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BIOFUNCTIONALIZED NANO-ELECTRO-MECHANICAL-SYSTEMS (BIO-NEMS):
ACOUSTIC TWEezERS—APPLYING ACOUSTICS IN MICROFLUIDICS AND
ACTIVE PLASMONICS

A Dissertation in
Engineering Science and Mechanics

by

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ABSTRACT

The ability to actively manipulate cells and microparticles on-chip is critical for numerous biological studies and applications such as flow cytometry, cell sorting, microarrays, tissue engineering, and regenerative medicine. Researchers have developed a variety of patterning techniques such as microcontact printing, optical tweezers, optoelectronic tweezers, magnetic tweezers, electro-/dielectro-phoresis, evanescent waves/plasmonics, hydrodynamic flows, and bulk acoustic wave-based acoustophoresis. However, none of these techniques simultaneously meet specifications for miniaturization, versatility, throughput, speed, and power consumption. This thesis presents an active manipulating technique named “acoustic tweezers” that utilizes standing surface acoustic wave (SSAW) to build an acoustophoresis platform which can (1) three-dimensionally focus or even line-up micro/nanoparticles in a microchannel to facilitate the flow cytometry/cell sorting; (2) pattern virtually all kinds of cells and microparticles in both one-dimensional and two dimensional manners regardless of their shape, size, charge or polarizability; (3) continuously separate particles with different sizes, densities or compressibility through a continuous flow in a microchannel. Its power intensity, approximately 500,000 times lower than that of optical tweezers, compares favorably with those of other active particle-manipulation methods. Its speed is among the highest reported in literature, and flow cytometry studies have revealed it to be non-invasive. The aforementioned advantages, along with this technique’s simple design and ability to be miniaturized, render the “acoustic tweezers” technique a promising tool for various applications in biology, chemistry, engineering, and materials science.

Furthermore, the “acoustic tweezers” technique was also verified to be effective in active tuning of surface plasmons—electron density waves that can potentially merge the photonics and electronics at nanoscale. Significant advances have been made in the development of sources, filters and waveguides, so called passive plasmonics devices though, for plasmonics to reach its
potential, devices such as switches and modulators - so called active devices must be perfected. This thesis discusses two “acoustic tweezers”-induced active plasmonic devices that utilize SSAW to tune the localized surface plasmon resonance (LSPR) of gold nanodisk arrays (1) through realigning the LC molecules surrounding them; and (2) through the SAW-induced charging/discharging on a piezoelectric substrate without any liquid medium. The acoustic-induced active plasmonics features low power, easy fabrication and assembly and high efficiency.

In the the appendix, there are two relative topics are included. Appendix A discusses a technique using phononic crystal composites to manipulate ultrasounds, which can be used in acoustic tweezers to confine the acoustic energy, improving its performance. Appendix B discusses nanoparticle manipulation through surface plasmon polaritrons, which is actually an alternative technology to overcome the difficulties that acoustic tweezers endure in nanoparticles (less than 500 nm) manipulation.
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Chapter 1

Introduction

§ 1.1 Basics of surface acoustic waves

A surface acoustic wave (SAW) is a special elastic wave mode that travels along the surface of an elastic material, with amplitude that typically decays exponentially with depth in the substrate (as shown in Figure 1-1) [1]. SAW is also known as Rayleigh wave for its discovery in 1885 by Lord Rayleigh, who reported the surface acoustic wave mode [2]. A SAW features a composite vibration mode containing both a longitudinal and a shear vertical vibrations, which means the substrate where a SAW propagates will attend two vibrations in both X and Z directions (Figure 1-1 a). As a result, a combined anti-elliptical movement is obtained along the surface, as shown in Figure 1-1b. Figure 1-1 is a schematic of a typical SAW device, showing a typical method to generate a SAW using interdigital transducers (IDTs) on a piezoelectric substrate. The piezoelectric effect, discovered in 1880 by the Curie brothers [3], characterizes the ability of some materials that can generate electric potentials in response to the mechanical stress, and vice versa. The IDTs are parallel electrodes with identical period from one end to the other end, which are normally fabricated through e-beam or thermal evaporation of metal (Au, Al, Cu, Ag etc.). With an applied AC signal, the redistribution of charges along the electrodes will generate mechanical stress on the piezoelectric substrate at the corresponding sites, resulting in mechanical deformation of the substrate and eventually forming the SAW [9]. Upon introducing another IDT (with identical period with the SAW generating IDT) in the propagation line of the SAW, it will convert the mechanical stress back into an electrical signal. The conversion
efficiency between electric and acoustic energy, known as electromechanical coupling coefficient ($\kappa^2$), is a key factor in deciding the performance of a piezoelectric material which generates an acoustic signal. Piezoelectric materials are generally divided into four categories: crystals (quartz (SiO$_2$), Lithium niobate (LiNbO$_3$), Lithium tantalite (LiTaO$_3$), tourmaline, topaz, Rochelle salt), ceramics (PZT, glass), polymeric piezoelectric materials (poly(vinylidene fluoride) (PVDF) and its copolymer with trifluoroethylene (TrFE)), and composite piezoelectric materials [4–8]. Among these, PZT, quartz, LiNbO$_3$, and LiTaO$_3$ are the most widely used materials in SAW generation. Comparing with the bulk acoustic wave (BAW), which propagates in omni-directions, SAWs localize most of their energy along the surface: with the depth increasing, the amplitude of the SAW decreases exponentially (Figure 1-1 c), implying the low loss in propagation and high sensitivity with surface modifications.

Figure 1-1: The principle of SAW: (a) generation method. (b) acoustic wave mode and coupled surface movement. (c) energy distribution along the surface through the substrate.
§ 1.2 Applications of SAW

§ 1.2.1 Traditional applications

One of the most widely used applications of SAWs lies in the radio frequency (RF) communications. Since the resonance frequency of a SAW is defined by the division of SAW velocity to the period of IDTs, the response of a SAW device is highly dependent on the frequency of the applied RF signal. This dependence makes the SAW device attractive in RF communications for transmitters and receivers, as shown in Figure 1-2 a [10]. SAWs are also very sensitive to the surface properties of the propagation line, as most of the SAW energy is

Figure 1-2: Some applications of SAW: (a) RF communication (b) Bio-sensor (c) Chemical sensor (d) precise motor control [10–14].
confined within 1~2 wavelengths normal to the surface of the substrate. This property can be used in chemical- or bio-sensing [11, 12]. In these applications, the propagation line of the SAW substrate was modified with chemical or biological coatings serving as bonding sites. When the analytes (normally in vapor phase) pass through the propagation line, the target objects bond with the substrate, changing the central frequency (resonance frequency) (known as mass loading effect [13]). The frequency change can be used to quantify the concentration of the target objects in the analytes. Figure 1.2b and c are examples of chemical and bio-sensors based on SAW technology, which are normally integrated with the integrated circuit (IC) for signal detection and processing. The amplitude of the SAW-induced surface vibration along an elastic substrate is normally within 10 nm, which can be used in precise motor control [14]. Due to the anti-elliptical movement of the substrate, the tiny slider ball in the propagation line of SAW will be subject to a net force in the opposite direction of the SAW propagation. This force then moves the ball in the opposite direction of the SAW propagation with nanometer resolution, as shown in Figure 1-2 d.

§ 1.2.2 Optical switches and modulators based on SAWs

As discussed in § 1.1, SAWs are normally generated on a piezoelectric substrate. The coupled mechanical vibration and electric field caused by the non-uniform charge distribution in

![SAW induced electric field and charge distribution along the piezoelectric substrate.](image)

Figure 1-3: SAW induced electric field and charge distribution along the piezoelectric substrate.
a SAW waveform enable many applications. As shown in Figure 1-3, the periodic mechanical deformations (stress) generate periodic distribution of electric charges across the crystal lattice. Due to the non-conductivity of the substrate, the applied charge will generate an electric field across the material, pointing from the positive to the negative.

In the presence of sound waves, certain materials (like LiNbO$_3$, LiTiO$_3$) will be subject to changes in refractive index [15]. These changes, generally due to the pressure fluctuations, can be used to affect the performance of the light passing through these materials, which is known as acoustooptic effect [15]. The effect consists in that a SAW travelling through the material induces a moving periodic refractive index change, thereby forming a grating, i.e. a phase transmission grating. A light beam incident at the proper Bragg condition direction will be diffracted by such a grating (Figure 1-4). The diffraction efficiency is decided by the refractive index modulation, acoustic intensity and wavelength [16], as expressed in equation 1-1 and 1-2:

$$\eta \cong \sin^2 \left( 2.2 \frac{I}{\lambda \sqrt{MI_{SAW}}} \right)$$  

(1-1)

Figure 1-4: Schematic of SAW-induced dynamic gratings on a piezoelectric substrate, which diffract the incident light that satisfies the Bragg condition.
\[ M = \frac{n^6 p_{\text{eff}}^2}{\rho \nu_{\text{SAW}}^3} \]  

where \( l, I_{\text{SAW}}, \lambda, n, p_{\text{eff}}, \rho, \nu_{\text{SAW}} \) are the interaction length, the SAW intensity, wavelength of the SAW, average refractive index of the material, effective photoelastic coefficient, mass density, and the SAW velocity in that substrate, respectively. The diffraction efficiency can be easily tuned when varying interaction length and acoustic intensity.

Figure 1-5: An optical modulator and switches based on the SAW on a GaAs substrate. (a) Schematic drawing of the device setup, (b) the measured modulations of the diffraction, and (c) the theoretical analysis and the comparison of the diffractions under SAW “on” and “off”, respectively [16].
As one application of the acoustooptic effect, Figure 1-5 demonstrated a light modulator and switch based on the SAW technology, where an optical resonator driven by a SAW is achieved. The resonator is formed by two Bragg mirror (BM) layers (GaAs/AlAs) sandwiching a cavity layer (Figure 1-5 a). Its reflection coefficient for normal light incidence reaches its maximum at a sharp response wavelength of:

\[
\lambda_c = 2n_c d_c
\]  

(1-3)

within the stop band created by the BMs, where \( n_c \) and \( d_c \) denote the refractive index and the thickness of the cavity layer, respectively. The operation of the device is based on the modulation of the resonance wavelength (\( \lambda_c \)) by the SAW. The modulation originates from three mechanisms: (i) the acoustooptic modification of the refractive index \( n_c \) by the SAW, (ii) the modulation of the cavity thickness \( d_c \) by the vertical deformation of the substrate caused by the SAW, and (iii) the modulation of the interface profiles by the SAW displacement field. The coupled effect of these three mechanisms makes it a travelling gratings corresponding to the fixed incident light, resulting in the modulated reflectivity and transmission (Figure 1-5 b). Figure 1-5 c shows the measured diffraction signal from an incident light (with the Bragg angle \( \theta_B \)) with and without SAW. A strong modulation effect is depicted in Figure 1-5 c, where the diffracted light was strongly enhanced by the SAW.

§ 1.2.3 SAW induced dynamic quantum dots in GaAs quantum well

Quantum effects in the low-dimensional semiconductor structures in nanometer level have garnered much research interest. The scaling down of semiconductor structures from micrometer scale to nanometer scale, however, normally requires sophisticated techniques and expensive equipments [17]. Simple but effective alternative methods that can achieve the structures in nanometer scale are definitely attractive. Figure 1-6 demonstrated an experimental
achievement of the coherent spin transport through dynamic quantum dots (DQDs) [18]. Two obliquely arranged IDTs are excited with identical radio frequency (RF) signals. The interference of the generated

Figure 1-6: (a) schematic of the generation of dynamic quantum dots (DQDs) using SAW on the GaAs substrate. Bright color regions correspond to negative DQDs, where the electrons are stored. (b) Generation, transportation and recombination of the charge carriers in the propagation line of the SAW. G: laser incident spot; M: metal strip for electron–hole recombination [18].
coherent acoustic phonons (CAP) results in a two-dimensional electric potential field in the lateral direction along the substrate. Taking into account the vertical potential of the quantum well located near the surface, a three dimensional confinement electric potential of the DQDs forms [18]. When photos are absorbed within the DQDs array, the strong piezoelectric potential efficiently ionizes the excitons and the generated electron-hole pairs are trapped by different DQDs, defined as positive and negative DQDs, respectively. Due to the moving property of the DQDs based on the propagating SAW, the separated electron and hole pairs can be transported over a much-longer distance than the situation when SAW is absent. A metal obstacle is placed in the propagation line of the DQD to help the recombination of the electrons and holes. As a result, the strong photoluminescence is detected along the metal obstacle upon the recombination of the electrons and holes [18].

§ 1.2.4 SAW induced rectified charge pumping

When SAWs propagate along a piezoelectric substrate, there will be a combined electric potential field in the propagation line, which have been used traditionally in transporting quantified electrons \( (e) \) through one-dimensional (1D) channels within a GaAs heterojunction, just like the pumping of water by an Archimedean screw [19]. Upon applying a SAW, quantified number \( (n) \) of electrons are transported through the heterojunction within one period \( T \) \( (1/f, f \) is the SAW frequency), thereby defining a current unit of \( I = nef \) [19, 20]. This current can be as small as 1 nA and can be dynamically tuned by changing the SAW frequency and intensity. In order to reduce the power consummation and miniaturize the device, singal-electron devices are highly desired. The recently developed charge pumping through carbon nanotube using SAW showed great promising in both current accuracy and tunability. Figure 1-7 a shows the setup for charge pumping through aligned carbon nanotubes in between the electrodes. Carbon nanotubes
are placed along the SAW propagation direction between the pre-deposited electrodes (source S and drain D) and contact with the central electrode (gate G) [20]. The distance between S and D is set to be one wavelength of the SAW such that the charge pumping frequency is identical with the SAW frequency. The SAW-induced electric potential locally tuned the band diagram of the

Figure 1-7: Charge pumping in a carbon nanotube (a) top view of the fabricated device, (b) zoomed in figure of the IDTs, (c) zoomed in figure of the charge pumping structure, containing source (S), drain (D) and gate (G) electrodes and the carbon nanotube from S to D. (d), (e) and (f) show the SAW-induced charge transportation process [20, 21].
carbon nanotube, as well as the junction barrier between the nanotube and the metal electrodes. At certain phase ($\Phi = 0$), the conductive band ($E_c$) of the carbon nanotube is lower than the Fermi band of the contact source electrode, resulting in the electrons tunneling through the potential barrier into the carbon nanotube. This process was demonstrated in Figure 1-7 d, e and f. With the propagation of SAW, the packets of electrons are transported along the SAW to the drain electrode, forming the current [20]. At the same time, holes will also be transported in the same mechanism, just in the opposite direction as the electron transportation.

