Simulation and Analysis of the Interdigital Transducers Surface Acoustic Waves Generation and Propagation in Acoustophoretic Lab-Chip

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Abstract. This work is devoted to the application of interdigital transducers for the formation of a standing acoustic wave in the microchannel of an acoustophoretic Lab-chip. 2D and 3D simulation of IDT operation was performed. The influence of IDT shape, its size, and location, geometric dimensions of the piezo-crystalline layer, as well as dimensions and material of the microchannel walls for the effective formation of standing acoustic waves were analyzed.

1. Introduction

The design, manufacturing, and application of microacoustofluidic Lab-chip devices combine technologies from solid and fluid mechanics, microelectronics, chemistry, biology and other domains [1-5]. Due to the processing of small volumes of liquids (from a few picolitres to several tens of microliters) the fluid flows in microfluidic devices comply with laminar flow (low Reynolds numbers), which allows to develop and use of various deterministic mechanisms for flow control. However, micro-and nanoscales require the consideration of surface-related phenomena like capillary forces, surface tension, roughness, fluid-structure interactions and others, which makes the Lab-chip engineering a complex multidisciplinary process. This is especially true for biological and biochemical mixtures, where non-contact transportation of microparticles is of crucial importance for the study of many biochemical phenomena. Typical non-contact methods based on electromagnetic principles have significant potential and are widely used in material science, but are limited for microfluidic Lab-chip applications because of particle size, fluid flow, certain material properties and/or other requirements. In the contrast, acoustic levitation is a non-contact and material-independent method of exploring microparticles, as well as does not require time-consuming sample preparation procedures.

The use of acoustic waves for focusing, separating, or transportation microparticles in the microchannels of Lab-chip devices attracts considerable attention from researchers due to the simple implementation of acoustic wave generators based on piezoelectric transducers. Since the sizes of acoustic waves generated by piezoelectric transducers correspond to the characteristic sizes of microchannels, there are plenty of successful experiments with both surface and bulk acoustic waves. The design, manufacture and control techniques of such interdigital transducers (IDT) are well developed in microelectronics, but their direct use in microfluidic devices requires adaptation and additional research. Mathematical modeling of the acoustic radiation spreading as well as modeling of microparticles movement in acoustofluidic Lab-chip devices is still a design challenge, which should be overcome during the development of new sensors, studying new materials or analyzing wave propagation in new designs.
The coupling and accurate interpretation of complex microacoustofluidic mechanisms including the IDT SAW generation, wave propagation in Lab-chip design, leaking SAW in fluids and its interaction with dispersed microparticles are the main topics of further discussion. The present continues our previous research on the acoustophoretic motion of plastic microparticles [3].

2. The specifics of acoustophoretic Lab-chip devices

All acoustophoretic Lab-chip devices are based on an acoustic field, which combines two types of acting forces – acoustic radiation force $F_{\text{rad}}$, and the indirect streaming drag force $F_{\text{drag}}$ caused by acoustically induced, circulating, streaming flow rolls (Figure 1). The figure shows that standing acoustic wave formed in half-wave microchannel cause the acoustic force, which eventually focuses particles towards the low-pressure nodal plane due to second-order effects.

![Figure 1. Schematic view of microchannel cross-section represented acoustic forces and streaming flow rolls and forces acting on microparticles.](image)

Depending on the design of the piezoelectric transducer, Lab-chip devices can utilize bulk acoustic waves (BAW) or surface acoustic waves (SAW) [6]. BAW devices are actuated through electrodes attached to both sides of a piezoelectric substrate, which generates acoustic waves in the entire transducer body. In SAW devices actuation is achieved through a pair of interdigitated opposite charged electrodes (IDT) formed on the piezoelectric substrate or layer. Further research here will be focused on SAW devices which are based on the Rayleigh mode. These waves include both longitudinal and transverse motions transmitted along the surface of the piezoelectric substrate and cause subnanometer movement of its molecules. At the point where SAW interacts with the liquid it changes its vibration mode into a leaky longitudinal wave which continuously travels through the liquid at a Rayleigh angle [7]:

$$\theta_R = \sin^{-1} \frac{v_L}{v_S},$$

where $v_S$ – SAW velocity on the piezoelectric substrate and $v_L$ – acoustic velocity in the liquid.

