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Proceeding Paper

Towards a Multi-Interdigital Transducer Configuration to Combine Focusing and Trapping of Microparticles within a Microfluidic Platform: A 3D Numerical Analysis [†]

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Abstract: In Lab-On-a-chip devices, the separation and manipulation of micro-particles within microfluidic channels are important operations in the process of biological analyses. In this study, the microfluidic flow is coupled with acoustic waves through a 3D multi-physics numerical solution in order to generate optimized acoustic pressure pattern. Exploiting interdigital transducers (IDTs), surface acoustic waves (SAWs) are generated on the surface of a piezoelectric substrate (lithium niobate). These waves interfere constructively to generate a standing pressure field within a fluid contained in a microchannel placed between them. Several studies and applications have been reported exploiting two facing IDTs, effective in particle focusing due to the acoustic radiation force developed by the acoustic pressure. In this work, a configuration made by four IDTs is investigated to enhance the focusing effect and provide trapping capabilities. A complex matrix of pressure wave nodes (zero wave amplitude) and antinodes (maximum wave amplitude) is generated and optimized to acquire the right acoustic pressure pattern. Results obtained show particle focusing effects but also trapping on specific sites depending on the distribution of waves. These innovative results, based on multiphysics 3D numerical analysis, highlight the versatility and the efficiency of this configuration depending on the design of the microfluidic structure implemented in the SAW-based platform. Applications towards biological cell sorting and assembling can be considered based on this principle.

Keywords: microfluidics; Lab-On-a-Chip; interdigital transducers; surface acoustic waves; numerical analysis; particles manipulation



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1. Introduction

Microfluidics is defined as the science of systems that process small amounts of fluid exploiting channels characterized by dimensions in the range from tens to hundreds of micrometers [1]. In recent years, microfluidics was integrated with electronics, optics and biosensors to develop the Lab-On-a-Chip technology (LOC), which can be used in chemical, biological and medical fields to perform sample analyses [2]. One or more steps in biological analyses can require the sorting, the trapping or the separation of particles and cells in respect to their properties. A versatile and improved manipulation of cells and particles, integrated in microfluidic platforms, can lead to precise diagnoses of diseases for patients.

Microparticles manipulation can be achieved with different techniques which exploit the physical properties of the particles to control their motion and position [3,4]. A non-contact and biocompatible solution is the acoustic manipulation technique. In particular, the acoustic-based technique is active, taking advantage on externally generated ultrasound waves, and label-free, exploiting the mechanical properties of particles for manipulation.

Acoustophoresis and acoustic streaming are the main phenomena involved in particles manipulation. Acoustically induced particle motion, referring to acoustophoresis, is obtained by generating a standing acoustic pressure field within a microfluidic channel. The particles dispersed into the fluid are subjected to two forces: the acoustophoretic radiation force, depending on size, density and compressibility of the particles, and the Stokes drag force induced from the fluid flow [5].

Surface acoustic waves (SAWs) can be generated through interdigital transducers (IDTs) deposited on the surface of a piezoelectric substrate. By applying an AC electrical signal to the electrodes composing the IDTs, the converse piezoelectric effect is activated, and surface Rayleigh waves are generated, called travelling surface acoustic waves (TSAWs). These waves propagate on the surface of the piezoelectric material and are transmitted to the fluid contained in a microchannel, placed above the substrate, in the form of pressure waves [6]. When two, or more, counter-propagating waves interact with a constructive interference, a standing surface acoustic wave (SSAW) is generated. In this way, a standing pressure field, composed by fixed pressure nodes (zero amplitude of the pressure wave) and antinodes (maximum wave amplitude), is transmitted to the fluid. Depending on the physical properties of the particles, they can be displaced towards the pressure nodes or antinodes [7]. Therefore, microparticles can be manipulated by adjusting the interaction between the SAWs and by generating a precise pressure distribution within the fluid [8].

