Formation and manipulation of two-dimensional arrays of micron-scale particles in microfluidic systems by surface acoustic waves


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The two-dimensional concentration and manipulation of micron-scale particles by orthogonal, surface acoustic, standing waves is demonstrated. The particles are organized by liquid pressure waves in a microfluidic system over a piezoelectric substrate and form a uniform two-dimensional array with a spacing governed by the mechanical nodes of the two orthogonal, surface acoustic, standing waves. The nodal spacing can be controlled in each orthogonal direction independently by adjustment of the radio frequency applied to the separate acoustic wave transducers. This technique could be used to enhance the particle concentrations at sensing locations in DNA or protein array detectors.

The aggregation of micron-scale particles in microfluidic systems by ultrasonic waves has recently attracted attention, particularly for potential application in DNA and protein sensor array technologies. One important aim of such work is to overcome the diffusion-limited transport of labeled micron-scale particles to sensing locations, so that optical or electrical detection can proceed faster. In Ref. 2, for example, liquid pressure waves generated by individual ultrasonic resonators induced an enhanced concentration of coated microbeads at each sensing location in an array.

Concurrently, surface acoustic wave (SAW) techniques have been developed for the controlled generation of fluid flow in microfluidic systems. Momentum transfer from a SAW to a fluidic system results in a number of distinct phenomena, particularly acoustic streaming, droplet transport and, in the case of particle suspensions, formation of lines of particles. For counterpropagating SAWs, the resulting standing SAW can induce one-dimensional alignment of coalesced particles from a suspension in the nodal (zero) displacement points of the SAW. This has been demonstrated both for carbon nanotubes and for latex microbeads. In this letter, we show that orthogonal standing SAWs, generated in a piezoelectric material, can be used to form a highly periodic two-dimensional array of coalesced particles in an adjacent microfluidic system. This has been achieved using two orthogonal pairs of counterpropagating traveling SAWs to produce a two-dimensional array of standing wave nodes, which drives the particles to agglomerate into a regular grid. This standing wave pattern can then be manipulated by adjusting the separate SAW frequencies.

Figure 1 shows a schematic diagram of the four-port devices used in our experiments. Lithium niobate was chosen for its high piezoelectric coupling coefficient in two orthogonal directions (the X direction, and the direction perpendicular to X, which we refer to as X’), on the widely available 128° rotated Y-cut of a single crystal. Four SAWs were generated, one each along the +X and +X’ crystal directions, and one each along the −X and −X’ directions. The reverse side of the substrate was roughened to suppress generation of bulk acoustic wave modes. Four interdigitated transducers (IDTs) were defined for the SAW generation, one for each of the four directions (Fig. 1), using optical lithography and electron-beam evaporation of a 10/50 nm titanium (adhesion)/gold layer.

The IDT finger pitch defines the SAW wavelength, \( \lambda_{\text{SAW}} = \frac{v_{\text{SAW}}}{f} \), where the acoustic velocity, \( v_{\text{SAW}} \), for the X- and X’-axes have values of 3997 ms\(^{-1}\) (Ref. 9) and 3640 ms\(^{-1}\) (Refs. 10 and 11), respectively, and \( f \) is the applied high-frequency signal. The IDTs for each axis were designed to give identical center frequencies of \( \sim 32.5 \) MHz, corresponding to IDT finger widths of 31 \( \mu \)m (124 \( \mu \)m pitch) and 28 \( \mu \)m (112 \( \mu \)m pitch) for the X- and X’-axes, respectively. Each IDT mark-to-space ratio was 1:1, and the acoustic aperture was 1.2 mm in both directions. Each transducer was impedance matched to 50 \( \Omega \) using lumped ele-

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ment circuits for microwave excitation, and the performance of each transducer pair evaluated using a network analyzer. The X- and X'-axes transducer pairs both yielded center frequencies of 32.4 MHz, with corresponding insertion losses of $-6.5$ and $-8.1$ dB, respectively. The increased insertion loss of the X'-axis transducers is likely to be a result of the slightly poorer piezoelectric coupling coefficient in this direction.$^{12}$

For the following experiments, the network analyzer was replaced by two signal generators (Marconi 2022E) and two power amplifiers (Minicircuits ZHL-1–2W). Each signal generator and amplifier pair provided 31.0 dBm output power at 32.4 MHz and were split two ways (Fig. 1) to provide equal coherent signals to opposing transducers, at applied powers per transducer of up to 28.0 dBm. Carboxylate functionalized fluorescent latex particles (Sigma Aldrich) with diameters of 0.5, 1, and 2 $\mu$m were used, with identical results verified for all three particle sizes (here we present exemplar results for the 1 $\mu$m particle diameters). 0.5 $\mu$l aqueous suspensions of the latex particles, at a concentration of $2.5 \times 10^5$ $\mu$l$^{-1}$, were pipetted onto the lithium niobate surface at the center of the two overlapping SAW beam paths, defined by the acoustic apertures between each transducer pair. Motion of the particles was monitored using a fluorescence microscope coupled to a high sensitivity charge coupled device camera.