§ 1.2.5 SAW induced acoustic streaming and its relative applications

As discussed in § 1.1, a propagating SAW generates traveling vibrations (deformations) along an elastic substrate, which eventually causes a relative vibration (or corresponding deformation) to the encountered medium like solid balls, water droplets or air [22, 23]. Among these, the effect when SAW encounters with a liquid droplet is more attractive because of its potential applications in microfluidics.

Figure 1-8 schematically introduces the SAW-induced streaming effect in a droplet, when a SAW encounters a droplet in semi-free space. When SAW encounters with an incompressible
liquid droplet in the propagation line, the SAW-induced vibrations along the substrate surface generates pressure fluctuations in the contacted droplet with the angle $\theta_R$ defined by the Snell’s law, which exert forces to the molecules of the liquid [24]. Because of the attenuation of the SAW energy in the propagation line, the vibration amplitude decays exponentially, resulting in a pressure gradient inside the droplet: the front edge of the droplet endures larger pressure fluctuations than the center. Due to the property of the semi-free space of the droplet, the pressure gradient causes a recirculation flow inside the droplet in the clockwise direction, as shown in figure 1-8. Figure 1-9 a demonstrates an experimental setup to manipulate a droplet on a hydrophobic substrate using arrayed SAWs [24]. In this design, by exciting the IDTs arrays sequently, the droplet can be transported to the desired positions in two dimensions [24]. Figure 1-9 b clearly depicts the streaming effect of the SAW, where the contact angle of the front edge

Figure 1-9: Droplet manipulation using SAW, (a) experimental setup, (b) Streaming effect on the contact angle of the droplet, and (c) the periodic deformation of the droplet in transportation [25].
of the droplet is smaller than that of the back edge due to the pressure gradient inside the droplet. When the SAW intensity is high enough, the droplet moves with the SAW and Figure 1-8 c records the four statuses of the droplets in movement. The streaming effect is widely used in droplet manipulation, suspension particle manipulation and laminar flow mixing. The following sections will discuss examples of utilizing SAW-induced streaming effect in fluidics.

**Droplet ejector**

The interests in droplet ejection microsystems have dramatically grown in recent years due to the demand for inkjet print-head [26]. Most of the current ink jets (thermal, piezoelectric, [26].

Figure 1-10: SAW based droplet ejector (a) experimental design, (b) and (c) the recorded droplet ejection with different applied powers [26].
etc.) eject ink droplets through nozzles, with a direction perpendicular to the nozzle surface. The complex fabrication of nozzles in micro or even nanometer scale, however, greatly limits their duration time and increased the cost. Figure 1-10 gives an example of nozzle-free droplet ejector using SAW on a lithium niobate (LiNbO₃) substrate [25]. When enough power (>1W) is applied to the IDTs, the generated SAW can eject satellite droplet from the liquid medium contacted with the SAW substrate. As illustrated in Figure 1-8, the direction of the pressure fluctuations inside the droplet is defined by Snell’s law, which gives:

\[
\theta_R = \arcsin\left(\frac{v_l}{v_{SAW}}\right)
\]

(1-4)

where \(v_l\) and \(v_{SAW}\) are the acoustic velocity in the liquid and the substrate, respectively. Given the velocity of \(v_{SAW} = 3900\) m/s and \(v_l = 1500\) m/s (water droplet on LiNbO₃), \(\theta_R\) is calculated to be 22.6°, which coincides well with the monitored results shown in Figure 1-10 b and c.

**Concentration of particles in droplets**

When a droplet is placed asymmetrically in the propagation line of a SAW, as illustrated in Figure 1-11 b, the asymmetric pressure fluctuations inside the droplet generate a recirculation of the suspended particles. Once the local particle concentration is sufficiently high within a particular streamline of the acoustic streaming convective flow, the shear-induced migration gives rise to an inward radial force that concentrates the particles at the centre of the droplet [26]. The concentration performance is strictly dependent on the comparison between the inward radial force originated from the particle concentration gradient and the outward centrifuge effect originated from the circular rotation, which is decided by the acoustic intensity. The SAW-based concentration method is superior to traditional concentration methods (magnetic field,
centrifuge), for it applies forces directly to the particles: no impurities or contaminations are introduced.

Figure 1-11: SAW induced micro particle concentration inside a droplet (a) schematic drawing of the setup, (b) the asymmetric arrangement of a droplet to the IDTs, (c) the concentration effect of fluorescent polystyrene beads (central area inside the droplet) and (d) the whole image of the droplet [27].

**Laminar flow mixing**

As illustrated in Figure 1-8, the SAW will generate pressure fluctuations inside the droplet, which apply forces to the molecules or the suspended particles. As a result, the particles will move in a convective flow inside the droplet. However, if the suspended particles are encapsulated by a microchannel, the particles will vibrate inside the enclosed environment,
resulting in interesting phenomena like laminar flow mixing in micrometer scale. Microfluidics has shown great promise in chemical or bio applications because they consume much fewer analysts and provide a more uniform environment. However, with the scaling down of the dimension scale, the fluidic properties at low Reynolds numbers are different from the fluidics in macro scale, resulting in a lot of novel phenomena like laminar flows: there exist clear interfaces between different fluids, characterized by high momentum diffusion, low momentum convection, pressure and velocity independent from time. For chemical or bio reactions where fast mixing of reactants are required, specific technique need to be adopted to overcome the laminar property of the fluids. A lot of mixing techniques have been introduced in microfluidics (bubble cavitations mixing, dielectric mixing and chaotic mixing, etc.), the intrinsic shortcomings of these methods,
however, limit their applications. For example, bubble-cavitation mixing requires precise control of the bubble size to fit the resonance working situation in an acoustic field; dielectric mixing happens only in very high electric field; chaotic mixing happens inside the droplet and requires specific (curved) channel design. Figure 1-12 provides a simple method to achieve a laminar flow mixing in a microchannel using SAW. An IDT is placed perpendicular to a two-inlet microchannel, where a fluorescent beads solution and DI water are injected separately (Figure 1-12 a, b). A laminar flow forms along the width of the channel with the interface clarified by the dotted line in figure 1.12c when SAW is absent. When SAW is turned on, the vibrations of beads inside the channel disturb the laminar flow and mixing is achieved (Figure 1-12 d).

In conclusion, SAW has been well known for more than one hundred years and has already been widely used in radio frequency communications in the past century. The novel properties of SAW, however, have not been totally utilized in more applications. The recent developed techniques based on SAW has shown great promising in applications like sensor designs, acoustooptic devices, microfluidics, dynamic quantum dots and current metrology. The coupled traveling mechanical vibration and electric potential along with SAW makes it a candidate for non-destructive manipulations; furthermore, the nanometer scale surface vibration implies great potential in actuating objects of nanometer scale. The barren research work done in exploring and extending the new applications of SAW gives us a big chance and motivation. In the following chapters some novel applications of SAW will be introduced, containing the working mechanism, experimental setup, device fabrication, most updated experimental result and comprehensive discussion.

References


Chapter 2

Standing surface acoustic wave (SSAW)-based fast focusing of micro/nano particles in microfluidic channels

§ 2.1 Motivation

The integration of microfluidics with single microparticle detection techniques enables the development of miniaturized platforms for flow cytometry [1] and fluorescence activated cell sorting (FACS) [2]. In these applications, fluorescently labelled microparticles (i.e., cells) are excited by a laser that is focused on a small volume within a microchannel to allow for accurate detection and sorting. However, because the dimensions of a laser’s focal volume are often smaller than those of a microchannel, many species of interest pass by the focal volume without being exited or detected. Therefore, a microparticle-focusing technique is often required to constrain the distribution of the microparticles so that all the particles can be registered by the detector. It also facilitates particle sorting by lining up the particles in the microfluidic channel.

Flow cytometry is a technique for analyzing the physical/chemical characteristics of microparticles in a continuous flow, normally through an optical detection apparatus. A schematic of the conventional flow cytometry system (together with a cell sorting system) is shown in Figure 2-1 [3]. A flow cytometry system normally consists of a light source, a flow chamber and optical detectors and assembly, and a computer system for analysis and storage of digitized data. The flow chamber plays a key role in determining the performance of the whole system, as it guarantees the registration of each particle when passing through the detection region. The process of lining up particles is typically achieved through a hydrodynamic process, in which a high-speed sheath flow (injected through the outer channel) is used to squeeze the relative slow sample flow (from the inner channel): the particles are focused in the center of the channel. A focused laser beam is used to illuminate the fluorescent particles passing through the channel, and
the forward scattering (FS) optical signal and the fluorescent light (FI) are recorded by the photodetectors and processed by the computer system. Particles with different physical/chemical properties will have different combination of FS and FI, so it is easy to tell how many different particles are contained in the sample. By adding a sorting system together with the flow cytometry setup, a FACS system can be developed. As shown in Figure 2-1, an applied electric field is used to force the particle droplets (positive or negative charged based on their property) to different containers.

In order to make sure each time only one particle is registered by the incident laser beam, the particles must be lined up along the flow direction to pass through the detection region one-by-one. However, due to the tiny size of the particles (normally within 1~10 µm), it is challenging to line up the particles. Conventionally, the focusing of the particles is through a hydrodynamic method: using sheath flows to squeeze the sample flow, as shown in Figure 2-1.

Figure 2-1: Schematic of a typical flow cytometry system [3].
such a method, the channel has to be designed in three dimensional manner: an inner channel for samples, which is surrounded by an outer channel for sheath flows. This con-circular design is relatively difficult for fabrication in the micrometer scale. Furthermore, the hydrodynamic-based method requires a high flow rate sheath flow, which will eventually dilute the sample. Due to its limitation, people have developed different techniques to focus particles in microfluidics. The following section will summarize some of the available techniques.

§ 2.2 Technical review

§ 2.2.1 3D channel for hydrodynamic focusing

In hydrodynamic focusing, the microparticle suspension is constrained in the middle of the channel by outer sheath flows of higher flow rates. Figure 2-2 shows a typical design of such a channel, which was composed of five-layer bonded channels [4]. The sample solution was infused through the center channel, and was squeezed by the sheath flows both from the lateral

Figure 2-2: Schematic of a 5-layer bonded microchannel for 3D hydrodynamic focusing of micro particles [4].
and vertical directions. At the outlet, the sample flow was focused. However, this 5-layer channel. This 5-layer bonded channel can be further reduced to a two-layer microchannel (as shown in Figure 2-3), which show the potential to be miniaturized and integrated with more functions on a chip [5].

In such a channel, three kinds of channels (with different depth) are bonded on the same substrate. By properly arranging the position of the inlets, the samples from inlet B can be squeezed (in vertical direction) by the sheath flow from inlet A and C (Figure 2-3 c). This vertically focused flow was then squeezed by another two lateral sheath flows from inlet E, thus focusing particles in three-dimensions. This channel does not need precise bonding between different layers, and can also be miniaturized. However, the fabrication of the channels with varying depth limited its applications. A recently developed single-layer channel hydrodynamic
focusing made a big step towards a real on-chip focusing technology, as it featured easy fabrication and handling, high throughput and fast speed [6]. As shown in Figure 2-4, a sample flow and sheath flow, in a laminar flow manner, passed through a curved channel, where the inner sample flow bend into the outer sheath flow due to the centrifugal effect. After passing through the curved section of the channel, the sample flow was focused in the vertical direction and ready for the lateral focusing. At position 8, two lateral sheath flows were introduced, which squeezed the sample flow (already focused in vertical direction) in the lateral direction; 3D focusing of particles was achieved at this stage.

Figure 2-4: Schematic of a single-layer microchannel for 3D hydrodynamic focusing of micro particles [6].

All hydrodynamic-based particle focusing techniques share the same principle—squeeze the sample flow with sheath flows inside a channel, but with different designs. This nature comes with a drawback: the introduction of excessive sheath solution will eventually dilute the sample flow, as the sheath flow has to be much higher than the sample flow in order to get better
focusing. To avoid the sample dilution, the particles need to be focused by direct forces without any medium. Electro-kinetic and dielectrophoresis (DEP)-based focusing techniques are good examples of focusing particles through direct forces.

§ 2.2.2 Electro-kinetic and dielectrophoresis (DEP) based focusing techniques

Electro- or dielectro-phoresis-based focusing techniques rely on the fact that most of particles carry on charges. Under the external electric field, the charges in the particles will redistribute and give certain polarizations [7]. The gives rise to the forces to manipulate the particles in solution. Figure 2-5 depicted a 3D focusing technique in a microfluidic channel, which is demonstrated to be capable of focusing molecules as small as ~1 µm [7]. The channel is etched in a silicon substrate. The sidewalls and bottom of the channel were coated with discrete electrodes, which were connected with AC signals. Once excited, the electric field generated between the electrodes on channel sidewall was used to focus the particles laterally at

Figure 2-5: Schematic of a 3D electrophoresis focusing technique, showing the electrodes covering both the sidewall (side electrodes) and bottom (middle electrode) of the channel [7].
the center of the channel. The bottom electrode was then used to trap the particles close to the bottom of the channel, thereby achieving 3D focusing. This electric-field based method, however, highly depends on the charge or polarizability of the particles, and also endures challenges in electrodes fabrication and device integration.