Several studies and applications have been reported, effective in particles focusing, sorting or trapping. Chen et al. [9] designed a sheath-less microfluidic flow cytometer (device used to detect and measure physical and chemical properties of a population of cells or particles) which integrates a SSAW-based device capable of 3D particle/cell focusing with a laser-induced fluorescence (LIF) detection system. The device is continuously able to focus microparticles at the pressure node inside a microchannel. Nam et al. [10] presented a method for density-based separation of monodisperse encapsulated cells using a SSAW-based microfluidic platform. The number of cells encapsulated inside the polystyrene (PS) microbeads is difficult to be controlled, therefore their density is different, depending on the number of cells contained. The microbeads are displaced by the acoustic waves at various distances depending on their density. Guldiken et al. [11] designed a SSAW-based system for size-based particles separation in a microchannel. The device is composed by two stages: first the particles are focused on the same line exploiting two facing IDTs and then, again using two facing IDTs, the same particles are separated. Depending on their size, the acoustic waves are more or less effective in displacing microparticles, which are collected at separated outlets. Wu et al. [12] reported a simple yet reliable acoustic method to rapidly assemble cell spheroids in capillaries, in a replicable and scalable manner. Exploiting SSAWs generated with two facing IDTs, they were able to generate 300 trapping pressure nodes along the capillaries where the cells were trapped and assembled in numerous spheroids for biomedical applications. Ding et al. [13] demonstrated the possibility to manipulate single microparticles, cells and organisms (*Caenorhabditis elegans* in the paper) designing a SSAW-based microfluidic device composed by four IDTs.

In this work, the microfluidic flow is coupled with acoustic waves through a 3D multi-physics numerical solution to generate an optimized acoustic pressure pattern in the fluid contained in a microchannel, exploiting SSAWs. A configuration composed by four IDTs is investigated to enhance the focusing effect and achieve particles trapping. A complex matrix of wave nodes and antinodes is generated and optimized to acquire a precise acoustic pressure pattern. The results obtained show particle focusing effects but also trapping on specific sites (the pressure nodes). These innovative results highlight the versatility and the efficiency of this configuration depending on the design of the microfluidic structure implemented in the SAW-based platform. Applications towards biological cell sorting and assembling can be considered based on this principle.

2. Numerical Model

2.1. Geometry and Materials

The SAW-based device is composed by a lithium niobate (LiNbO_3) piezoelectric substrate, above which a PDMS design, containing microchannels and chambers, is placed. Four IDTs are deposited on the substrate, tilted by 45° with respect to the reference x -direction of the principle micro-channel. With this configuration, four TSAWs should be generated and interact in the region between the four IDTs to develop a standing SAW. In order to investigate the versatility of this platform, two different PDMS structures have been modelled: first, a straight microchannel containing flowing water passing in the region between the IDTs, to achieve the focusing effect on particles dragged by the fluid, and then a squared-base chamber containing static water and particles to achieve the trapping effect. The particles considered are made of polystyrene (PS) with a diameter of $8 \mu\text{m}$. The dimensions of the components of the SAW-based platforms are reported in Table 1 and the geometries are shown in Figure 1. The IDTs are made of 15 couples of $70 \mu\text{m}$ wide gold finger electrodes. Therefore, the SAWs wavelength, which is equal to the pitch of the IDT, is $280 \mu\text{m}$. All the properties of the materials have been taken from the material library of COMSOL Multiphysics, the software used to solve the problem.

Table 1. Geometrical dimensions of the SAW-based device components.

	LiNbO ₃ Substrate	PDMS Channel	Water Channel	PDMS Chamber	Water Chamber
Width	8627 μm	1650 μm	280 μm	1650 μm	1400 μm
Length	8627 μm	8627 μm	8627 μm	1650 μm	1400 μm
Thickness	500 μm	100 μm	50 μm	100 μm	50 μm

