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Particle manipulation by phase-shifting of surface acoustic waves

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ABSTRACT

An acoustic-based method for manipulating particles using phase-shifting is demonstrated. The location of the pressure node was changed simply by adjusting the phase difference (phase-shift) applied to the two interdigital transducers in the design. As a result, polystyrene particles of 5 μm diameter trapped in the pressure node were manipulated laterally across the microchannel fabricated. The lateral particle displacement from −72.5 μm to 73.1 μm along the *x*-direction was accomplished by varying the phase-shift with a range of −180° to 180°. In this paper, the particle displacement as a function of the phase-shift of SAW was obtained experimentally and close agreement with the theoretical prediction of the particle position was demonstrated.

1. Introduction

Lab-on-a-chip (LOC) technology is capable of carrying out chemical, biological, and biomedical processes on a microchip [1–3]. There are many advantages of scaling down the laboratory setups below sub-millimeter range, such as faster reaction rates due to the larger surface to volume ratio, smaller sample volume, high throughput, potentially low cost by utilizing mass production, and capability for compact and portable analysis systems [4,5]. LOC integrates various functionalities of analytical processes in a miniaturized flow system, such as sample preparation, manipulation, mixing, and separation.

The ability of precise manipulation of biological particles or cells in LOC is critical in cell biology, and biomedical engineering [6–8]. To date, variety of techniques have been studied to manipulate cells or particles in a microfluidic channel including optical [9,10], electric [11,12], magnetic [13,14], and mechanical methods [15,16]. However, these methods have drawbacks, such as the need for a complicated optical setup, damage to biological cells due to high heating, requirement of labeling of particles, and need for relatively long channel. Consequently, the development of precise, easy, biocompatible, and label-free manipulation technique is required.

The acoustic manipulation technique has inherent advantages such as label free, relatively inexpensive, high-throughput, and fast response time manipulation. The particle manipulation has been demonstrated by the bulk acoustic wave (BAW) [17–20]. As the acoustic radiation force is proportional to the particle volume and the operating frequency of the acoustic wave [21], the higher operating frequency is required to manipulate the smaller particles [22]. Thus, the BAW-based methods are not preferred choice for sub-micron particles manipulation due to inherent low frequency of BAW [23]. In addition, using BAW is not applicable to common microfluidic channel materials, such as PDMS, because of the requirement of high acoustic refection coefficient material for microfluidic channel [24]. Also, the BAW-based devices are challenging to integrate with planar components of the lab-on-a-chip and micro total analysis systems due to non-planar structures [25].

To overcome these disadvantages, surface acoustic waves (SAWs) excited by interdigital transducers (IDTs) patterned on a piezoelectric substrate have been investigated due to their flexibility in microfluidic channel materials, high energy efficiency, and good system integration and mass production [23]. For instance, standing SAW generated by interdigital transducers has been demonstrated to focus polystyrene particles [26]. Recently, the manipulation techniques for the various biological objectives (particles, cells, microbubbles, and natotubes) in one- and two-dimensions have been investigated by using the operating frequency change [27,28] and controllable phase of the SAW [29–32]. Especially, the manipulation of single particle and cell by employing tunable SAWs has been reported [33]. The tunable SAW was generated by chirped interdigital transducer (IDT), in which the pitch of the IDT electrodes ranges linearly. The gradient in the chirped IDT pitch leads to a wide range of working frequencies of SAWs. Thus, the pressure node position induced by SAW in the microfluidic channel was changed precisely by tuning the frequency of SAW so that the suspended particles were manipulated toward target outlet. However, the accurate fabrication of the chirped IDT with small pitch ranged linearly is one of drawbacks of this technique. In this paper, the SAW-based particle manipulation using phase-shift with conventional single-electrode-type IDTs is

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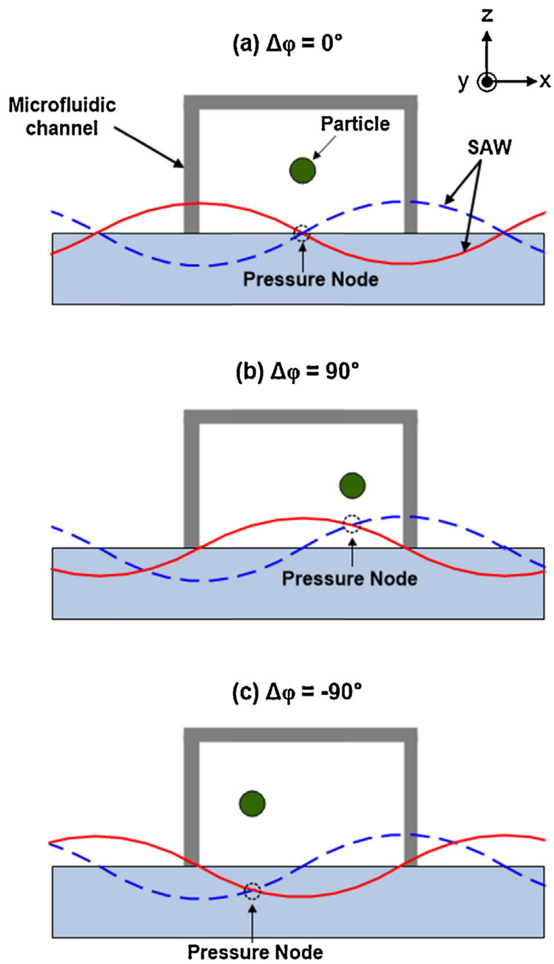

Fig. 1. Schematic diagram showing working mechanism of particle manipulation using phase-shift of SAW: (a) no phase-shift, (b) 90° phase-shift, and (c) −90° phase-shift.

investigated. The single-electrode-type IDT is widely used because of its structural simplicity and relatively wide strip width (a quarter of wavelength) which offers the ease of fabrication.