§ 2.3 SSAW-based 3D focusing of microparticles in microfluidics

§ 2.3.1 Working mechanism

In this work we introduce a novel standing surface acoustic wave (SSAW) microparticle focusing technique that uses a PDMS channel fabricated by standard soft lithography. Schematic of the SSAW focusing device is shown in Figure 2-6. A pair of interdigital transducers (IDTs) is deposited on a piezoelectric substrate and a PDMS-based microfluidic channel is bonded with the substrate and positioned between the two IDTs. Microparticle solutions are infused into the microfluidic channel by pressure-driven flow. Once an RF signal is applied to both IDTs, two series of SAWs will propagate, in opposite directions, toward the particle suspension solution inside the microchannel. The constructive interference of the two SAWs results in the formation of SSAW and the periodic distribution of the pressure nodes (minimum pressure amplitude) and anti-nodes (maximum pressure amplitude) on the substrate. When the SSAW encounters the liquid medium inside the channel, leakage waves in longitudinal mode are generated, causing pressure fluctuations in the medium (as shown in Figure 1-8, with the angle \( \theta = \arcsin(\frac{v_l}{v_{SAW}}) \approx 22^\circ \), where \( v_l = 1500 \text{ m/s} \), \( v_{SAW} = 4000 \text{ m/s} \), are the velocity of the leakage wave and the SAW in the substrate, respectively) \[8\]. These pressure fluctuations result in acoustic radiation forces that act laterally on the particles in the \( x \)-direction \[9–12\]. As a result, the suspended particles inside the channel will be forced toward either the pressure nodes or antinodes, depending on the density
and compressibility of the particles and the medium. If the channel width covers only one pressure node (or antinode), the particles will be trapped in that node and consequently, focusing is achieved.

§ 2.3.2 Device fabrication and system setup

The device fabrication process (Figure 2-7) includes: (1) SAW substrate fabrication; (2) PDMS microchannel fabrication; (3) the bonding of PDMS microchannel to the SAW substrate. Figure 2-7 a–d shows the fabrication procedure of SAW substrate.
**SAW substrate material selection**

The criteria for selecting a piezoelectric substrate for SAW generation in microfluidic applications include (1) relatively high electro-mechanical coupling coefficient, (2) transparent to the incident light within 400 nm ~ 850 nm (visible light), (3) high yield stress and mechanical robustness, and (4) available in market at relatively low price. In order to generate enough acoustic force to manipulate the micro/nano particles inside the liquid medium with relatively low power consumption, a piezoelectric material owing high electro-mechanical coupling coefficient is highly desired. The purpose of this work is to present an on-chip focusing technique, which can be used in a series of bio-applications (i.e. flow cytometry and cell sorting), so the SAW substrate has to be compatible with the characterization system used in bio-applications. As one of the most widely used characterization system, an inverted microscopy requires the device to be transparent, at least to the visible light range (~400 nm to ~700 nm). Table 1 summarizes the coupling coefficients and SAW velocity of some commonly used piezoelectric materials with high transparency.

Table 1 SAW properties of piezoelectric material [13–15]

<table>
<thead>
<tr>
<th></th>
<th>ST-X Quartz</th>
<th>128° Y-cut LiNbO3</th>
<th>Y-cut LiNbO3</th>
<th>ZnO/Quartz</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAW velocity</td>
<td>3158 m/s</td>
<td>3980 m/s</td>
<td>3488 m/s</td>
<td>2900 m/s</td>
</tr>
<tr>
<td>$K^2$ (%)</td>
<td>0.14</td>
<td>5.5</td>
<td>4.9</td>
<td>1</td>
</tr>
</tbody>
</table>

It is clear from Table 2.1 that the 128° Y-Cut LiNbO3 demonstrates the highest coupling coefficient and SAW velocity. The high SAW velocity also means it is easier to generate higher frequency SAW, which is another way to improve the acoustic force (as acoustic force is proportional to the working frequency of SAW). At the same time, the 128° Y-Cut LiNbO3 wafers (3” or 4”) are relatively cheap (~$70/piece for 4” wafer) and robust, can be easily
processed using the standard MEMS fabrication techniques (including photolithography, metal deposition, plasmon etching and device bonding). Taking into account all its advantages, the 128° Y-Cut LiNbO3 was chosen as the SAW substrate. Some of the basic properties of LiNbO3 are listed in Table 2.

Table 2 Basic properties of LiNbO3 [16]

<table>
<thead>
<tr>
<th>Crystal density (Kg/m³)</th>
<th>Heat Capacity (J/K·mol)</th>
<th>Melting Point (°C)</th>
<th>Hardness (Mohs)</th>
<th>Transparency region (nm)</th>
<th>Optical Anisotropy</th>
<th>Refractive Indices</th>
</tr>
</thead>
<tbody>
<tr>
<td>4647</td>
<td>89</td>
<td>1260</td>
<td>5</td>
<td>350~5,000</td>
<td>Uniaxial, c-axis</td>
<td>n₀=2.286, nₑ=2.203</td>
</tr>
</tbody>
</table>

**SAW device fabrication**

A thin-layer photoresist SPR3012 (MicroChem, Newton, MA) was spin-coated (1000 rpm for the first 10 s, in which the photoresist was gradually form a thin layer covering the whole wafer surface; then 4000 rpm for 45 seconds to get a ~1.2 µm photoresist layer on the wafer) on a Y+128° X-propagation lithium niobate (LiNbO₃) wafer (4” in diameter, 500 µm in thickness) (Figure 2-7 a). The wafer was preheated on a hot plate (95 °C) for 1 minute, and followed by light exposure using a UV light source (7.5 s exposure, can be varied for different feature size). After the exposure, the wafer was post-heated on another hot plate (115 °C, 1 minute) for post-exposure process. When LiNbO3 wafers endure high temperatures, the thermal expansion inside the wafer results in stresses, which may break the wafers, especially when the wafer are tightly stick on the surfaces of hot plates. To avoid this, a step-temperature procedure was used to gradually improve
the temperature to the desired quantity, and then decreased to the lower temperature. In this fabrication process, the temperature procedure was set as 60 °C (90 s) → 90 °C (90 s) → 115 °C (90 s) → 90 °C (90 s) → 60 °C (90 s). After post-exposure bake, the wafer was developed in photoresist developer (MF CD-26, Microposit, 1~1.5 minutes), and totally rinsed with DI water. This gives the openings for electrodes deposition (Figure 2-7 b). The patterned wafer was then examined under a microscopy to check if the wafer was poor-exposed or over-exposed. Before the metal deposition for IDT fabrication, the

![Figure 2-7: Fabrication process of the device. (a)–(d), fabrication of the IDTs on a piezoelectric substrate; (e)–(h), fabrication of the PDMS microchannels through a soft-lithography and mold-replica procedure.](image-url)
LiNbO3 wafers with the patterned photoresist were processed with an oxygen plasma etching (50 sccm, 1000 mTorr and 150 W, 2 minutes) to remove the photoresist residue at the bottom of the openings. This process is critical in obtaining high quality SAW device, because any residue will cause the uncontinuity of the electrodes. After the plasma etching, the wafers were put inside an e-beam evaporator (Semicore Corp), and a double metal layer (Ti/Au, 50A/800A) was deposited on top of the wafer (Figure 2-7 c). In the deposition process, the wafers are mounted on a wafer holder, which was placed on the top of the chamber. The wafer holder kept rotating in the deposition process to guarantee the uniformity of the metal layer across the wafer. After the metal deposition, the wafers were immersed in Nano™ Remover PG (MicroChem, Corp., MA), which dissolved the photoresist, removing the metal attached to the photoresist and leaving the metal deposited on the LiNbO3 wafer. Due to the slow penetration of the solvent to the photoresist (through the edge of the wafer), this process took several hours (smaller the feature size of interdigital transducers, longer the lift-off process). In order to speed up this process, the solvent can be heated up to 80–90 °C. If the feature size of the IDTs are relatively big (period larger than 200 µm, ultrasonic vibration can also be used (normally 10 seconds sonic vibration). When the metal layer peel away from the wafer, use isoproporal (IPA) solvent clean the wafer for 10 seconds, which will totally remove the attached metal layer. At last, the wafers were totally rinsed with DI water for 1 minute, thus obtaining the SAW device (Figure 2-7 d).

**PDMS microchannel fabrication**

The polydimethylsiloxane (PDMS) microchannels were fabricated using the standard soft-lithography and mold-replica technique (with the procedure shown in Figure 2-7 e–h). A 4” silicon wafer was patterned with a photoresist (Shipley 1827, MicroChem, Newton, MA) with the same spin-coating procedure as what was used in the SAW device fabrication. The exposure was
processed (~16 seconds) and a subsequent post-exposure bake was processed to harden the photoresist. After the development in developer (MF CD-26, Microposit, 1~1.5 minutes), a patterned silicon wafer with photoresist was ready for etching. The thickness of the photoresist decides the maximum depth that the silicon wafer can be etched as the photoresist serves as the protection layer in the etching process. To etch different depths, the thickness of the photoresist has to be tuned, which can be achieved by changing the spinning speed, spinning time, or changing the photoresist. Table 3 listed the combined parameters of the photoresists that were commonly used in the mold fabrication. The patterned silicon substrate was then etched by a deep

Table 3 Parameters used for different photoresist in DRIE

<table>
<thead>
<tr>
<th></th>
<th>Spin (rpm)</th>
<th>T_{PR} (µm)</th>
<th>Prebake</th>
<th>Expo(^a) (s)</th>
<th>Post-bake</th>
<th>Develop (s)</th>
<th>D_{max} (^b) (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPR3012</td>
<td>4000</td>
<td>1.2~1.35</td>
<td>95 °C, 60s</td>
<td>8</td>
<td>115 °C, 60s</td>
<td>60+30s</td>
<td>30</td>
</tr>
<tr>
<td>Shipley1827</td>
<td>4000</td>
<td>2.6~2.9</td>
<td>105 °C, 60s</td>
<td>16</td>
<td>No</td>
<td>60+30s</td>
<td>80</td>
</tr>
<tr>
<td>Z220</td>
<td>2000</td>
<td>9.7~10</td>
<td>60 °C, 90s → 90 °C, 90s → 120 °C, 90s</td>
<td>10, 9 times</td>
<td>60 °C, 90s → 90 °C, 90s → 120 °C, 90s</td>
<td>60+30s</td>
<td>230</td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td>7.5~7.9</td>
<td>60 °C, 90s → 90 °C, 90s → 120 °C, 90s</td>
<td>8, 8~9 times</td>
<td>60 °C, 90s → 90 °C, 90s → 120 °C, 90s</td>
<td>60+30s</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>4000</td>
<td>7~7.4</td>
<td>60 °C, 90s → 90 °C, 90s → 120 °C, 90s</td>
<td>7, 8~9 times</td>
<td>60 °C, 90s → 90 °C, 90s → 120 °C, 90s</td>
<td>60+30s</td>
<td>190</td>
</tr>
</tbody>
</table>

\(^a\)Exposure: Z220 photoresist needs multiple exposures. In between each exposure, at least 30 seconds waiting time. After exposure, 30~45 minutes waiting time is needed before development.

\(^b\)D_{max}: maximum etching depth that can be achieved using this recipe in DRIE.
reactive ion etching (DRIE, Hingham, MA. One such machine is Localized in PSU EE
department). The etch depth was set at 50 µm in this SAW-based focusing experiment. After
DRIE, the photoresist residue on top of the silicon wafer was totally removed by immersing the
wafer in an Acetone solvent (10 minutes), and followed by isoproporal (IPA) and deionized water
rinsing. At last, the wafer was dried in hydrogen flows. In order to reduce surface energy and
hence the damage to the PDMS channel during the demolding process, the silicon mold need to
be coated with a hydrophobic layer. In this experiment, the silicon mold was put inside a vacuum
chamber, and a drop of 1H,1H,2H,2H-perfluoroctyl-trichlorosilane (Sigma Aldrich, St. Louis,
MO), stored in a glass tube, was put inside in the vacuum chamber. Upon vacuuming the chamber,
the 1H,1H,2H,2H-perfluoroctyl-trichlorosilane formed a self-assembly-monolayer (SAW) on
top of the silicon surface, which helps in the PDMS demolding process. Sylgard™ 184 Silicone
Elastomer Base and Sylgard™ 184 Silicone Elastomer Curing Agent (Dow Corning, Midland,
MI) were mixed at a 11:1 weight ratio, cast onto the silicon mold. The mold was then put inside
the vacuum chamber to totally remove the bubbles generated in the mixing process. After the de-
bubble process, the silicon mold was cured at room temperature for overnight (time can be varied
for different hardness). After peeled from the silicon mold, inlets and outlets are created in the
PDMS channel using a silicon carbide drill bit (with the diameter of 0.5 mm).

**Bonding of PDMS channel to SAW substrate**

In order to improve the bonding stiffness between the PDMS channel and the
piezoelectric substrate, the surfaces on both the PDMS channel and the SAW device are activated
with oxygen plasma (Oxygen flow rate 50 sccm, chamber pressure 750 mTorr and power 150 W).
In order to achieve precise alignment between the channel and the IDTs, four Ti/Au metal
alignment markers were fabricated in the same process of IDTs fabrication. The alignment
markers are located between two parallel IDTs, corresponding to the four inner corners of the side openings parallel to the channel, as shown in Figure 2-8. The alignment of SAW device and PDMS channel are conducted manually under the microscope. A drop of ethanol is placed on the surface of the SAW device as lubricant so that the PDMS channel can slide on top of SAW device till the alignment markers overlap the corresponding corners of the side openings. After alignment, ethanol was removed by leaving the aligned device in a vacuum chamber with the temperature of 50°C for 15 minutes. The entire bonding process was processed in a clean room to avoid dust contaminations in the channel. Finally, polyethylene tubing (inner diameter 0.28 mm, outer diameter 0.61 mm, Becton Dickson, Franklin Lakes, NJ) were inserted into the inlets to connect the device to a syringe pump (KDS 210, KD scientific, Holliston, MA). In order to get the working frequency, an AC signal with fixed input power but varying frequency was applied to one of the IDT, and another IDT served as a receiver. When the output signal reaches its

Figure 2-8: Alignment between the PDMS microchannel and the SAW substrate showing two alignment markers (on LiNbO₃ substrate) on the left side of the openings (in PDMS) along the microchannel.
maximum, the applied frequency was determined as the working frequency. Figure 2-9 shows the device used in our study. The period of the IDTs was 100 μm and each IDT electrode was 9 mm by 25 μm in length and width, respectively. A PDMS microchannel with a width and depth of 50 μm and a length of 1.3 cm was bonded to the LiNbO₃ substrate and aligned between the two IDTs. A smooth side opening aligned in either side of the PDMS channel was used to precisely define the working area of the SSAW and reduce the propagation loss.