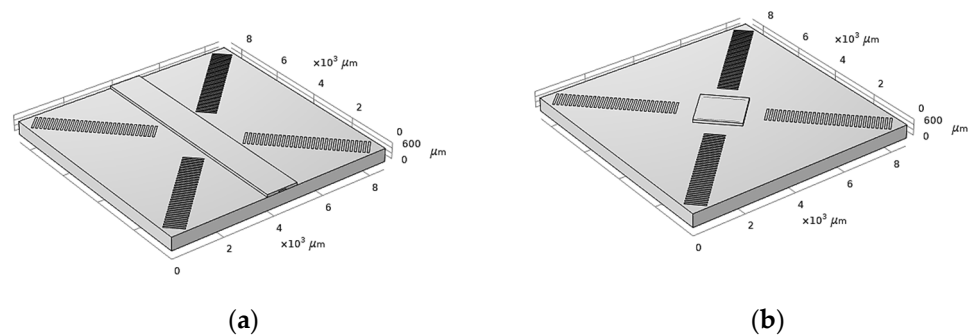


Figure 1. Geometry of the two configurations exploited to study the focusing and the trapping effect on particles contained in different PDMS structures. (a) Configuration with the PDMS channel containing flowing water and PS particles released from the inlet. (b) Configuration with the PDMS chamber containing static water and dispersed PS particles.

2.2. Physics Involved and Boundary Conditions

A 3D multi-physic finite element method (FEM) numerical model was used to study the acoustophoretic phenomenon driven by a SSAW field. The lithium niobate substrate is governed by the linear piezoelectric constitutive equations, the Maxwell's equations for the electric field and the stress–strain equations for the mechanical motion, given as

$$T = C^E \cdot S - e^{tr} \cdot E \quad (1)$$

$$D = e \cdot S + \varepsilon^S \cdot E \quad (2)$$

in which T is the mechanical stress tensor, C^E is the elasticity matrix, S is the strain tensor, e is the piezoelectric coupling matrix between the mechanical quantities and the electric fields, E is the electric field vector, D is the electric displacement and ε is the permittivity tensor. The superscripts E and S indicate that these two quantities should be kept fixed

to define the associated matrices, while the superscript *tr* represents the transpose of the matrix.

The harmonic acoustic field in the fluid is governed by the Helmholtz wave equation,

$$\frac{1}{\rho_i^*} \nabla^2 p - \frac{\omega^2 p}{\rho_i c_i^2} = 0 \quad (3)$$

$$\rho_i^* = \frac{\rho_i c_i^2}{\omega^2} \left(\frac{\omega}{c_i} - j \ln(10) \frac{\alpha_i}{20} \right)^2 \quad (4)$$

where p is the acoustic pressure, ρ_i^* is defined above, ρ_i is the density of the fluid (998 kg/m³), c_i is the speed of sound in the fluid (1500 m/s), $\omega = 2\pi f$ is the angular frequency (where f is the wave frequency) and α_i is the acoustic attenuation coefficient associated to the fluid. In the model this coefficient was set equal to 36.67 dB/m [14].

The low-reflecting boundary condition was associated to the lateral and bottom surfaces of the lithium niobate substrate to avoid the reflection of the waves, phenomenon which can cause interferences. The same condition was applied to the upper surface of the PDMS structures. The upper surface of the substrate was set free, not to constrain the propagation of the waves.

To generate the SSAW, an AC signal was applied to the electrodes composing the IDTs with an amplitude of 8 V. The piezoelectricity interface in COMSOL, exploiting Equations (1) and (2), converts the electrical stimulus in a mechanical surface displacement, which corresponds to the surface acoustic waves.

Several particles were released in the fluid domain to demonstrate the acoustophoretic phenomenon. When the acoustic pressure field is obtained, the acoustic radiation force can be computed, and the motion of each particle is governed by the Newton's second law. The particles are subjected to the ARF, defined as

$$\mathbf{F}^{ARF} = \frac{4\pi}{3} r^3 \nabla \left[\frac{1}{2} \text{Re}(f_1) \kappa_i \langle p^2 \rangle - \frac{3}{4} \text{Re}(f_2) \rho_i \langle v^2 \rangle \right] \quad (5)$$