Using two pairs of orthogonally opposing IDTs that generate opposite leaky waves, one can obtain in microchannel or chamber the standing acoustic wave at ultrasonic frequencies with formed acoustic nodes and antinodes. These pressure nodes form streamlines in the microchannels and focus suspended particles similar to hydrodynamic or electrokinetic effects.

3. Analysis of piezoelectric SAW generators for Lab-chip devices

A typical acoustofluidic SAW Lab-chip device consists of a substrate covered by a thick piezoelectric lithium niobate layer with one or two aluminum IDT placed at the opposite sides of the rectangular microfluidic channel (Figure 2). By applying an oscillating electrical signal to IDT contacts, we activate SAW at a resonant frequency [8]:

$$f = \frac{c_S}{\lambda_{\text{SAW}}},$$

where $c_S$ is the sound speed in lithium niobate, and $\lambda_{\text{SAW}}$ is the spacing between successive IDT finger-pairs.
In general, for defined piezoelectric material (known speed of sound), the resulting SAW frequency, its amplitude, and wave-front orientation are defined by the design and dimensions of the IDT electrodes, frequency and input power of the applied electrical signal.

![Figure 2. Schematic design of acoustofluidic Lab-chip.](image)

1 - a piezoelectric layer of LiNbO3; 2-5 - IDTs, 7 – microchannel of PDMS, 6 - liquid.

However, depending upon required functionality there exist several IDT configurations, which have recently been used in various Lab-chip applications. The main design is presented in Figure 3.

![Figure 3. Typical IDT configurations in various Lab-chip designs: a) Straight IDT; b) Chirped IDT; c) Slanted IDT; d) Focused IDT.](image)

The straight IDT design (a) is a fundamental one, which consists of uniform electrode fingers, where each metal strip has a width of $\frac{1}{4} \lambda_{\text{SAW}}$. In specific cases of narrow microchannels when lateral displacement needs to be formed, a concentric circular arc structure of focused IDT (d) may be used for generating SAW with higher intensity. Next transducer configurations, like Chirped IDT (b) and slanted IDT (c), respectively, consist of fingers with varying spacing and dimensions to enable operation at a range of resonant frequencies [10].

4. Simulation of IDT for Lab-chip devices

The Lab-chip device analyzed in this work consists of a rectangular microfluidic channel with a cross-section 1,0x1,0 (mm) made by PDMS material. SAWs were generated by straight IDT designed with sets of 2, 3, 4 and 5 connected metallic finger pairs. The IDT fingers with 12,0 mm length, 10,0 mm aperture (overlapping width) and 0,25 mm pitch were formed by 1,0 μm aluminum film on top of the piezoelectric layer. In this simplest equidistant IDT, which has a constant spatial half-period of the electrodes $h_n = \frac{\lambda_0}{2}$ and a constant electrodes length, the partial waves are added in phase with the same amplitude. As a result, the frequency response of such transducer equal to the IDT acoustic synchronism frequency has the form of $\sin \frac{x}{x}$. To increase the selectivity of the IDT and implement various frequency characteristics, a variety of IDT designs have been proposed for weight processing of the amplitudes and phases of partial waves.
3D simulation of IDTs in the COMSOL environment allows obtaining the electrical potential on the surface of the LiNbO$_3$ electric potential (V) when applying an RF signal with an operation frequency of 1.48 MHz to one contact pad, while the other is grounded (Figure 4). The simulation results show that the penetration depth of the electrical signal is about 4.0 mm.

**Figure 4.** Distribution of electric potential for acoustophoretic Lab-chip.

To analyze the influence of various SAW lengths (channel width 2λ, λ, and λ/2) and microchannel location on the formation of stable standing acoustic waves, several simulations were carried out (Figure 5).