§ 2.3.3 Results and discussion

The bonded device was mounted on the stage of an inverted microscope (Nikon TE2000U). A solution (1.176x10⁷ beads/mL) of fluorescent (Dragon Green) polystyrene particles (diameter 1.9 μm, Bangs Laboratories) were injected into the channel using a syringe pump.
(KDS210, Kd Scientific). An AC signal generated by an RF signal generator (Agilent E4422B) was amplified through a power amplifier (Amplifier Research 100A250A). Following that, it was split into two coherent signals, which were subsequently applied to the two IDTs to generate SSAWs. The signal frequency was set to be 38.2 MHz (resonance frequency) and the applied power was 24 dBm (~250 mW), resulting in a much smaller acoustic intensity of 62.5 mW/cm² (~2 cm x 2 cm) comparing with the bulk acoustic wave (BAW) situation (125~500 mW/cm²) [13].

Figure 2-10: The schematic in (a) indicates the positions of the chosen sites (I–IV) for monitoring the focusing effect. (b–e) are the recorded fluorescent images at sites (I–IV), respectively.
The distribution of fluorescent microparticles was recorded during the focusing process at four different regions marked as I, II, III and IV in Figure 2-10 a. Site I is not within the SSAW propagation area, therefore microparticles barely experience acoustic forces in this region. As a result, the distribution of microparticles in this region is uniform across the width of the channel (Figure 2-10 b). As particles enter the area in which SSAW propagates (site II), the acoustic force exerted on particles begin to drive them toward the center of the channel (pressure nodes), as evidenced by Figure 2-10 c. As the particles exit site II, they have been well focused into a narrow stream in the middle of the channel. Based on the flow velocity (6.7 cm·s⁻¹) and the distance (300 µm) in which particles travel from the no-focusing site to the complete-focusing site, we can calculate the duration of the focusing process to be around 5 ms. In site III, the focused stream is well stabilized, and the width of the stream was measured to be approximately 5 µm (Figure 2-10 d) – less than three times the diameter of a single particle, 5% of the SSAW wavelength, and 10% of the channel width. We further monitored the particle distribution in region IV (Figure 2-10 e), in which SSAW does not propagate, and observed that the width of the focusing stream remained constant. This phenomenon is caused by the laminar nature of the flow

We also observed that the SSAW focusing effect is dependent upon the working frequency. Figure 2-11 a and b depict the experimental results monitored from two devices with different wavelengths (λ₁=100 µm, λ₂=200 µm) but applied with the same power (25 dBm). The measured focusing width δx₂ (~10 µm, Figure 2-11 b) for device II is about twice of δx₁ (~5 µm, Figure 2-11 a). This observation can be explained by the balance of the acoustic radiation forces and the interparticle forces (Bjerknes forces, repulsive van der Waals force, electrostatic forces), which are originated from the acoustic oscillation between particles in the focusing band, where the particles are close to each other [11, 12]. When particles are driven close to each other toward the pressure node by the acoustic radiation forces, the total effect of the interparticle forces will
become repulsive to balance the minimum acoustic radiation force [11, 12]. Figure 2-11 c shows the pressure field and force balance diagram for particles in devices I and II, which experience acoustic waves with identical pressure amplitude but different wavelengths ($\lambda_2 = 2\lambda_1$). The

![Diagram](image)

Figure 2-11: Experimental data for the focusing performance at a working frequency of (a) 38.2 MHz (corresponding to $\lambda_1 = 100\, \mu\text{m}$) and (b) 19.116 MHz (corresponding to $\lambda_2 = 200\, \mu\text{m}$). (c) Qualitative analysis of the particle aggregation at pressure nodes at two different working frequencies (drawing not to scale).
acoustic radiation force exerted on a particle $F_a$ is inversely proportional to the acoustic wavelength [9], implying that under the same condition, the acoustic radiation force exerted on particles in device I is twice of that in device II. Higher acoustic radiation force requires larger repulsive interparticle force to balance it (Figure 2-11 c), resulting in more closely-packed particles and narrower focusing width in device I (Figure 2-11 a) than those in device II (Figure 2-11 b). As we continue to increase the working frequency, we expect to achieve even smaller focusing widths. This frequency-dependent characteristic presents another advantage of SAW over BAW: it is relatively easy to fabricate IDTs with smaller periods and to generate higher-frequency (hundreds of MHz) SAW, while most of the current BAW-based particle manipulating techniques are based on piezo transducers with ~2 MHz [8, 11, 12].

In conclusion, we have introduced a novel acoustic manipulation technique, SSAW, to enable fast and effective microparticle focusing inside a microfluidic channel. In comparison to other particle focusing techniques, including hydrodynamic, electro-kinetic and DEP focusing, this method is simple, fast, dilution-free, and applicable to virtually any microparticles. Moreover, the transparency of the focusing device makes it compatible with most optical characterization tools used in biology and medicine. In contrast to the BAW-based microparticle manipulation method [8, 11, 12], the SSAW-based technique localizes most of the acoustic energy on the surface of the substrate and has little loss along the propagation line, thus lowering the power consumption and improving the uniformity of the standing waves. More importantly, it is highly compatible with the standard soft lithography techniques. The current work presented a technique for two dimensional (2D) microparticle focusing. However we realize a three dimensional (3D) focusing [17] is eventually needed for applications such as the flow cytometry. We noticed recent work by Ravula et al [18] reported the particle levitation phenomena caused by BAW inside the microchannel, implying the potential to achieve the microparticle positioning in the vertical direction using acoustic waves. Our future work will focus on investigating the 3D positioning of
microparticles in the microchannel, by taking advantage of angled leakage of SAW inside the microchannel which provides position control of microparticles in the vertical direction.

References


Chapter 3

Acoustic tweezers—patterning and manipulating microparticles using SSAW

The ability to arrange cells and microparticles into desired patterns is critical for numerous biological studies and applications such as microarrays [1,2], tissue engineering [3,4], and regenerative medicine [5,6]. Researchers have developed a variety of patterning techniques such as microcontact printing [7], optical tweezers [8,9], optoelectronic tweezers [10], magnetic tweezers [11], electrokinetic forces [12, 13], evanescent waves/plasmonics [14,15], and hydrodynamic flows [16,17]. However, none of these techniques simultaneously meet specifications for miniaturization, versatility, throughput, speed, and power consumption. Here we present an active patterning technique named “acoustic tweezers” that utilizes standing surface acoustic wave (SSAW) to manipulate and pattern cells and microparticles. This technique is capable of patterning cells and microparticles regardless of shape, size, charge or polarity. Its power intensity, approximately 500,000 times lower than that of optical tweezers, compares favourably with those of other active patterning methods [10,15]. Its speed is among the highest reported in literature, and flow cytometry studies have revealed it to be non-invasive. The aforementioned advantages, along with this technique’s simple design and ability to be miniaturized, render the “acoustic tweezers” technique a promising tool for various applications in biology, chemistry, engineering, and materials science.

§ 3.1 Technical review
§ 3.1.1 Electrophoresis/dielectrophoresis (DEP)

“Generally, electrophoresis is the motion of dispersed particles relative to a fluid under the influence of an electric field that is space-uniform. Alternatively, similar motion in a space non-uniform electric field is called dielectrophoresis (DEP) [18]”. Due to the fact that most particles in fluids carry charges, under the excitation of an applied electric field, electrostatic forces are applied to the particles and move them in a certain direction. Based on the double-layer theory, all surface charges around the particles in fluids are screened by a diffuse layer, which has the same charge value but opposite sign from the surface charges. The external electric field works both on the diffusion layer and the surface charges [19]. One straight application of this electrophoresis/dielectrophoresis is the concentration of particles in fluids. The schematic shown in Figure 3-1 illustrates the working principle of such a concentration technique [13]. A low frequency AC signal was applied to the co-circular electrodes, the variable electric field among the outer and inner electrode will force the particles toward the center region, thus focusing the particles. The performance of this design is highly dependant on the applied voltage and working frequency, which can be tuned in a relatively large range for different purposes.

![Figure 3-1: Schematic of the working principle of an electrophoresis-based particle focusing [13].](image)

By properly designing the electric field, particles with different sizes and properties can also be sorted as they will be moved with different speed or direction inside the fluids. Figure 3-2
shows an electrophoresis-based cell patterning technique [20]. A sharp electrode was placed right above a substrate which was coated with an electro-sensitive polymers. The high electric field between the electrode and the substrate will make the local region adhesive to cells. By tuning the distance between the electrode tip to the substrate, the electric field was tuned, as well the trapping forces to cells. As a result, different quantities of cells were trapped around the tip of the electrode. The electrode can work in static or scanning mode. In the static mode, cells or particles will slowly migrate toward the electrode tip, which in the scanning mode, the electrode slowly moved along some routine and cells were patterned along the routine. More conventionally, electrodes were deposited with specific geometry inside a microfluidic channel, and the electric field generated from the electrodes was used to manipulate the particles inside the channel. Figure 2-5 demonstrates one electrophoresis-based focusing technique, which uses three pre-deposited electrodes on both the sidewall and the bottom of the channel to focus the particles. In this design, the lateral electric field between the two sidewall electrodes was used to focus the big molecules

Figure 3-2: Electrophoresis-based cell patterning technique showing the cell patterning (left). The schematic of the working manner (right) [20].
laterally, while the bottom electrode was used to attract the molecules toward the bottom of the channel, thus achieving the 3D focusing [21].

All the electrophoresis/dielectrophoresis-based particle manipulation techniques are highly dependant on the polarizability of the particles and the working situation (electrode size, gap, working voltage, frequency…) has to be specified for better performance. Most importantly, the deposition of the electrodes requires the substrate to be hard material (silicon, glass, etc.). Soft-polymer materials like PDMS—a material that was widely used as the channel material in microfluidics—cannot be used due to poor stiffness. This makes fast prototyping methods, such as soft lithography, incompatible with this technique. Furthermore, the high electric field applied to manipulate the particles, may generate damage to the particles, a more serious issue when manipulating bio-objects like cells and DNAs.

§ 3.1.2 Optical tweezers

The invention of optical tweezers [8,9] and developments in optofluidics [22, 23] have spurned a new platform for manipulating and patterning micro/nanoscale objects with unprecedented precision. Figure 3-3 illustrates the working principle of a conventional optical tweezers. A focused laser beam (normally originates from a Gaussian laser beam and focused with a high numerical aperture lens) impinges onto a particle, and the light will be bent through refraction and/or reflection on the particle, changing the momentum of the incident light. Due to the conservation of the momentum, the particle endures an equally but opposite momentum as the momentum change of the incident light. This gives rise to a force acting on the object. Due to the nature of the light intensity profile (Gaussian profile), the light intensity at the edge of the laser beam (1 in Figure 3-3 a) is much lower than that of the central beam (2 in Figure 3-3 b), such that the particle at the edge of the laser beam experiences a net force toward the center. Once the
particle reaches the center of the laser beam, the lateral net force will decrease to zero and the particle is then steadily trapped. The basic principle behind the optical tweezers can then be summarized as the momentum transfer upon light bending. Optical tweezers can work directly on the single particles, and can also work on a bunch of particles through a projection. Figure 3-4 demonstrated an optical tweezers setup, where the micro particles were trapped in an 2D array. The incident laser beam was reflected first by a diffraction grating. The reflected laser beam was modulated to own a periodic intensity distribution, which was then projected on a substrate and the nearby microparticles were trapped locally, forming a 2D array. Optical tweezers works to move particles within a relative large range from 10 nm to over 100 mm [25].

However, the minimum optical intensity requirement in the optical trapping is about $\sim 1 \times 10^9$ W/m², which required the incident laser beam to be high power. In order to reduce the
power consummation, researchers developed different techniques, among which one optoelectronics tweezers (OET) are believed to be capable of patterning microparticles with a reduced power consummation by $1 \times 10^5$ times [26]. As shown in Figure 3-5, a laser beam from a light-emitting diode (LED) was incident onto a DMD (Digital Mirror Display) system, which can project different patterns upward to a composite layer, where the optical incident patterns were converted to the corresponding electrodes. The electric field generated from these electrodes results in the electrophoresis forces, driving the particles within the field. Since the electrodes are optical-induced virtual contour, they can be easily tuned by adjusting the DMD system, making it

Figure 3-4: A typical optical tweezers system using a grating to generate an array of trapping points, resulting in a patterned trapping array of particles [25].
more feasible than conventional optical tweezers, as the programmable DMD system is much easier to tune than gratings in optical tweezers. Furthermore, the throughput of this OET system was also improved. Figure 3-6 demonstrated some experimental results using this OET technique [26]. This technique was capable of manipulating particles as small as 1 µm, although even smaller particles can also be trapped (reasons are not fully understood). As a big advantage of OET in comparison to the optical tweezers, it consumes much less energy (1×10^4 W/m²), which makes an expensive high power laser unnecessary. The OET system, however, shares a common
drawback with the optical tweezers: it requires a bulky optical system, although other components of this system (channels, substrate) can be miniaturized to a small scale. This limitation hinders the device integration and miniaturization, making it less attractive for mass production.