where r is the radius of the particles (4 μm), f_1 and f_2 are coefficients depending on the density and compressibility of the fluid and the particles, κ_i is the compressibility of the fluid, while $\langle p^2 \rangle$ and $\langle v^2 \rangle$ are the time average of the pressure and velocity fields generated by the sound waves. For the configuration (a) in Figure 1, also the laminar flow of the fluid into the channel is modelled. Therefore, the particles are subjected to another force which is the drag force, defined as

$$\mathbf{F}^{Drag} = 6\pi\eta r (\mathbf{v}_i - \mathbf{v}_p) \quad (6)$$

where η is the dynamic viscosity of the fluid (1.002 mPa·s), \mathbf{v}_i is the fluid velocity (1 mm/s) and \mathbf{v}_p is the velocity of the particles. In the models, the particles are dragged by the fluid from the inlet towards the outlet of the channel and are displaced by the ARF towards the pressure nodes of the acoustic pressure field.

A frequency-domain analysis was performed to investigate the steady-state condition of the phenomenon. To find the resonant frequency for this configuration, the analysis was performed for frequencies between 11 MHz and 12 MHz. The best results in terms of surface displacement and pressure magnitude were achieved with a frequency of 11.685 MHz.

3. Results and Discussion

3.1. Standing Surface Acoustic Waves and Standing Pressure Field

In order to investigate the interaction between four TSAWs, another simpler configuration was modelled. The materials, the governing equations and the boundary conditions applied are the same used in the main model. With this configuration, the waves are constrained to move along the 45° tilted x -direction and to interact in the central region. The four waves constructively interfere in this region of the platform generating a SSAW, which is characterized by a regular distribution of nodes (green regions in the plot (a)

of Figure 2) and antinodes (blue and red regions in the plot (a) of Figure 2). The same pattern is transmitted to the fluid contained in the PDMS structure, positioned above the piezoelectric substrate, in the form of standing pressure waves.

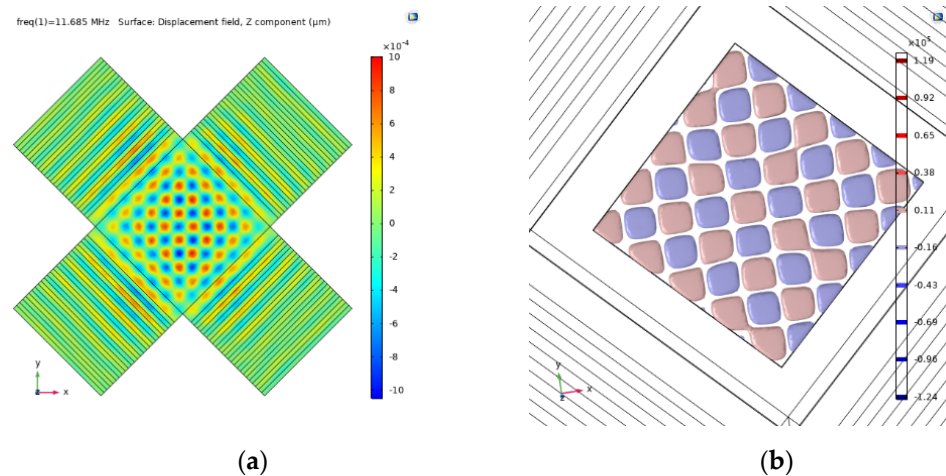


Figure 2. (a) Plot of the surface displacement in the z-direction of the reference frame. (b) Iso-surface plot of the pressure field transmitted to the fluid contained in the PDMS chamber. The four TSAWs interact in the middle region of the platform to generate a SSAW, characterized by a regular distribution of wave nodes and antinodes. Both the plots are seen from above the platform.

Due to the effect of the ARF, the particles should be moved from the pressure antinodes (blue and red regions in Figure 2b) towards the pressure nodes (white regions in Figure 2b) being collected there. The results reported are in a steady-state condition, obtained as solution of the frequency-domain analysis performed. The pressure field is used by COMSOL to compute the acoustophoretic radiation force, which is exploited to manipulate the particles.

