Sensors and Actuators A 196 (2013) 1–7

Contents lists available at SciVerse ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Dual surface acoustic wave-based active mixing in a microfluidic channel

Myeong Chan Jo, Rasim Guldiken*

Department of Mechanical Engineering, University of South Florida, Tampa, FL 33620, USA

A R T I C L E I N F O

Article history:
Received 17 August 2012
Received in revised form 14 March 2013
Accepted 25 March 2013
Available online 1 April 2013

Keywords:
Surface acoustic wave
Mixing
IDT
Microfluidic channel

A B S T R A C T

Many applications need fast and efficient mixing of the sample and reagent with high throughput in a microfluidic channel. Due to low Reynolds number, mixing based on molecular diffusion plays an important role in a microfluidic channel. However, the diffusion based mixing process is very slow and the efficiency is low. The development of a highly efficient mixing technique is essential for lab-on-a-chip and micro-total-analysis systems. In this paper, we introduce a highly efficient active mixing technique using dual acoustic streaming field induced by surface acoustic waves in a microfluidic channel. The rapid and high efficiency active mixing of a fluorescent dye solution and deionized water in a microfluidic channel was demonstrated with single acoustic excitation by one interdigitated transducer (IDT) as well as dual excitation by two IDTs. The mixing efficiencies were investigated as a function of applied voltage and flow rates. Our results indicate that with the same operation parameters, the mixing efficiency with dual-IDT design increased to 96.7% from 69.8% achievable with the traditional single-IDT design. The effect of aperture length of the IDT on mixing efficiency was also investigated.

1. Introduction

Microfluidic systems are employed in variety of bio and chemical applications including cell separation and detection, genetic analysis, drug screening, and chemical synthesis and reactions. These applications need fast and efficient mixing of the sample and reagent with high throughput. Since the flow in a microfluidic channel is laminar due to low Reynolds number, obtaining efficient mixing is a formidable task. The inherently slow molecular diffusion mixing in a microfluidic channel requires very long channel design which conflicts with miniaturization and integration needs. To address these requirements, various techniques for efficient mixing have been studied. In general, the mixing techniques are classified into two types according to the actuation and control mechanism, such as passive and active mixing.

Passive mixing methods rely completely on the geometry of the microfluidic channel to increase the contact surface and decrease diffusion path between adjacent fluid streams, such as wedged shaped inlets [1], zigzag channels [2], folding structure [3], creeping structure [4], stacked shim structure [5], embedded barriers [6,7], and twisted channels [8]. On the other hand, active mixing methods employ external force fields including dielectrophoretics [9], electrokinetics [10,11], electrohydrodynamics [12,13], magnetics [14], and acoustics [15]. Although integration of active mixers with microfluidic system is more challenging due to the requirement of external power sources, it has been shown that active mixers perform better than passive ones in terms of efficiency and mixing time [16].

Acoustic-based active mixing technique has been studied as acoustic actuation causes a pressure variation within the fluids. Acoustic-based mixing has been demonstrated by using acoustic streaming with piezoelectric zinc oxide thin film [17], lead zirconate titanate membrane [18] and acoustically driven sidewall-trapped air bubble [19]. Recently, the acoustic streaming induced by surface acoustic wave (SAW) has been investigated as SAW-based method features low propagation loss, low power consumption, and ease of integration [20]. SAW-based mixing studies have been conducted in two different fluidic conditions; in a droplet [21–26] and in a confined microchannel [27–30]. Highly efficient mixing inside a droplet has been demonstrated using internal streaming induced by SAW. On the other hand, there are only few reports of the SAW-based mixing in a microfluidic channel. Tan et al. [27] have reported the phenomena of vortical flow for mixing in a microchannel fabricated directly onto a piezoelectric substrate with high frequency SAW transducers. Sritharan et al. [28] has conducted SAW-based mixing between water and microbeads solution in a Y-shape microfluidic channel. The interdigitated transducer was directly located below the channel inlets. Luong et al. [29] has demonstrated SAW-based mixing with a solution of fluorescent dye and deionized water in a T-shape microfluidic channel at high flow rates. The effects of two different interdigitated electrode configurations (parallel and focused) and the applied voltages with different flow rates on the mixing efficiency were reported. Zeng et al. [30] have investigated fast mixing with DI water and

* Corresponding author. Tel.: +1 813 974 5628; fax: +1 813 974 3539.
E-mail address: guldiken@usf.edu (R. Guldiken).

0924-4247/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.sna.2013.03.028

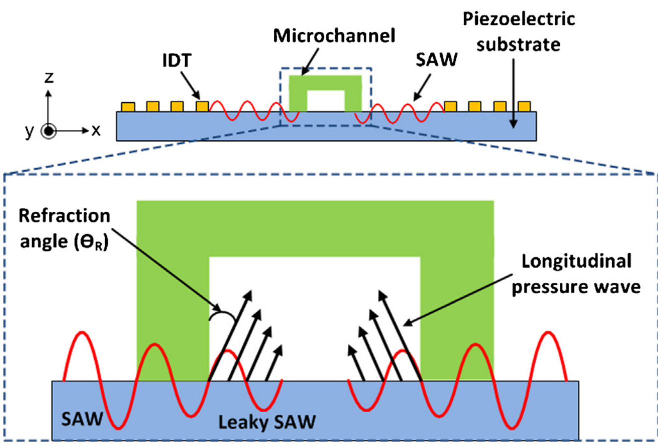

Fig. 1. Schematic diagram illustrating working concept of the dual SAW-based active mixing. The acoustic energy is radiated into the sample liquid at the refraction angle, leading to acoustic streaming inside the sample liquid.

quantum dots solution using focused SAW. The solutions were mixed in milliseconds by concentrated acoustic radiation in a Y-shape microfluidic channel. However, these previous studies used a single interdigitated transducer to generate a single acoustic steaming in a microfluidic channel. In this paper, we introduce a dual SAW-based active mixer design using dual acoustic streaming generated by two interdigitated transducers. We also compare mixing performance obtained with dual SAW-based mixing with the traditional single interdigitated transducer design. In addition, effect of aperture length of the interdigitated transducer on mixing efficiency is also presented.