§ 3.1.3 Magnetic method

Although optical tweezers are capable of manipulating objects as small as 10 nm, it does not demonstrate high efficiency in such small scale manipulation, and the manipulation of small objects, such as virus, DNAs, molecules etc., remains challenging. The magnetic method may serve as an alternative, as it uses magnetic beads to pre-label the small objects. Figure 3-7 gives the basic working principle of a typical magnetic-based particle manipulating method [27]. In this

Figure 3-6: Parallel trapping and transportation of microparticles using the OET system [26].
design, the virus sample and magnetic beads (pre-coated with antibodies) were flowing through a microchannel (a-1 in Figure 3-7). After total mixing, the target virus are bonded with the antibodies immobilized on the magnetic beads, while the non-target virus stays in the solvent (Figure 3-7 a-2). An array of microcoils fabricated on the substrate of the channel was used to generate an array of magnetic fields, which trapped the magnetic beads together with the target virus (Figure 3-7 a-3). A sheath flow was then used to remove the non-target particles inside the channel. The microcoils were turned off, the magnetic beads were set free and pure target virus were collected. The magnetic-based particle manipulation method can be used to manipulate most of the bio-objects due to its unique working principle; however, the pre-treatment of the magnetic beads, as well as the releasing of the target objects from the magnetic beads limits its application. Furthermore, the electro-magnetic coil consumes notable quantity of powers as large current is required.

Figure 3-7: A magnetic-based virus purification system [27].
§ 3.1.4 Hydrodynamic method

By introducing the trapping sites in a microfluidic channel, particles can be trapped there. This provides a method for particle manipulation—hydrodynamic-based method. Trapping sites can be fabricated either by etching wells, or placing obstacles within the channel. Figure 3-8 demonstrated a hydrodynamic trapping system. A PDMS substrate with an array of trapping obstacles was introduced into a microchannel, which was covered with a glass cover. When particle sample passed through the channel, particles with similar size as the trapping sites were trapped. This technique can be used to obtain long range ordered array of microparticles without applying external forces. However, it is a passive method, lack of feasibility. The trapping performance is highly dependant on the size comparison between the trapping sites and particles.
§ 3.2 SAW-based patterning of microparticles in microfluidics

Surface acoustic wave (SAW) is a sound wave that propagates along the surface of an elastic material [28]. When SAW propagates, most of its energy is confined within one to two wavelengths normal to the surface of the substrate [28]. This energy-confining characteristic makes SAW an energy-efficient tool for manipulating particles and biomaterials. Furthermore, SAW-based techniques are dilution-free, only introducing low-power mechanical vibrations to the suspension. Recently, researchers have demonstrated SAW-based mixing [29], pumping [30] and particle focusing [31]. We reveal an “acoustic tweezers” technique, in which microparticles and cells can be effectively patterned using standing surface acoustic waves (SSAW). This technique is versatile, non-invasive, and amenable to miniaturization; both its power consumption and speed compare favourably to those of existing cell-patterning techniques.

§ 3.2.1 Working mechanism

Figure 3-9 illustrates the working principle of the “acoustic tweezers.” The device consists of a polydimethylsiloxane (PDMS) microfluidic channel and a pair of interdigital transducers (IDTs) deposited on a piezoelectric substrate in a parallel (Figure 3-9 a) or orthogonal (Fig. 3-9 b) arrangement. A solution of microparticles or cells is infused into the microchannel by a pressure-driven flow. Once the distribution of particles or cells stabilizes in the channel, a radio frequency (RF) signal is applied to both IDTs to generate two series of identical SAWs propagating either in the opposite (Figure 3-9 a) or orthogonal (Figure 3-10 b) direction. The interference of these two series of SAWs forms a SSAW, as well as a periodic distribution of pressure nodes (with minimum pressure amplitude) and antinodes (with maximum pressure amplitude) on the substrate—the pressure distribution can be visualized from the simulated results in Figure 3-16.
When the SSAW encounters the liquid medium inside the channel, longitudinal-mode leakage waves are generated, causing pressure fluctuations in the medium [29–32]. These fluctuations lead to acoustic radiation forces that act on the suspended particles, moving them to the pressure nodes or antinodes in the SSAW field (depending on the comparative densities and compressibilities of the materials involved).

Figure 3-9: Schematic of the SSAW-based patterning devices. a, 1D patterning using two parallel IDTs. b, 2D patterning using two orthogonal IDTs (the angle between the IDTs can be changed to achieve different patterns).
between the particles and medium [31–33]). In a one-dimensional (1D) SSAW field, the pressure nodes (or antinodes) are aligned in multiple lines, which are parallel to the wave fronts (see details in Figure 3-15 b), resulting in a 1D pattern of particles along these lines (Figure 3-9 a). In a two-dimensional (2D) SSAW field, instead of forming parallel lines, pressure nodes (or antinodes) form orthogonal 2D arrays (see details in Figure 3-15 d). Particles move towards nearby pressure nodes (or antinodes), forming 2D patterned aggregations (Figure 3-9 b).

§ 3.2.2 Results and discussion

Results

We first examined the “acoustic tweezers” technique in patterning fluorescent (Dragon Green) polystyrene beads of mean diameter 1.9 μm. The device fabrication takes the same procedure as what we have demonstrated in chapter 2.3.2, except the channel dimension and geometry. Figure 3-10 shows optical images of the 1D and 2D patterning devices. When the SSAW was applied, the beads aggregated at the pressure nodes, forming 1D and 2D patterns. The periods of the patterns were measured to be approximately 50 μm (1D pattern in Figure 3-10 c) and 140 μm (2D pattern in Figure 3-10 d). The experimentally measured data matched well with the simulated results (Figs. S2b and S2d in the Supplementary Information), which predicted that the period of the 1D pattern would be half of the SAW working wavelength (50 μm) and that the period of the 2D pattern would be $\sqrt{2}/2$ times the SAW working wavelength (141 μm). The size of the bead aggregations at the pressure nodes (Figure 3-10 c and d) can be tuned by altering the applied power. Higher power leads to larger acoustic radiation forces, resulting in closer bead aggregations (data not shown). By reducing the concentration of the beads, single-particle patterning can be achieved.
Figure 3-10: Patterning of fluorescent polystyrene microbeads. a, b, Optical images of the “acoustic tweezers” devices used in 1D and 2D patterning experiments, respectively. c, Distribution of the microbeads before and after the 1D patterning process. The microchannel (width = 150 μm and depth = 80 μm) covered three lines of pressure nodes of the generated SSAW. The wavelength of SAW was 100 μm. d, Distribution of the microbeads before and after the 2D patterning process. The wavelength of SAW was 200 μm.
We further proved that the “acoustic tweezers” technique, can readily be used to pattern different types of cells—bovine red blood cells (bRBC) in Figure 3-11 a and *E. coli* cells in Figure 3-11 b. These results verify the versatility of our technique as the two groups of cells differ significantly in both shape (spherical bRBC vs. rod-shaped *E. coli*) and size (~6 μm vs. ~1 μm). Furthermore, the patterning performance is independent of the particles’ electrical/magnetic/optical properties. One concern about this technique is that the mechanical forces generated by the acoustic waves may potentially damage cells during the patterning process. Generally speaking though, acoustic fields are considered less invasive than electrical or optical fields [33–38]. For example, bulk acoustic waves (BAWs) have been widely used in ultrasonic imaging, cell sonoporation, and ultrasound-enhanced drug delivery [32, 37, 38]. In comparison to these BAW-based techniques, which operate at larger power intensities (2,000 – 6,000 W/m²) for tens of minutes or even hours without reducing cell viability obviously, our “acoustic tweezers” technique used nominal power intensity and took only seconds to drive cells to pressure nodes. Damage caused by acoustic forces during this period should be trivial. Once the cells reached the pressure nodes, the acoustic pressures, and thus acoustic forces applied to the cells, were nearly zero; cells were steadily patterned in the “wells” defined by the pressure gradients around the pressure nodes. These characteristics suggest that the “acoustic tweezers” technique would be non-invasive to cells.

In order to confirm the non-invasive nature of our technique, we studied the integrity of the cell membranes before and after the patterning process. We used a membrane-potential-sensitive dye, DiBAC₄(3) (bis-(1,3-dibarbituric acid)-trimethine oxanol), as an indicator for cell viability. DiBAC₄(3) is an anionic lipophilic fluorescent dye which is found mainly in the outer cytoplasmic membranes of intact cells [39]. It enters the cell body and accumulates in the cytoplasm when the cell membrane is damaged. Thus, the amount of dye accumulation, which is indicated by the average fluorescent intensity (FI), can be used to quantify the degree of membrane
Figure 3-11: SSAW-based cell patterning. a, Patterning of bRBC. The wavelength of the applied SAW was 100 μm. b, Patterning of E. coli cells pretreated with Dragon Green fluorescent dyes. The wavelength of the applied SAW was 300 μm. I-IV shows the dynamic process of E. Coli cells aggregating at a pressure node.
disruption caused by our technique. We performed flow cytometry experiments to quantitatively analyze the viability of cells, in which FI and the forward scattering (FS) signals represented the cell viability and size distribution, respectively [39]. As shown in Figure 3-12 a–d, the *E. coli* cells after the SSAW patterning process (average FI = 0.536; Figure 4-14 c) exhibited distribution peaks almost identical to those of the cells prior to the patterning process (positive controls of average FI = 0.530–0.536; Figure 3-12 a and b). On the other hand, the cells incubated at 70°C for 30 min (negative control; Figure 3-12 d) exhibited a much higher FI (2.2), implying that the cell
membranes were severely damaged. These results (as detailed in Table 4) confirm that our SSAW-based “acoustic tweezers” technique is non-invasive.

There are two other concerns when using acoustic method to manipulate biological objects like cells: the mechanical damage and the thermal effect. In our experimental setup, the working wavelength (100 μm~ 200 μm) of the SAW device is much larger than the diameter of single cell (<10 μm), such that the sheath force caused by the leakage wave will not cause lysing of cells in the focusing band (at the pressure node in our experiments). We also measured the temperature change versus varying applied power along the surface of the SAW device, especially the working region. A thermometer was used to record the peak temperature of the whole surface. All experiments were processed in the lab temperature (~20°C) and the sample is mounted under the same conditions as in pattern experiments. Figure 3-13 plotted the surface temperature changing versus the varying applied power at the center of the SAW devices, where the channels were bonded. It is clearly shown that under the applied power used in cell pattern experiment, the surface temperature is ~25°C, which should be harmless to the cells.
The behaviour of cells or other objects in a SSAW field can be predicted via theoretical force analyses. The primary forces involved in the SSAW patterning process are as follows: (1) acoustic radiation forces [29–33]; (2) viscous forces; (3) buoyant forces; and (4) gravity. Among these forces, buoyant forces are typically balanced by gravitational forces as they are of similar magnitudes and in opposite directions. Figure 3-14 a shows the dependence of these forces on the size of the polystyrene beads. Figure 3-14 b shows the dependence of acoustic and viscous forces on the working wavelength for different objects. Figure 3-14 c shows the distribution of trapping force around a pressure node. The forces on beads and *E. coli* are magnified 10 times for clear visualization. The wavelength of SAW was 100 μm. The inset indicates the force vectors and equal force contours around the pressure node in the 2D SSAW field. Figure 3-14 d shows the calculated and experimental response time for the SSAW-based patterning process. The applied SAW power was 200 mW (working area of 1 cm²) in a ~ d. The speed of the particles was assumed to be 1 μm/s in a, b and d. AF: acoustic force; VF: viscous force; and PN: pressure node.
particle size. It reveals that when the diameters of the particles are >1 µm, acoustic forces dominate under the applied power intensity. Figure 3-14 a shows that when the SAW wavelength is smaller than 100 µm, the acoustic forces acting upon the targets (polystyrene beads with diameter of 1.9 µm, bRBC, and E. coli cells) are significantly stronger than the viscous forces. In this study, all the particles were trapped at the pressure node, where the acoustic force was minimal and particles were immobilized due to the force gradient around the pressure node. Figure 3-14 c shows the acoustic force distribution within a half wavelength region centered at a pressure node. The results show that the acoustic forces change sinusoidally and point to the pressure node, forming a trapping well (inset of Figure 3-14 c). To release a particle from the trapping well, one must overcome the maximum acoustic force in the field (25 pN for bRBC). By increasing the operation power or reducing the SAW working wavelength, one can further increase the stiffness of the trapping well built by the acoustic forces gradient around the pressure nodes or antinodes, making it possible to manipulate and pattern nanoscale particles such as viruses and DNA [13,21–25]. In addition, our experimental and calculated results (Figure 3-14 d) show that the process for patterning polystyrene beads and bRBC takes less than 1s, a speed much faster than those of the previously reported studies [10, 12, 13, 17]. Detailed description of the theoretical model used in Figure 3-14 can be found in the Supplementary Information.

It is also noticed from the experiments that if the working frequency is slightly changed around the resonance frequency, the patterned results changed apparently. Figure 3-15 showed the dynamic changing process of the patterned results when working frequency changed from 19.07 MHz to 19.11 MHz, where the originally patterned two cell aggregations were re-patterned into three aggregations in less than one minute (30 s). It is clear from the figure that in the re-patterning process, the E. coli cells moved from both the original aggregations to the newly generated aggregations (marked by the dotted circle), which is believed to be caused by the re-distribution of the SSAW filed along the substrate. Due to the fixed geometry of the IDTs, the working frequency
of the IDTs is within a narrow band centered on the resonance frequency. With the applied frequency apart from the central frequency, the efficiency of the SAW generation decays significantly. Fortunately, a slanted IDT that has varying period from one end to the other end of the electrodes has a relative wide working band, which can be used to actively pattern microparticles dynamically.