3.2. Particles Focusing and Trapping

The model described in Section 2.1 was used to simulate the acoustophoresis on particles dragged by a flowing fluid in a straight channel and dispersed in a static fluid inside a chamber. In Figure 3a, the trajectories of the particles (the colored lines) dragged by the fluid in the PDMS channel are plotted. The focusing effect is demonstrated: the particles, due to the fluid flow, move and, when interacting with the pressure field, are focused on the pressure nodes. Usually, the same result is achieved using only two IDTs positioned one in front to the other. By applying the AC signal to the electrodes with the same frequency, a pressure node at the mid-width of the microchannel can be generated. Therefore, the particles are displaced by the ARF from the pressure antinodes to be focused on the central pressure node. The results obtained with the four IDTs configuration highlight the possibility to adjust the design of the SAW-based platform to exploit the versatility of the system. For example, by modifying the geometry of the channel and its position above the piezoelectric substrate, knowing the SSAW distribution, the location and the number of pressure nodes can be selected. This solution can be useful if intended to sort cells at different outlets, depending on their physical properties, or can be exploited for particles focusing on a single line, phenomenon that can avoid obstructions in microchannels when several particles are transported. In reference [14], a 2D simulation of a simple microfluidic SSAW-based platform made of two facing IDTs and a PDMS rectangular section microchannel is reported. Particle focusing is demonstrated with satisfying results which were used as a basis to model our four IDTs configuration. The main difference is the use of the low-reflecting boundary condition that completely avoids reflection of the waves: this effect can be replicated in real devices by combining to the device boundaries wave-absorbing materials or SAW absorber. The focusing effect, as reported in references [9]

and [11], can be achieved with two IDTs, instead of four transducers as in our work. In our study, the main innovation consists in the possibility of tuning the waves from four SSAW transmitters in order to control the direction towards where the particles are moved.

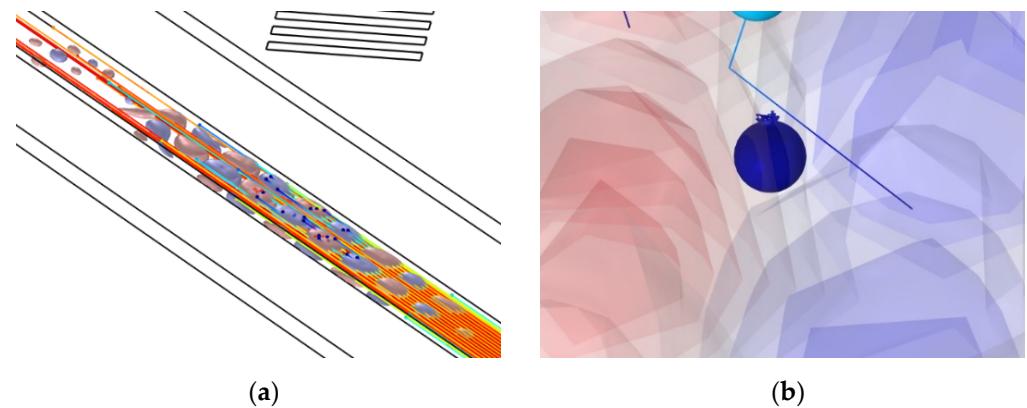


Figure 3. Acoustic manipulation phenomena on 8 μm PS particles exploiting a configuration made of four IDTs. (a) The focusing effect. The particles, being dragged by the fluid flowing within the PDMS channel, interact with the pressure field to be focused on the pressure nodes. (b) The trapping effect. Zoom on one particle trapped within a pressure node of the pressure field generated in the fluid contained in a PDMS chamber.

In Figure 3b, a zoom on one particle trapped in a pressure node is shown. The phenomenon is the same exploited for the focusing: the particles are displaced by the ARF towards the pressure nodes. In this case, the fluid is static, and the particles are dispersed into the fluid inside the PDMS chamber. The acoustic pressure continuously pushes the particle towards the pressure node causing its oscillation within this region (as can be seen in Figure 3b, the dark blue lines above the particle highlight its trajectory). This effect lasts for 0.2 s in the solution and then the particle is collected at the bottom of the pressure node.