![Simulation results of standing acoustic waves](image)

**Figure 5.** Simulated surface electric potential (upper row), surface acoustic pressure field (middle row), and contours of standing acoustic wave in microchannels with 2λ (a), λ (b), and λ/2 (c) channel width.

The top row of the figure shows the distribution of the electric potential for a three-finger IDT. The excitation RF source generated a sinusoidal wave (\(\sin (2\pi/T_0 t)\)). The maximum value of the potential is 0.37 V for the channel’s width of 2λ and 0.36 V for the channel width of λ/2. As can be seen from all three figures, the total penetration depth of the electric potential under IDT equals λ/2, and at
the thickness of the piezoelectric layer needs to be at least one \( \lambda \) or 1.0 mm in our case.

The middle row of the figure shows the distribution of the acoustic pressure field. The acoustic pressure varies between -3.76...2.48 Pa for the channel width of \( 2\lambda \); -5.36...3.75 Pa for the channel width \( \lambda \); and -5.89...4.14 Pa for the channel width \( \lambda/2 \). The positive pressure value is shown in red, and the negative – in blue. The area depicted in white means zero pressure regions, where acoustic standing wave nodes are placed.

The focuses of the standing wave are well shown in the bottom row of the figure. It presents linear graphs of acoustic pressure along the line parallel to the channel bottom at a height of \( \lambda/4 \). Each line corresponds to a time step from 0 to 6.7568E-6 s with an interval equal to the wave period \( T_0 = 1/f_0 \), where \( f_0 \) is the frequency of the wave. As can be seen from Figure 5, at channel width \( 2\lambda \) three acoustic focuses appeared, at channel width \( \lambda \) or \( \lambda/2 \) – one acoustic focus. However, for the channel width \( \lambda/2 \), the acoustic focus is more accurate. Considering that for channel width \( \lambda/2 \) the acoustic pressure gradient is higher, one can assume that for such condition the focusing of suspended particles will be the most stable.

The theoretical analysis and obtained simulation results confirmed that IDT’s operational efficiency is determined by the substrate and electrode materials, IDT electrodes aperture, width, and height. These factors can be easily optimized by certain design parameters, like operation frequency. Additionally, the number of finger pairs can be modified to adjust the IDT impedance of the excitation, which plays a critical role in achieving efficient operation of SAW.

Conclusions
The increased popularity of the SAW-driven Lab-chip devices requires a fundamental understanding of physical phenomena appeared in IDTs, piezoelectric substrate, microchannel walls, fluid mixture and solid particles in fluid flow. However, the effective generation of SAW in acoustofluidic Lab-chip devices can be possible only through the design and optimization of the IDTs structure with the help of the CAD/CAE tool.

To increase the performance and stability of IDT, it is important to reduce signal loss and avoid unwanted side effects. It is shown that in addition to the choice of the piezoelectric substrate material with a high coefficient of electromechanical coupling, this can be achieved by optimizing the design and parameters of IDT, as well as optimizing the size and location of the microfluidic channel:

1. For the efficient manipulations with microparticles dissolved in the fluid flow, the optimal microchannel configurations have a width from \( \lambda/2 \) to \( 2\lambda \) and a height equal to either the wavelength \( \lambda \) or twice less \( \lambda/2 \).

2. The thickness of the piezoelectric layer (lithium niobate) critically affects the formation of standing acoustic waves only when it was reduced up to \( \lambda/2 \). To prevent such edge effects which lead to a decrease in the acoustic pressure in the microchannel, the thickness of the piezoelectric layer should be greater than \( 2\lambda \).

3. The number of IDT fingers has an important influence on the time of standing acoustic wave stabilization. For the studied configurations, the 4-finger IDT was the most optimal. Calculations proved that for such structures, the stable distribution of acoustic pressure in the microchannel was achieved in 10 cycles, and the standing acoustic wave is fully formed within 0.12 s.

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