Figure 3-15: Dynamic pattern of the e. coli cells when working frequency changes from 19.07 MHz to 19.11 MHz: (a)–(l) the formation process of a new aggregation based on the two original aggregations.
In conclusion, we have demonstrated a SSAW-based “acoustic tweezers” technique that enables one to actively pattern cells and microparticles. This technique does not require pre-treatments on the substrates or cells/microparticles. It is applicable to virtually any type of cell/microparticle regardless of size, shape, or electrical/magnetic/optical properties. We verified this versatility by patterning polystyrene beads, bRBC, and *E. coli* cells. The required power intensity of acoustic tweezers (2,000 W/m²) is ~500,000 times lower than that of optical tweezers (1.0×10⁹ W/m²) [10, 15] and compares favorably to those of other patterning methods. The low power intensity also contributes to the technique’s non-invasive nature, as confirmed by our cell viability studies. With its advantages in versatility, miniaturization, power consumption, speed, and technical simplicity, our “acoustic tweezers” technique is a powerful tool for applications such as tissue engineering, microarray, cell studies, and drug screening and discovery.

Methods

The SSAW-based patterning device was mounted on the stage of an inverted microscope (Nikon TE2000U). Solutions of fluorescent beads, bRBC, and *E. coli* cells were injected into the device through a syringe pump (KDS210, Kd Scientific). An AC signal generated by an RF signal generator (Agilent E4422B) was split into two coherent signals, which were subsequently connected to the IDTs to generate SSAW. A CCD camera (CoolSNAP HQ2, Photometrics, Tucson, AZ) was connected to the microscope to capture the patterning processes. The power of the applied SAW was 200 mW (working area of 1 cm²) in all of our experiments.

Fluorescent (Dragon Green) polystyrene beads (1.176×10⁷ beads/mL, ~1.9 μm in diameter, Bangs Laboratories), bRBCs (~6 μm in diameter, Innovative Research, Inc.), and *E. coli* cells (~800 nm in diameter, 1–3 μm in length) dyed with green fluorescence proteins (GFP) encoded plasmids were used in the patterning experiments. After the induced GFP expression, *E.
coli colonies were selected and re-suspended in PBS buffer to desired concentrations. The freshly-prepared E. coli cells grown to mid-logarithmic phase in LB media were divided into four parts for different sets of experiments. After the patterning process, the cells were collected and diluted to a 1:100 ratio in PBS buffer, and 2 μL stock solution of DiBAC₄(3) (Molecular Probes, USA) was added to a 1 mL of a diluted cell suspension, resulting in a dye concentration of 5 μg/mL. The cells were then stained for 30 min before the flow cytometry measurement. The flow cytometry test was performed on a Beckman-Coulter XL-MCL flow cytometer using a blue-light (488 nm) excitation source. Other groups of E. coli cells (positive and negative controls) followed the same testing procedure.

**Simulation of Standing Surface Acoustic Waves**

The propagation of SAW excited by IDTs on a piezoelectric substrate can be simulated by plane waves propagating with frequency-dependent attenuation. The acoustic pressure field is assumed to be uniform along the direction transverse to the wave propagation and can be expressed as

\[
p(x) = p_0 \cdot e^{-\alpha x/2} \cdot e^{i(kx - 2\pi f t)}, \quad (3-1)
\]

where \( p_0 \), \( \alpha \), \( k \), and \( f \) are the original acoustic pressure amplitude, attenuation coefficient, wave vector, and operation frequency, respectively [40]. Using the same parameters employed in the experiments (input AC signal power \( P=200 \) mW, SAW working area \( A= 10^{-4} \) m²), the original acoustic pressure was calculated as

\[
p_0 = \sqrt{PZ/A} = 1.904e5 \text{ (Pa)}, \quad (3-2)
\]

where \( Z = \rho \cdot c \) is the acoustic impedance, and \( \rho = 4650 \text{ kg} \cdot \text{m}^{-3}, \ c = 3900 \text{ m} \cdot \text{s}^{-1} \) are the density and SAW velocity of the LiNbO₃ substrate, respectively [41]. The frequency-dependent
attenuation coefficient of SAW on this piezoelectric substrate is given by [42]

\[
\alpha = 0.19 f + 0.88 f^{1.9} \,(dB / \mu s \cdot c),
\]

where \( f \) is the SAW operation frequency (unit: GHz). When \( f = 0.02 \) GHz, the attenuation coefficient of SAW on LiNbO\(_3\) was calculated to be \( \alpha = 1 \) dB/m. Thus, the acoustic pressure field on LiNbO\(_3\) could be calculated based on Equations 3-1–3. By simulating the interference of two identical SAWs in opposite or orthogonal direction, we obtained the acoustic pressure fields (Figure 3-18 b and d) of the 1D and 2D SAW-based patterning devices (Figure 3-16 a and c).
**Flow Cytometry Measurements**

Table 4 Comparison of the flow cytometry testing results for *E. coli* cells under different situations.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Total cells</th>
<th>Ave. FL&lt;sup&gt;a&lt;/sup&gt;</th>
<th>PkPos in FL&lt;sup&gt;b&lt;/sup&gt;</th>
<th>PkCnt of cell&lt;sup&gt;c&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>E. coli</em> cells cultured for 12 h</td>
<td>20,000</td>
<td>0.536</td>
<td>0.102</td>
<td>6782</td>
</tr>
<tr>
<td><em>E. coli</em> cells that passed through the channel without applying SSAW</td>
<td>20,000</td>
<td>0.530</td>
<td>0.102</td>
<td>6816</td>
</tr>
<tr>
<td><em>E. coli</em> cells that experienced SSAW patterning</td>
<td>20,000</td>
<td>0.536</td>
<td>0.102</td>
<td>6811</td>
</tr>
<tr>
<td><em>E. coli</em> cells heated at 70°C for 30 min</td>
<td>20,000</td>
<td>2.200</td>
<td>2.240</td>
<td>171</td>
</tr>
</tbody>
</table>

<sup>a</sup>Median value of the average fluorescence intensity for all cells.

<sup>b</sup>Peak position along fluorescence axis.

<sup>c</sup>Counted cell numbers at the original peak position.

Freshly-prepared *E. coli* cells, grown to mid-logarithmic phase in LB media, were divided into four parts: (a) pre-treated cells cultured for 12 h (Positive Control 1), (b) cells that flow through the microchannel without applying SSAW (Positive Control 2), (c) cells that experienced the SSAW patterning process in the microfluidic system (SSAW Sample), and (d) cells that were heated at 70°C for 30 min (Negative Control). After the treatment, each group of cell culture was diluted in PBS buffer at a 1:100 ratio, and a 2 μL stock solution of DiBAC<sub>4</sub>(3) (Molecular probes, USA) was added to a 1 ml diluted cell suspension, resulting in a dye concentration of 5 μg/mL. The cells were then stained for 30 min before the flow cytometry measurement. The flow cytometry test was performed on a Beckman-Coulter XL-MCL flow cytometer using a blue-light (488 nm) excitation source. For each test, 20,000 cells were counted.
**Quantitative Force Analysis**

The primary acoustic force exerted on an object in a SSAW field can be expressed as

\[ F_r = -\left(\pi p_0^2 V_c / 2\lambda\right) \cdot \phi(\beta, \rho) \cdot \sin(2kx), \]

(3-4)

\[ \phi(\beta, \rho) = \frac{5\rho_c - 2\rho_w - \beta_c}{2\rho_c + \rho_w - \beta_w}, \]

(3-5)

where \( p_0, \lambda, V_c \) are the acoustic pressure, wavelength, volume of the object, respectively; and \( \rho_c, \rho_w, \beta_c, \beta_w \) represent the density of the object, density of the medium, compressibility of the object, and compressibility of the medium, respectively. \( \phi \) determines the balanced positions of the objects: if \( \phi > 0 \), the objects will aggregate at pressure nodes, and vice versa.

Based on the Stokes’ law, the viscous force can be expressed as

\[ F_v = 6\pi \eta r_c v_h, \]

(3-6)

where \( r_c, v_h, \) and \( \eta \) represent the radius of the particles, relative velocity between particles and medium, and viscosity of the surrounding medium, respectively. As \( r_c \) decreases, the viscous force \( F_v \) decreases linearly while the acoustic force \( F_r \) decreases much faster since it is proportional to \( r_c^3 \) (Figure 3-14). The calculations based on Equations 3-4–6) reveal the dependence of acoustic and viscous forces on acoustic wavelength and particle size (Figure 3-14 b).

When a microparticle maintains constant velocity in the SSAW field, the acoustic and viscous forces balance each other [44]. Based on Equations 3-4–6), we conclude

\[ v_h = -\left[ p_0^2 V_c \beta_w / (12\lambda \eta r_c^2) \right] \phi(\rho, \beta) \sin(4\pi x / \lambda). \]

(3-7)

Rewriting \( v_h = -dx/dt \) and separating variables, we obtain:

\[ \csc(4\pi x / \lambda) dx = \left[ p_0^2 V_c \beta_w / (12\lambda \eta r_c^2) \right] \phi(\rho, \beta) dt. \]

(3-8)
Since the particles will move to the pressure nodes nearby, \( dx \) should be in the range of \((0, \lambda/4)\).

Therefore the time needed for bead migration will be

\[
t = (3\lambda^2 \eta_c \rho_c / \pi) \left[ \ln(\tan(2\pi x / \lambda)) \right]_{x_1}^{x_2} / \left[ p_0^2 V_c \beta \phi(\rho, \beta) \right],
\]

where \( x_1 = 0.1(\lambda/4) \) and \( x_2 = 0.9(\lambda/4) \) [45]. Figure 4d indicates that the calculated response time for the patterning processes matches with experimental results for different microparticles or cells at different wavelengths.

References


Chapter 4

Continuous particle separation in a microfluidic channel via acoustic tweezers

§ 4.1 Motivation and technical review

Simple and efficient particle separation methods are fundamentally important in biological and chemical analyses such as cancer cell detection, drug screening, and tissue engineering [1–4]. To date, many methods capable of particle separation in microfluidic systems have been demonstrated, including centrifugal [5–7], magnetic [8, 9], hydrodynamic [10–21] and electrokinetic/dielectrophoretic (DEP) [17, 20, 22–26] methods. Centrifugal separation is one of the most widely used particle separation methods, using centrifugal force—generated by spinning a sample in a rotating chamber—to separate heavier particles from lighter particles. The magnetic method is operated by first labeling the particles of interest with magnetic materials and then applying an external magnetic field to the sample, thereby separating the labeled particles from the mixture. An additional continuous on-chip separation scheme employs hydrodynamic methods in which properly designed channels (i.e., asymmetric obstacles inside the channel) direct particles of different sizes to different channel outlets. This method permits versatile device design and continuous operation without requiring the input of external forces. However, the device layout and channel obstacles are static, significantly limiting device use by preventing its sorting parameters from being changed. Another example of continuous on-chip particle separation is through dielectrophoresis (DEP), in which an external electric field is used to separate particles with different charge/polarization properties.
Recently developed bulk acoustic wave (BAW)-based acoustophoresis techniques have enabled the separation of microparticles of different sizes and densities in microfluidic channels [27, 28]. This approach uses bulky transducers to generate BAWs, which are then coupled into a silicon-based microchannel with a width equal to half the BAW wavelength. The resonance of the BAWs inside the channel results in a standing BAW field with a pressure node at the channel center. Particles injected along the sidewalls of the channel experience axial acoustic forces whose magnitudes depend on the particle size, density, and compressibility. These differing forces reposition the particles with different lateral displacements, thus achieving particle separation [28]. This method is notably advantageous because it requires no pretreatment of the particles and can be applied to virtually all kinds of particles, regardless of optical or charge properties. However, the formation of the standing BAW requires the channel material to possess excellent acoustic reflection properties (e.g., silicon, glass, etc.)—properties that the soft polymer materials commonly used in microfluidic applications, such as polydimethylsiloxane (PDMS), do not have [29]. Additionally, the transducer required for BAW generation is bulky, hindering device integration and miniaturization.

§ 4.2 Continuous Particle Separation through a SSAW

§ 4.2.1 Working mechanism

A schematic of the SSAW-based separation device is shown in Figure 4-1 a. A pair of interdigital transducers (IDTs) was deposited on a transparent piezoelectric substrate, and a PDMS microchannel (with 3 inlets and 3 outlets) was positioned and bonded between these two IDTs. A mixture solution of dissimilar particles was injected through the side inlets and a sheath flow was injected through the central inlet, forming a laminar flow of three liquid streams.
Applying AC signals to the IDTs generated two series of identical-frequency surface acoustic waves (SAWs) which propagated in opposite directions toward the channel. The constructive interference of these two SAWs resulted in a SSAW in the area where the microchannel was bonded [30]. When the SSAW encountered the liquids encapsulated in the microfluidic channel, it generated longitudinal leakage waves, causing pressure fluctuations inside the liquids. These pressure fluctuations resulted in lateral acoustic radiation forces (along X axis in Figure 4-1) on the suspended particles, driving them to either the pressure nodes.
(minimum pressure amplitude) or antinodes (maximum pressure amplitude), depending on the relative density and compressibility between the particles and the medium [31–38].