To create a microfluidic channel, a glass superstrate was pressed onto the particle suspension,$^{7,8}$ which produced a uniform distribution of particles across the acoustic aperture [Fig. 2(a)]. The thickness of the confined fluid was 20 $\mu$m, calculated from the volume of fluid used and the area over which the channel extended. Two counterpropagating SAWs were then applied along the X-axis. The resulting standing SAW launched a vertical pressure wave into the liquid within the capillary.$^8$ Ordered lines of particles were found to form parallel to the X'-axis (rectilinear to the X-axis and in the same plane) at the lithium niobate/water interface; these lines spanned the acoustic aperture, as observed previously.$^{7,8}$ The lines formed throughout the length of the capillary, demonstrating that the SAW amplitude remained high along the full length of the channel (1.2 mm). The lines correspond to points of minimum amplitude at the nodal positions of the SAW standing wave. A second orthogonal standing wave was then generated along the X'-axis of the substrate, which formed a second series of nodes running parallel to the X-axis. The two standing waves acted orthogonally within the channel, forming a clear array of coalesced particles [Fig. 2(b)], which comprises $\sim 456$ nodes. The array formation was unaffected by the order in which the IDTs were activated. Occasional defects in the array (accounting for approximately 15% of the nodes) appear to be caused by residual acoustic streaming within the fluidic channel. Figure 2(c) shows the evolution of a single node of particles with time after the transducers have been activated. The initial node forms over a time period of less than 1 s, although dissociated particles continue to accrue at the node positions while the SAWs are active or until the local population of dissociated particles is depleted.

The latex particles within the fluidic channel arranged themselves at the standing wave nodes, separated in the X and X' directions by $\lambda_{SAW}/2$. The different acoustic velocities of the two crystal directions result in unequal node separation along the two axes, as shown by the line scans taken along the paths depicted in Fig. 3(a) and plotted in Fig. 3(b). The acoustic wave velocities were measured from this data to be $4013 \pm 20$ and $3628 \pm 20$ m s$^{-1}$ for the X- and X'-axes, respectively, in excellent agreement with the literature values mentioned above.

Arrays were also formed by applying microwave power to the pairs of orthogonal transducers simultaneously. Irrespective of which formation technique was used, the nodes were found to contain an average of $16 \pm 2$ particles, calculated using image analysis of particles dispersing from the nodes on deactivation of the SAWs. This figure agrees well with calculation of the expected number of particles per node ($=17$), assuming a uniform distribution of particles within the fluidic channel prior to SAW activation. We note that misaligned latex particles, located in areas between the acoustic wave nodes, account for approximately 10% of the particle density: these immobile particles are assumed to be charge-bound to the uncoated lithium niobate by its strong static surface charge.$^{13}$

To demonstrate further spatial control of the array, the frequency of the applied SAWs was systematically adjusted within the 3 dB passband of the IDTs along each axis. Small adjustments in applied frequency altered the wavelength and
manipulating the SAW frequencies, the spacing of the two-
dimensional nodes can be adjusted, providing a mechanism
to alter the array’s spacing dynamically in either direction.
We note that tuning the applied phase (not possible in our
present SAW excitation circuit) is likely to result in a dy-
namic translation of the array, with no adjustment to its spac-
ing, which may be useful when using the technique to align
concentrated particles to structures predefined using lithog-
raphy. We further note that, since the technique only requires
the fabrication of a single ultrasonic transducer along each
edge of the substrate, it is potentially scalable to the forma-
tion of larger scale coalesced arrays, with many thousands of
independent nodes. This makes it an attractive technique to
enhance the sensitivity of large-scale DNA or protein arrays,
for example. Furthermore, the well-known ability to tune the
SAW wavelength by lithography over many orders of mag-
nitude may enable widespread applications of the technique
in the control and manipulation of suspended particles and
biological systems in microfluidic systems across many
length scales.

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