2. Working mechanism

The working mechanism of the proposed dual SAW-based active mixer is shown in Fig. 1. The dual SAW-based active mixer consists of a pair of interdigital transducers (IDTs) patterned on a piezoelectric substrate and polydimethyl-siloxane (PDMS) microfluidic channel. Two series of SAWs are generated when AC signals with same amplitude are applied to both IDTs. When the SAWs propagating in opposite directions reach the sample fluid inside the microfluidic channel, the SAWs are transformed to leakage waves inducing pressure fluctuations, and then the longitudinal pressure waves are radiated into the sample fluid at the reflection angle (called the Rayleigh angle [20]). This reflection angle of the radiated wave is determined as:

$$\theta_R = \sin^{-1}\frac{C_f}{C_s} \tag{1}$$

where C_f and C_s are the speed of sound in the fluid and on the substrate, respectively. Acoustic streaming is generated inside the sample liquid by longitudinal pressure waves, resulting in internal net flow circulation. This acoustic streaming effect causes the active fluid mixing in the microfluidic channel. Based on this working mechanism, a single acoustic excitation by one IDT design as a reference (Fig. 2(a)) and dual excitation by two IDTs (Fig. 2(b)) were used to investigate the effect of excitation type/configuration on the mixing efficiency. In addition, the effect of the IDT aperture length of the dual SAW-based active mixer (shown in Fig. 2(b)) on the mixing efficiency was investigated. As illustrated in Fig. 2, the region of interest (ROI) was selected 2 mm downstream from the end of the SAW working region defined by IDT aperture for all experiments to quantitatively determine the mixing efficiency.

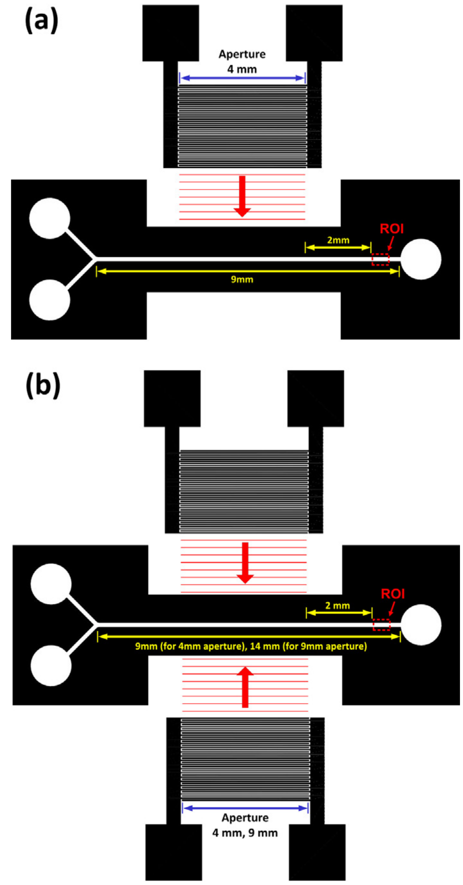

Fig. 2. Schematic diagram of the two different SAW-based active micromixers used in this study (note the figure is not to scale); (a) a single acoustic excitation by one IDT and (b) double acoustic excitation by two IDTs.

3. Design, fabrication and experimental characterization

3.1. Fabrication process

The dual SAW-based active mixing device consists of two parts: IDTs fabricated on a piezoelectric substrate to generate SAWs and Y-shape PDMS microfluidic channel for transporting the sample fluid. A 128° YX lithium niobate ($LiNbO_3$) was selected for the substrate of the device due to its good optical transparency and a larger electromechanical coupling coefficient (k^2 = 5.5%) as compared to other piezoelectric substrates which generate SAW [31].

The IDTs was fabricated with photolithography process. A chrome layer of 100 nm thickness was first deposited on a double-side polished 128° YX $LiNbO_3$ wafer with DC sputter (Torr International, New Windsor, NY). The $LiNbO_3$ wafer was then coated with S1813 photoresist of 1.6 μm-thick (Shipley, Marlborough, MA), patterned using a UV light source, and developed in MF 319 developer (Shipley, Marlborough, MA). The chrome layer was then etched with CR-7S chrome etchant (Cyantek, Fremont, CA). Lastly, the photoresist was removed with AZ-400T photoresist stripper (AZ Electronic Materials, Somerville, NJ). The fabricated IDTs have 25 pairs of fingers with pitch of 300 μm and width/gap of 75 μm. Since the wavelength of SAW generated by the IDT is equal to the IDT finger pitch, wavelength is 300 μm for the selected design. The operating frequency of the IDT is defined by the ratio the speed of sound on the substrate to the wavelength of SAW. The operating frequency of the IDT used for this study is 13.3 MHz based on the speed of sound on the 128° YX $LiNbO_3$ substrate of 3990 m/s