As shown in Figure 4-1 b, particles in such a SSAW field experience four types of forces: lateral acoustic force (along X axis), viscous force (opposite direction of particles’ velocity relative to flow stream), gravity force (along Y axis downward), and buoyant force (along Y axis upward). Among these forces, the gravity force and buoyant force are almost balanced as they are similar in magnitude but opposite in direction. As a result, the behavior of particles inside the channel can be analyzed by examining the viscous force and the acoustic force. In a SSAW, the primary acoustic force \( F_r \) and the viscous force \( F_v \) on a particle can be expressed as [14,15,39,40]:

\[
F_r = -\left(\frac{\pi p_0^2 V_p \beta_m}{2 \lambda}\right) \phi(\beta, \rho) \sin(2kx),
\]

\[
\phi = \frac{5 \rho_p - 2 \rho_m - \beta_p}{2 \rho_p + \rho_m - \beta_m},
\]

\[
F_v = -6\pi \eta \nu,
\]

where \( p_0, V_p, \lambda, k, x, \rho_m, \rho_p, \beta_m, \beta_p, \eta, r \) and \( \nu \) correspond to pressure amplitude, particle volume, ultrasonic wavelength, wave vector, distance from a pressure node, density of the medium, density of particles, compressibility of medium, compressibility of particles, medium viscosity, particle radius, and relative velocity, respectively. In the experiments, all particles were of the same density and compressibility, but were different in size. Due to the fact that the acoustic force is proportional to the volume \( (r^3) \) of the particles, while the viscous force is proportional to the radius of the particles \( (r) \), larger particles experience much larger net forces and therefore move towards the pressure node faster than smaller ones.
When the channel width covers half a SSAW wavelength with a single pressure node at its center, dissimilar particles flowing along the sidewalls of the channel will be displaced towards the channel center by dissimilar net forces: the larger the particle, the larger the net force. Thus the particles are repositioned with different lateral displacements along the cross-section of the channel, which is split into multiple collection outlets. The collected sample is thus separated based on particle size, density, and compressibility.

§ 4.3.2 System setup

The device fabrication was fully described in § 2.3.2. An optical image of the final device is shown in Figure 4-2 c. The width and pitch of the IDTs were 75 µm and 150 µm, respectively, corresponding to a SAW with a working wavelength of 300 µm. The PDMS channel is 150 µm in width and 80 µm in depth. The experiment was conducted on the stage of an inverted microscope (Nikon TE2000U). A mixture solution of fluorescent polystyrene beads (Particle I: 4.17 µm diameter, dragon green, ~2.53×10⁷ beads/ml; Particle II: 0.87 µm diameter, Rhodamine WT, 2.76×10⁸ beads/mL; both from Bangs Laboratories) was injected through the middle inlet, as shown in Figure 4-2 c. DI water was injected through the inlets labeled sheath flow I and sheath flow II in Figure 4-2 c. The central sheath flow separated the two particle streams, and the outer sheath flow prevented particles from trapping and aggregating along the sidewall of the channel due to surface roughness. All three flows were injected using syringe pumps (KDS210, KD Scientific). Thus, a five-layer sandwiched laminar flow was formed across the channel (layer one: 1/2 sheath flow II; layer two: 1/2 particle flow; layer three: sheath flow I; layer four: 1/2 particle flow; layer five: 1/2 sheath flow II). An AC signal generated by an RF signal generator (Agilent E4422B) was amplified with a power amplifier (Amplifier Research 100A250A) and split into
Figure 4-2: (a, b) Schematic of the fabrication process and (c) optical image of the fabricated device. (a) A metal deposition (Cr/Au) followed by a lift-off process forming the IDTs on a piezoelectric substrate for SAW generation. (b) A mold-replica and soft-lithograph process forming the PDMS microchannel. (c) Optical image of the device used in the experiments, showing the inlets, outlets and zoom-in figure of the IDTs (inset).
two signals, which were then applied to the two IDTs to generate two identical SAWs. The signal frequency was set at 12.6 MHz (resonance frequency of a SAW on LiNbO₃ at $\lambda=300 \, \mu m$).

Following that, the applied power (15−22 dBm, or 30−160 mW) and flow speed of the particle solution (0.6−2 µL/min) were tuned to achieve high separation efficiency. After passing through the microchannel, the particle solutions were collected at the outlets for quantitative analysis.

§ 4.2.3 Results and discussion

Particle separation process

Two rectangular openings in the PDMS were fabricated on either side of the channel to define the working region of the SSAW. They also reduce the amount of PDMS in contact with the substrate, thus reducing propagation loss of the SAWs. Three positions marked as I, II and III along the channel were chosen to record the particle distribution in the channel when the SSAW was applied (Figure 4-3 a). At site I, particle flows and the sheath flow were entering the main channel. At this location, the particle mixture was outside of the working region of the SSAW, and small particles (red color) and large particles (green color) were flowing together along the sidewalls of the channel (Figure 4-3 b). Note that in site I the large particles are distributed in thin streams near the channel sidewall while the small particles form wider streams in the lateral direction of the channel; this is attributable to the hydrodynamic effect within the laminar flows.

As the particle mixture entered the working region of the SSAW (site II), the acoustic forces acting on the large particles were greater than those acting on the small particles, pushing the large particles out of the particle mixture and towards the SSAW pressure node at the center of the channel. The acoustic forces acting on the small particles were insufficient to push them into the central stream; thus the small particles remained in the side streams (Figure 4-3 c). As the
large particles approached the SSAW pressure node, the acoustic forces acting on those particles decreased to zero, ensuring that the large particles remained in the central stream. An examination

Figure 4-3: The schematic indicates the positions of the monitoring sites (I–III) for particle separation. (b–d) are the recorded fluorescent images at sites (I–III), respectively. Excitation light: 550 nm for 0.87 μm beads (with Rhodamine WT), and 480 nm for 4.16 μm beads (with dragon green). Fluorescent light: 590 nm for Rhodamine and 520 nm for dragon green. Each image shown in (b–d) is a composite of two images taken at the same position with different excitation light but the same working parameters.

of Figure 4-3 c indicates that the large particles migrated to the central channel within a span of ~900 μm. Taking into account the flow speed (2.5 mm/s) of the particle flows, it is determined that the particle separation process took ~360 ms. It should be noted that by tuning the working
parameters (increasing the flow speed and applied power), this separation time can be decreased further. At the outlet of the channel (site III), the large particles in the central stream were collected by the central outlet and the small particles in the two side streams were collected by the side outlets. At this point the particles were successfully separated (Figure 4-3 d).

**Separation efficiency analysis**

To quantitatively evaluate the separation efficiency of this method, samples of particles collected from the side and central outlets were collected and analyzed for size distribution. A free software ImageJ® was used to count the number of particles collected from each outlet. The remaining rate (the ratio of particles remaining in the side channel after SSAW to the particles before experiencing SSAW) and separation efficiency (the ratio of particles in the central channel after SSAW to the particles before experiencing SSAW) are shown in Figure 4-4 a and b. Whereas, ~90% of small particles remained in the side flow, more than 80% of large particles immigrated from the side flow to the central flow. This high separation efficiency implies the high purity of the separated samples and the resulted high accuracy in sample detection and analysis, making this method attractive for a series of bio/chemistry applications, e.g. microarray, drug screening and regeneration, and tissue engineering, where the experimental performance is highly dependent on the purity of samples [33–38]. The separation efficiency in this technique is highly dependent on the channel geometry (length, width) and working parameters including SAW powers, IDT period and length. By properly designing the channel width and length, the particles (more than two types) can form a stable distribution along the channel width based on their size. The splitting of the channel to different outlets separates the particles. Acoustic forces are also dependent on the density and compressibility of the particles, which means this technique can also be used to separate similar sized particles but different densities or compressibilities.
Figure 4-4: Quantitative analysis showing (a) the ratio of particles remaining in the side channel (remaining rate) upon applying SSAW, and (b) ratio of particles in the central channel (separation efficiency) after experiencing SSAW. (c) particle samples before experiencing SSAW; (d) particles in the central channel before experiencing SSAW; (e) particles in the side channel after experiencing SSAW, and (d) particles in the central channel after experiencing SSAW.
Discussion

When a microparticle maintains constant velocity in the SSAW field, the acoustic and viscous forces balance each other [39]. Based on Equations (4-1–3), we conclude

\[ v_h = -[p_0^2 V_c \beta_w / (12 \lambda \eta \rho_c)] \phi(\rho, \beta) \sin(4 \pi x / \lambda). \quad (4-4) \]

Rewriting \( v_h = -dx/dt \) and separating variables, we obtain:

\[ \text{cosec}(4 \pi x / \lambda) dx = [p_0^2 V_c \beta_w / (12 \lambda \eta \rho_c)] \phi(\rho, \beta) dt. \quad (4-5) \]

Since the particles will move to the pressure nodes nearby, \( \delta x \) is in the range of \((0, \lambda/4)\).

Therefore the time needed for bead migration will be

\[ t = (3 \lambda^2 \eta \rho_c / \pi) \left[ \ln(\tan(2 \pi x / \lambda)) \right]_{x_1}^{x_2} / [p_0^2 V_c \beta_w \phi(\rho, \beta)] \quad (4-6) \]

where \( x_1 \) and \( x_2 \) are the starting and ending positions in the lateral direction (x axis). In such a way, the flowing track of the particles with different properties (size, density and compressibility) inside a SSAW can be predicted. This ray-tracing of the particles helps in optimizing the channel design and SAW working situations. In a simplified model (Figure 4-5 a), two particles with same properties but different sizes enter the working region of the SSAW along the sidewall of the channel. Due to the acoustic force difference (as shown in Figure 4-5 b), these two particles take different time to reach the PN at the center (as shown in Figure 4-5 c). Figure 4-5 d plotted the lateral displacements of particles (polystyrene beads) with different sizes at varying time, where the relative distance \( \delta x \) between the particles used in the experiment (0.87 \( \mu \)m and 4.17 \( \mu \)m polystyrene beads) was calculated to be \( \sim 26 \mu \)m in 360 ms, which coincides well with the experimental result observed in Figure 4-3 c.

By introducing a SSAW in a microfluidic channel, particles of varying sizes can be effectively and continuously separated. The excellent energy-confinement of SAWs propagating on a piezoelectric substrate makes this particle separation device highly energy efficient: 13,000
particles were separated from a dissimilar mixture in one minute using 30 mW of power, notably smaller than the 500-2000 mW required by BAW-based acoustophoresis in an equivalent situation [27, 28]. In addition, while the BAW-based method requires the channel material to possess excellent acoustic reflection properties (e.g., silicon, glass, etc.), this SSAW-based approach confines the acoustic wave to the substrate, permitting the use of convenient channel materials such as PDMS. This particle separation device is fabricated via standard MEMS and

Figure 4-5: The schematic in (a) indicates the model for calculation: parallel flowing particles along the sidewall of the channel experience lateral acoustic forces and translate different lateral displacements (δx), resulting in the separation. (b) Primary acoustic force distribution along a pressure node (PN) within half wavelength; (c) time required for particles with varying size to translate from the sidewall of the channel to the PN at the center; (d) relative lateral displacement (along x axis) versus the working time of SSAW.
soft-lithography procedures, permitting easy fabrication, miniaturization, and integration—and making it highly cost-effective for potential mass production. Furthermore, the separation efficiency of this technique (~80%) is comparable to or higher than the efficiencies of other techniques. And the separation efficiency and speed of this technique can be readily adjusted by tuning applied SAW power, working wavelength of the SAWs, sample flow speed, and channel geometry. These characteristics make the SSAW-based particle separation method presented here promising in many bio/chemical applications.

References


Chapter 5
SAW-induced active plasmonics of gold nanodisk arrays

§ 5.1 Introduction

§ 5.1.1 Surface plasmons

Figure 5-1: (a) surface plasmon on thin metal film deposited on a dielectric substrate (longitudinal mode); (b) surface plasmon around metal sphere array (transverse mode) [1].
Surface plasmons are electromagnetic waves that propagate in the direction parallel to the metal/dielectric interface [1]. The excitation of surface plasmons by light from a planar surface (Figure 5-1 a) is called as a surface plasmon resonance (SPR), while the excitation of surface plasmons for nanometer-sized metallic structures (Figure 5-1 b) is called localized surface plasmon resonance (LSPR). Surface plasmons are normally generated by the help of coupling medium such as a prism or grating to match the photon and surface plasmon wave vectors, although they can be excited by both electrons and photons (as shown in Figure 5-2).

In the photon-based generation case (the Kretschmann configuration shown in Figure 5-2), the wave number of the excited surface plasmons obeys the relation [1]:

\[ K_{SP} = \frac{\omega}{C} \sqrt{\varepsilon_1 \varepsilon_2} \]  
\[ \varepsilon_2 = \varepsilon_2' + \varepsilon_2'' \]  
\[ K_{SP} = K_{SP}' + iK_{SP}'' = \frac{\omega}{C} \sqrt{\frac{\varepsilon_1 \varepsilon_2}{\varepsilon_1 + \varepsilon_2}} + i \left[ \frac{\omega}{C} \left( \frac{\varepsilon_1 \varepsilon_2'}{\varepsilon_1 + \varepsilon_2} \right)^{\frac{3}{2}} \frac{\varepsilon_2''}{2(\varepsilon_2')^2} \right] \]
where $\varepsilon_1$, $\varepsilon_2$ are the dielectric functions of the prism (glass) and metal, respectively. When $\varepsilon_1 + \varepsilon_2 = 0$, surface plasmons is launched. For most dielectric materials, $\varepsilon_1$ is real and positive; while $\varepsilon_2$ can be expressed as in equation 5-2, including the real part $\varepsilon_2^r$ and imaginary part $\varepsilon_2^i$. In practice, we define surface plasmon generation when $\varepsilon_1 + \varepsilon_2^i = 0$. In analyzing the properties of surface plasmons, quantum theory and the Drude model are widely used [1].

One good example of surface plasmons is in the Lycurgus Cup, which was fabricated in the Roman empire (Figure 5-3) [2]. It looks green under normal illumination (light source outside of the cup). When a light source is placed inside the cup, the outside of the cup looks red. The

![Figure 5-3: Lycurgus Cup indicates different colors under the reflection and transmission modes, respectively [2].](image-url)
color difference is attributed to the surface plasmons effect of the gold nanoparticles composite in the paint on the cup. It was synthesized that the dichloric glass (of which the cup was made) contained gold nanoparticles with ~70 nm in size, and such particles give ~520 nm resonant frequency of surface plasmons. Under normal illumination, the nanoparticles scattered the light of wavelength of ~520 nm, yielding a yellow-green color; while in the transmission mode, the nanoparticles inside the cup absorbed the 520 nm light, letting red light pass.