The image reported in Figure 3 is taken at a time step of 0.101 s. Again, this result demonstrates the versatility of the configuration, which can be exploited to achieve different results (cells sorting, focusing, or trapping). The trapping effect can be used to isolate single cells, to perform aimed biological analysis on them, or to aggregate cells in spheroids which can be collected from the platform and then analyzed. With respect to the device described in reference [12], in our configuration the aggregation of cells in spheroids can be achieved with a two-dimensional distribution. If the phase of the AC signal on one IDT is modified, also the phase of the surface waves is tuned, causing a modification to the SSAW pattern on the surface of the piezoelectric substrate. By controlling the phase change, the particles can be manipulated and moved towards the required position. With this configuration, the effect can be obtained in full 2D directions instead of 1D as in reference [12].

As reported in reference [13], a SSAW-based platform made of four IDTs can be exploited for a precise manipulation of microparticles, cells or organism. The innovative side of our configuration is the versatility, which means not to limit the device use for just one single application but exploit all the possibilities that the device can offer simply by designing different disposable PDMS microfluidic channels (as reported in Figure 1). Of course, it is possible to modify the configuration of the IDTs (orientation, number or dimensions) for improving the versatility, but it means having to think about the design and the fabrication steps. In Table 2, a comparison of the data and the applications between the reference works and our work is shown. As one can notice, the frequency of actuation for SAW-based devices exploiting piezoelectric substrates is in the range of tens of MHz. Micro-sized particles, cells or organisms can interact with the acoustic waves; Wu et al. [15] showed the possibility of separating 100 nm and 500 nm particles using two facing IDTs, increasing the frequency of actuation to 33.13 MHz.

Table 2. Comparison of data and applications between our configuration and references.

Reference	Actuation Frequency	Particle Dimension	Focusing	Sorting	Trapping	Manipulation
[9]	19 MHz	7–10 μm	Yes	No	No	No
[10]	3.94 MHz	150.7 μm	Yes	Yes	No	No
[11]	13.2 MHz	3–10 μm	Yes	Yes	No	No
[12]	20.7 MHz	6–10 μm	Yes	No	Yes	Possible
[13]	18.5–37 MHz	6 μm	No	No	Yes	Yes
Paper	11.685 MHz	8 μm	Yes	Possible	Yes	Possible

4. Conclusions

A 3D multi-physic FEM model of a versatile SAW-based platform made of four IDTs to achieve the focusing and the trapping of particles was described. The advantage of this configuration relies in the achievement of different applications exploiting one single platform, simply by packaging different disposable PDMS design. Two PDMS frames (a channel and a chamber), containing PS particles within water, were positioned above a lithium niobate piezoelectric substrate to demonstrate these phenomena. A standing SAW is generated in the region between the four IDTs by applying an AC signal to the electrodes and activating the piezoelectric effect. The SSAW is transmitted, in the form of standing pressure waves, to the fluid contained in the PDMS structures. Exploiting the acoustophoretic radiation force, caused by the acoustic pressure, the microparticles can be manipulated and displaced towards the pressure nodes (zero wave amplitude). One limitation of the configuration is the minimum size of manipulated particles: the standing pressure field is effective in manipulating microparticles down to 4 μm of diameter, keeping reasonable dimensions for the device (not too long IDTs). The two effects, focusing and trapping, were demonstrated and reported, highlighting the versatility and the efficiency of the configuration depending on the design of the PDMS microfluidic structure implemented in the SAW-based platform. Applications towards biological cell sorting, isolation, and assembling can be considered based on this principle. In order to become enough efficient to be fabricated and used, also the design of the microchannels, in terms of width and length, presence of inlets and outlets, should be carefully considered and improved to satisfy the requirements for all the application fields.

Supplementary Materials: The poster presentation is available online at <https://www.mdpi.com/article/10.3390/ecsa-8-11256/s1>.

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