel hybrid technique combines the advantages of fast electronic response with hydrodynamic control of droplet flow and redundant external labelling for manipulation. It is independent of the properties of the objects to be sorted such as dielectric constant or charge because it actuates a bulk fluid flow. However, it uses conventional PDMS molding techniques and therefore offers all the advantages of PDMS stamping. To switch the droplet flow we do not need to actuate syringe pumps with large relaxation times but instead we have high-speed control: a fast alternating electric RF-field generates an elliptically oscillating displacement of an amplitude in the nm-range on the surface of a piezoelectric substrate. This wave propagates at the velocity of sound and is known as Rayleigh wave. When a microfluid channel is placed on top of the substrate the RF-wave couples into the fluid transferring momentum and ultimately pushes droplets along the direction of wave propagation as shown in Fig. 1. This effect of acoustic streaming4,4 has been recently applied to enhance mixing,5,6 pumping7 and agitation8 in open microfluidic systems which were chemically modified to achieve hydrophilic/hydrophobic wetting contrast and to confine the liquid and is reviewed in ref. 10 and 11. Using standing surface acoustic waves (SSAW) a focusing technique using microbeads was recently reported as an alternative to conventional flow focusing12 and to extract or wash beads.13 However, the underlying physical working principles of SSAW and SAW are significantly different. In the former case a standing SAW wave is developed and causes a so called acoustic radiation force depending on material constants contrast between bulk and object such as density and sound velocity difference.14 In contrast, acoustic streaming is a result of the compressibility of the bulk fluid at the high frequency used for SAW excitation (~140 MHz) and actuates the bulk fluid where the object is embedded.6 To quantitize the effect therefore compressible fluid dynamics has to be considered, where the mass density of the bulk fluid is not constant but part of the problem.9 Here, a microfluidic device produced highly monodisperse water droplets in oil,15 demonstrating that the application of a SAW can direct the droplet flow.

Such drop-making devices have great potential for applications in biochemistry, diagnostics and analytical chemistry since they provide containers of equal volume and therefore control of the number of molecules,16 in addition they can serve as vessels that isolate a fixed number of objects such as cells or other droplets.7 To further prove the applicability of our approach to objects of different properties, we direct the motion of custom made polyacrylamide particles (PAM-particles). These hydrogel particles consist of linked polymers in water, and therefore provide a low contrast of physical properties, such as dielectric constant or density, as compared to the surrounding water solution.

The hybrid device we are presenting in this communication directs fluid droplets using acoustic streaming excited by an interdigital transducer (IDT). The IDT consist of two gold electrodes on a piezoelectric substrate, each having a comb-like structure which are interdigitated at fixed finger repeat distance as shown in Fig. 1. The ratio of the sound velocity in the substrate and twice the finger distance defines the operating frequency of the IDT. The chip presented here has a finger spacing of 13 μm and works at 140 MHz. Its gold electrodes were produced by vapour deposition and standard lithography. The anisotropic piezoelectric substrate is a Y-cut of LiNbO3 with the crystal axis rotated around the X-axis by 128° (128° Y-Cut). The fingers of the IDT are carefully aligned perpendicular to the X-axis and the alternating RF frequency therefore excites a Rayleigh wave propagating in the direction of the X-axis. To apply the high frequency voltage we use a GHz-signal generator (Hewlett Packard, HP8647A) and subsequently amplify the signal to a power of ~10 dBm. After treating both the substrate and the PDMS in ozon plasma, the microfluidic PDMS channel is carefully assembled onto
The piezo-substrate under a microscope to complement the device. The channel is fabricated using soft lithography and designed with a branch that splits the inlet channel into two outlet channels as shown in Fig. 1. The bonded PDMS–SAW hybrid device is mounted on the stage of an inverted microscope and imaged by a fast camera (Phantom V9.0, V7.0). To demonstrate the ability to direct drops, we produce water drops in HFE-7500 fluorocarbon oil with 5% (vol/vol) 1H,1H,2H,2H-perfluoro-1-octanol (Sigma), stabilized by 1.8 wt% of the fluorosurfactant ammonium carboxylate of DuPont Krytox 15718 in a drop making nozzle. By switching the acoustic wave power on and off the water drops can be directed in the corresponding outlet channel, as shown in Fig. 1.

To demonstrate the generality of this method for directing objects, we use it to direct polyacrylamide particles, which consist primarily of water, dispersed in a water continuous phase. We synthesize the particles using microfluidic droplet polymerization.19 We added 10% of the acrylamide monomer as well as 10% of the cross-linker BIS-acrylamide to the middle channel, while oil flowed through the two side channels. For comparison, the diameter of the resulting uniformly sized PAM particles was adjusted to be ~20 μm, to roughly match the size of the water drops. Again, we can control the gel particle flow by the SAW as shown in Fig. 2. In both experiments, we could direct the path of water droplets in oil and PAM particles in water respectively into designated channels and thereby demonstrate the generality of our approach of using SAW to direct the drops.

The actuation of acoustic streaming by SAWs allows a non-labeling, fast and material independent controlled droplet direction in PDMS microfluidic channels. Our device should be particularly useful for soft objects. It is especially easy to integrate into more complex fluidic devices such as detection and sorting systems since it is operated electronically. Hence, a detected signal from a fluorescent reader can be directly coupled to the SAW device to create a sorting device.

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Notes and references

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