2. Operation principle

Fig. 1 illustrates the operation principle of particle manipulation using phase-shift of SAW. Two sets of IDTs are patterned on a substrate (piezoelectric in this study) that excites the standing SAWs propagating toward the microchannel that is positioned at the center of these two sets of IDTs. The constructive and destructive overlapping of the two SAWs that propagate toward the microchannel causes the periodic generation of pressure nodes and anti-nodes. As particles in a liquid buffer are exposed to standing SAW field, the particles or cells are driven toward a pressure node or pressure anti-node by an acoustic radiation force. Typically, most particles and cells in a medium move toward the pressure node [34].

The pressure node position within the microfluidic channel can be manipulated by varying the phase difference (phase-shift) of the signal voltages inputted to the two sets of IDTs. As seen in Fig. 1(a), as the microchannel is located right at the center of the two IDTs, particles are accumulated at the center of microchannel (coinciding with the pressure node) with no phase-shift (reference position in *x*-direction). If the phase shift of 90° is applied by changing the phase of one of the SAWs (red solid line in Fig. 1), the pressure node is moved in the positive *x*-direction, and the particle moves

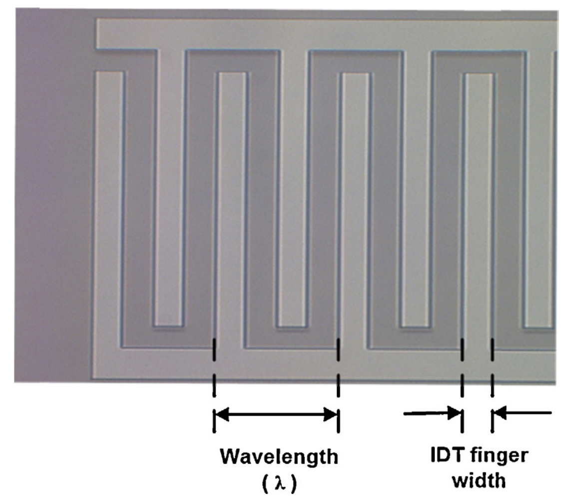

Fig. 2. Top view of a single-electrode-type interdigital transducer.

toward the new pressure node location (Fig. 1(b)). If the phase shift of −90° is applied, the pressure node moves along negative *x*-direction, and the particle is manipulated to the new pressure node location (Fig. 1(c)). By adjusting the phase difference (phase-shift) applied to the two IDTs, pressure node position within the microfluidic channel changes linearly, resulting in the manipulation of a particle trapped to the pressure node.

3. Materials and methods

The interdigital transducer (IDT) is most commonly used for excitation and detection of SAW. The IDT is composed of a pair of metal comb-shaped electrodes patterned onto the piezoelectric substrate. Fig. 2 illustrates the top view of conventional single-electrode-type IDT. A voltage applied between the pair of electrodes generates an electric field in the piezoelectric substrate, and then it excites a strain of the substrate by piezoelectric effect. The spatial periodic pattern of the electrodes generates traveling acoustic waves along the surface of the substrate due to the periodic strain field, resulting in the SAW. The response is most efficient when the period of the electrodes is equal to the acoustic wavelength (λ) in the substrate as seen in Fig. 2. The electrode finger width is the same as the finger spacing in the most commonly used single-electrode-type IDT. Thus, the acoustic wavelength is four times the electrode finger width. The IDT used for this study consisted of 25 electrode finger pairs with finger width/spacing of 75 μm.

The operation frequency, *f* is a function of the acoustic wavelength (λ) and the SAW velocity on the selected piezoelectric substrate (V_{SAW}) as following; $f = V_{SAW}/\lambda$. To accomplish higher operating frequency, the piezoelectric substrate having larger SAW velocity is selected or the acoustic wavelength is decreased by reducing the periodicity of the IDT fingers. The frequency of the interdigitated transducers was designed as 13.3 MHz, which was obtained with the SAW velocity on the lithium niobate piezoelectric substrate of 3990 m/s and the acoustic wavelength of 300 μm.

The single-electrode-type IDTs were fabricated by deposition of chrome layer with 100 nm thick on a 128° Y-rotated, X-propagating lithium niobate ($LiNbO_3$) piezoelectric substrate using photolithography procedures. Soft lithography replica molding methodology was employed to fabricate the microchannel in the design. The depth and the width of the microchannel used in this study were designed to be 100 μm and 150 μm, respectively. The detailed fabrication process of the SAW-based microfluidic devices used in this study can be found in [35]. Fig. 3 shows a fabricated SAW-based microfluidic device for particle manipulation by phase-shifting.