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 polydimethysiloxane (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 electrophoresis.[1, 2] 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 redundantize 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 streaming[3, 4] has been recently applied to enhance mixing,[5, 6] pumping[7] and agitation[8, 9] 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 focusing[12] 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.[4] 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.[17] 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 $LiNbO_3$ 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

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† Electronic supplementary information (ESI) available: Movie showing the direction of drops into the lower channel when the SAW device is switched on. The drops flow along the upper channel when the device is swiched off. See DOI: 10.1039/b906819h

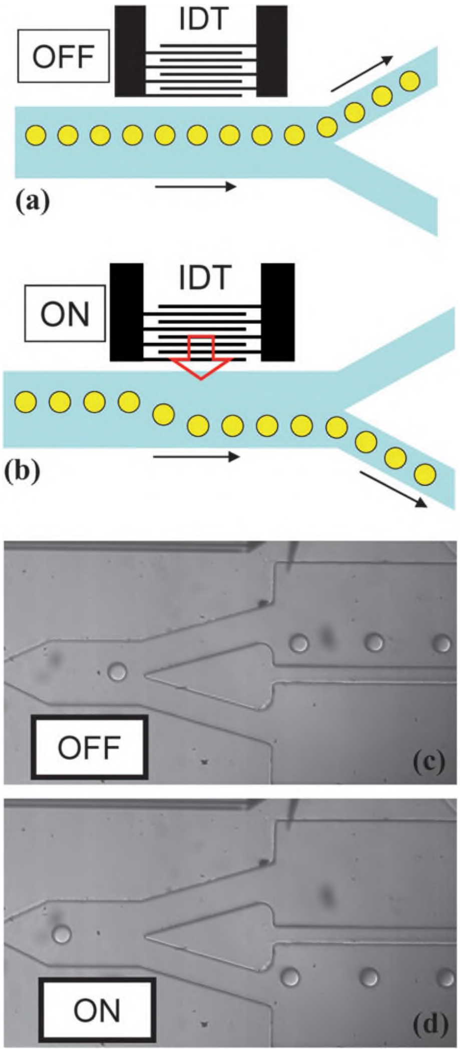

Fig. 1 (Color online) (upper two images (a),(b)): Schematic of the hybrid PDMS–SAW chip as seen from above: a branched PDMS channel is coupled to a SAW device. (a) If the SAW power is switched off all drops flow along the upper channel because of its lower flow resistance. (b) If SAW power is switched on the acoustic streaming induced by the IDT (red arrow) drives the droplets in the lower channel of the branch. (Lower two images (c), (d)): Top view of hybrid device showing a branched PDMS channel. Monodisperse water droplets are entering at constant separation from the left and are produced further upstream in a nozzle combining oil and water inlets (not shown here). The IDT is positioned below the PDMS and carefully aligned parallel beside the channel and can be partly seen at the top of the images (dark horizontal lines). The dark tip on the right side of the IDT is a feature to facilitate alignment and should roughly aim at the upper left corner of the upper outlet reservoir. However, a misalignment of approximately 100 μm did not affect the ability to direct the drops in our experiments. (c) When the SAW is switched off all the drops take the upper outlet channel because its cross-section is designed to be slightly larger. (d) Applying a RF signal of approximately 10 dBm to the IDT all drops are pushed into the lower channel. The device is 50 μm high and 100 μm in width right before the branch. Flow rates were 100 μl/h for the dispersed phase and 1000 μl/h for the continuous phase (see also ESI†).

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 157[18] 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, dipsersed 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.

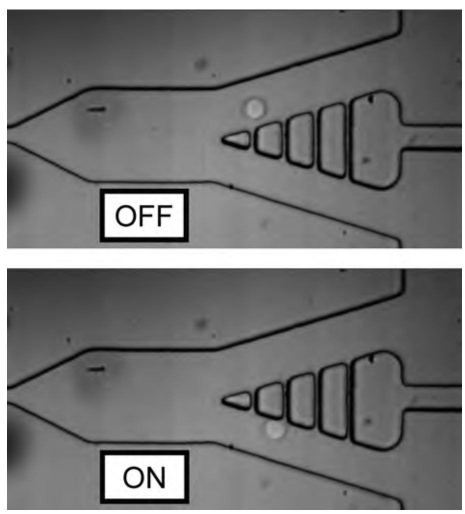

Fig. 2 PAM particles can be also directed and sorted with the PDMS–SAW hybrid device. The density of PAM particles is chosen to be very low to prevent crowding and clogging of the channels. Similarly to the setup in Fig. 1 particles flow into the upper reservoir when the IDT is switched off and can be collected in the lower reservoir when the RF signal is switched on. Note that the contrast of the hydrogel PAM particles in water is significantly lower than the contrast of water particles in oil as shown in Fig. 1. As compared to the channel in Fig. 1 this device has additional shunts short circuiting the two outlets. This additional feature decouples the active branch region from possible pressure variations further downstream and hence stabilizes the fluid flow.

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