One of the most promising potential applications of the surface plasmon is in the fast communication and computation, as it lets one “squeeze” optical signals into novel metallic minuscule structures (e.g. nano thin film, nano wires, and nano particles of Au, Ag and Cu et al.). This characteristic makes it a candidate in building fast interconnects in computer chip design that could move much more data across a chip than its electronic counterpart, because the frequency of an optical signal is much higher than that of an electrical one—more than 400,000 gigahertz versus ~10 gigahertz. Since surface plasmons are strictly localized on the boundary of the metal/dielectric interface, they are very sensitive to any change of the boundary—a phenomenon that was widely used in chemical and biological sensing. In sensing applications, nanostructures (thin films, spheres, prisms, nanoholes) of novel metal (Au, Ag, Cu etc) were coated with the active bonding sites and exposed to the target solution or gas. The bonding of the targets to the bonding sites changed the environment of the metallic nanostructure (refractive index/electron distribution), as well as the resonance wavelength of the surface plasmons. The difference of the resonance wavelength of surface plasmons was used to quantify the target concentration in the sample. Other applications of surface plasmons rely on the plasmon-induced electric field enhancement at the metal/dielectric boundary. This property can be used to improve the resolution of microscopes (molecular detection), the efficiency of light-emitting diodes (LED), and kill the cancer cells in vivo (cancer therapy). Figure 5-4 demonstrates the working principle of surface plasmon-enhanced cancer therapy. In this application, gold nanoshells coated on
silica particles are injected through the blood stream. The gold nanoshells will concentrate at the tumor region. An infrared laser is used to pass through the skin (with low loss) and illuminate the tumor region. The incident light will generate resonant electron oscillation in the nanoshell. The generated heat will kill the tumor cells without affecting the surrounding healthy cells [3]. In comparison with the conventional ultrasonic therapy, the plasmon-based tumor therapy features the following advantages: (1) higher performance with lower power consumption. Since the gold nanoshells can be selectively functionalized with specific bonding sites, which help to bond the nanoshells only to the tumor cells with an increased concentration. At the same time, lasers can be focused in a much smaller region than that of ultrasound, such that a lower-power laser can be used to generate enough heat at local region to kill the tumor cells without affecting the

Figure 5-4: Schematic showing the working principle of plasmonic therapy for cancer [3].
neighboring cells; (2) Longer working distance. As the resolution of ultrasounds is inversely proportional to the working frequency, high-frequency ultrasounds (~10 MHz) is required. However, high-frequency ultrasound features shallow penetration depth (normally within several millimeter). This limits its application to tumors near the skin. By using the infrared or near-infrared lasers, the increased power can penetrate much longer distance than the ultrasounds, making plasmonic therapy attractive for deep-tumor treatment.

§ 5.1.2 Motivation

![Figure 5-5: Plasmonics—merging photonics and electronics at nanometer scale [1].](image)

In the past half-century, the boom of the integrated circuit (IC) industry has resulted in tremendous developments in communications and computing. According to Moore's law, processing speed and memory capacity of the electronic devices double approximately every two years. However, Moore’s law faces a challenge: when the features of an electronic device are scaled down to tens of nanometers, the electron-based signal operation is limited to several GHz working frequency. As a promising candidate to overcome this limitation, the principle of total-
optical communication has for years been proposed to achieve high-speed operation both in communication and calculation, however, the features of optical devices are normally several to hundreds of micrometers, hindering device integration and increasing fabrication costs. Surface plasmon-based nanophotonics, or “plasmonics”, can potentially guide and manipulate light at sub-wavelength scales, enabling the merging of advantages of photonics (high frequencies) and electronics (miniaturization) at the nanoscale (Figure 5-5). These striking abilities of this surface plasmon-based photonics, or “plasmonics”, has garnered a resurgence of interest in the past two decades [4-6]. To date, significant advances have been made in the development of light sources, filters and waveguides, so called passive plasmonics devices [7-12]. However for plasmonics to reach its potential, devices such as switches and modulators - so called active devices must be perfected. In this paper we propose an “acoustic tweezers”-induced active plasmonic device that utilizes a standing surface acoustic wave (SSAW) to tune the LSPR of a gold nanodisk array through realigning the LC molecules surrounding it.

§ 5.2 Active plasmonics via acoustic tweezer-induced molecular realignment of liquid crystals

Many avenues have been pursued in order to develop active plasmonic devices. One such method takes advantage of localized surface plasmon resonance (LSPR) of nanostructures of noble metals (Ag, Cu, Au) [13-18]. LSPR is intrinsic to the nanostructure’s properties such as: size, shape, inter-spacing and dielectric characteristics of the surrounding environment [19, 20]. By modulating these properties, one can tune the levels of LSPR and thereby achieve active plasmonic devices. Wang and Chumanov have demonstrated the electrochemical modulation of the intensity and frequency of the LSPR of Ag nanoparticles embedded in a tungsten oxide matrix [21]. Zheng et al. have achieved active tuning of the plasmonics of rotaxane molecule-coated
gold nanodisk arrays, by chemically switching the molecules between the oxidization and reductant states [22].

Liquid crystals (LCs), rod shaped molecules demonstrating relatively large optical anisotropy in the ordinary and extraordinary orientations, are believed to be a good candidate for use in active plasmonics [23-26]. Hsiao et al. have demonstrated an all-optical plasmonic switch based on reorientation of photoresponsive LCs by a pump light [27]. Kossyrev et al. have reported electric field tuning of plasmonic response of a gold nanodot array in a LC matrix [23]. We have noticed that the nematic LCs have shown to possess acousto-optic effects: an acoustic wave can change the orientation of the LC molecules and thus the effective refractive index (RI) [28, 29]. In this paper we propose an “acoustic tweezers”-induced active plasmonic device that utilizes a standing surface acoustic wave (SSAW) to tune the LSPR of a gold nanodisk array through realigning the LC molecules surrounding it (See Figure 5-6 a.). A SSAW-driven active plasmonic device offers several advantages: low power consumption due to the energy confinement nature of surface acoustic wave (SAW); also the fabrication process for such a device is compatible with MEMS technology, and can be easily miniaturized and integrated on an industrial scale.

§ 5.2.1 Working mechanism

The active plasmonics device consists of a piezoelectric substrate and a bonded PDMS microchannel filled with nematic LCs (TL213, Merck, n_o=1.5271, n_e=1.7658), which covers an Au nanodisk array immobilized on the piezoelectric substrate (Figure 5-6 a). A pair of interdigital transducers (IDTs), deposited on the piezoelectric substrate, was utilized to generate two identical SAWs. The interference of these two SAWs resulted in a standing SAW (SSAW) in the cross-sectional area under the PDMS channel. When SAWs encountered the LCs inside the
microchannel, leakage waves in longitudinal mode were generated, with the direction decided by the Snell’s law [30]. The leakage waves caused pressure fluctuations, as well as torques, which

\[ n_{\text{eff}} = \frac{n_0 n_e}{\left(n_0^2 \sin^2 \beta + n_e^2 \cos^2 \beta \right)^{1/2}} \]

Figure 5-6: A schematic of the proposed active plasmonic device. (a) Experimental setup: a probe light passes through the device and the resulting absorbance was measured on the other side. A pair of IDTs is used to generate a SSAW, which realigns LCs enclosed in the PDMS microchannel, resulting in the LSPR shift of the Au nanodisk array. (b) Atomic force microscopy (AFM) characterization of the Au nanodisk array. (c) The dependence of effective refractive index on the molecular orientation of LCs. (d) When a SSAW is applied, the SAW-induced force torques on the LC molecule make it normal to the substrate, implying an effective refractive index of \( n_{\text{eff}} = n_0 \). (e) Distribution of LCs molecules on top of the Au nanodisk array. The orientation of LCs are modified by the Au nanodisk morphology and gave an effective RI of \( n_{\text{eff}} = 1.66 \). (f) Reorientation of LC molecules under the applied SSAW.
acted on the rod-shaped LC molecules to realign their orientations. As a result, the effective RI of
the LCs surrounding the Au nanodisk array was changed in light of the normal incident beam,
thus tuning the LSPR of the Au nanodisk array (Figure 5-6 c, d). The Au nanodisk array was
fabricated through a nanosphere lithography technique that was reported previously [19]. The
period of the Au nanodisk array (arranged in a hexagonal geometry) is 320±32 nm, and the
diameter of single nanodisk is 170±14 nm, as measured from an acoustic force microscopy
(AFM) image (Figure 5-6 b). A white light (non-polarized) was generated from a halogen lamp,
passing through the Au nanodisk array in normal direction, and the transmitted light was
collected and detected by a spectrometer (HR4000G-UV-NIR, Ocean Optics), where the
extinction spectrum of the Au nanodisk array was recorded and analyzed (Figure 5-6 a).

Nematic LCs feature no positional order, but have long-range orientational order [32]. The
LCs surrounding the Au nanodisks, however, lose their long-range orientational order within
a certain distance away from the interface, due to the surface modulation caused by the gold
nanodisks (Figure 5-6 e). In order to quantitatively analyze the SAW effect on the LCs’
realignment, the original effective RI of the LCs surrounding the nanodisk array has to be first
characterized. Based on the fact that the peak wavelength of LSPR of the Au nanodisks changes
linearly with the changing of the RI of the surrounding medium [19], a spectrum-fitting
experiment was conducted. In this experiment, the Au nanodisk array was immersed in a series of
media with different RIs (total rinse of the samples before changing the medium guaranteed the
complete removal of any former medium residue) and the corresponding LSPR spectrums were
recorded (Figure 5-7 a). The dependence of the peak positions of LSPRs versus the corresponding
Figure 5-7: (a) Response of the LSPRs of a Au nanodisk array with different surrounding mediums with varying refractive index. (b) Peak position versus the refractive index. Red line is the linear fitting to the experimental data. The effective refractive index of the LCs surrounding the Au nanodisk array can be characterized through the linear extension of the fitting curve.
RIIs was plotted and a linear curve fitting to the experimental data revealed the sensitivity of the LSPR shift to the RI changing. A linear extension of the curve fitting concluded that the effective RI of the LCs surrounding the Au nanodisk array was \( \sim 1.66 \), corresponding to a peak wavelength of \( \lambda = 881 \) nm for the LSPR of the Au nanodisk array immersed in the LCs (Figure 5-7 b). This effective RI may arise from a complex combination of LC molecules with different orientations affected by the morphology of the Au nanodisk array. In a simple model, we can view all the LC molecules orientated at an angle \( \beta_0 = 51.3^\circ \) (Figure 5-6 c) to the normal line; such an orientation of LCs gives the same effective RI as the real case [28]. When a SSAW was applied, the acoustic forces originated from the SAW-induced pressure gradients inside the LCs applied force torques on the LC molecules and realigned them to the balanced orientation. As can be seen from Figure 5-6 d, the minimum effective RI of the LCs is \( n_{\text{eff}} = n_o = 1.5271 \), occurring when the LC molecules are balanced in the orientation normal to the substrate (\( \beta = 0^\circ \)), in such an orientation the net force torque on a LC molecule was minimum.

§ 5.2.2 Device fabrication

To fabricate the gold nanodisks onto the piezo-substrate, a thin layer of photoresist (PR) SPR3012 (MicroChem, Newton, MA) was spin-coated (4000 rpm, 45 seconds, 1.2 \( \mu \)m thickness) on a Y+128° X-propagation lithium niobate (LiNbO\(_3\)) wafer; then it was exposed with a UV light source with a mask defining the regions for nanodisks. After development in a photoresist developer (MF CD-26, Microposit, 1 minute), the LiNbO\(_3\) substrate with openings defined by the photoresist was ready for nanodisk fabrication. In this experiment, a simple and cost-effective method—nanosphere lithography—was utilized to fabricate the gold nanodisk arrays on top of the piezoelectric substrate. Nanosphere lithography is an effective method to fabricate large area periodic nanostructures at much lower cost in comparison to other available technologies, such
as e-beam lithography or focused ion beam (FIB) lithography. It uses self-assembled polystyrene beads as templates to generate a series of nanostructures, including nanodisks, nanoholes, prisms.

Figure 5-8 Fabrication process of the SAW substrate with gold nanodisks. (a)–(f) A nano sphere lithography is used to form gold nanodisk arrays (period and diameter of 310 nm, 170 nm, respectively) on a piezo-substrate. (g)–(i) A lift-off process is used to form two parallel gold IDTs for SAW generation, with the gold nanodisk arrays in between. (j) Final device used in experiments. (k) AFM figure of the fabricated gold nanodisk arrays encircled by the dashed square in (j).
A typical nanosphere lithography used for gold nanodisk array fabrication was demonstrated in Fig. 5-8 a-f. Firstly, a double metal layer (Ti/Au, 30Å/300Å) was deposited on top of the piezoelectric substrate using an e-beam evaporator (Semicore Corp) (Fig. 5-8 b). The metal layer in the openings defined by the photoresist was tightly bond with the piezoelectric substrate, while the metal layer in other regions are on top of the photoresist. The piezoelectric substrate was put inside a Petri dish and a polystyrene nanobeads (diameter of 320 ± 32 nm in this experiment) solution was injected into the Petri dish till totally immerse the piezoelectric substrate. To avoid any perturbation in the solvent evaporation process, the Petri dish was put on an optical table with air-suspension. In the evaporation process (normally takes overnight in summer, and several days in winter at lab temperature), nanobeads immersed in the solvent self-assembled in close-packed geometries in both monolayer and multiple layer manners (Fig. 5-8 c). In obtaining a high quality nanodisk array, monolayer nanobeads array is highly desired. After the formation of the self-assembly-monolayer (SAM) of nanobeads on the piezoelectric substrate, it was etched with oxygen plasma till the bead size down to 170 nm in diameter (Fig. 5-8 d). Argon plasma was then used to etch through the gold thin film with the polystyrene beads as hard mask (Fig. 5-8 e). After removing the PR and attached metal layer in a followed lift-off process, the device was immersed in a toluene solution to remove the polystyrene beads on top of the gold nanodisks, thus yielding the gold nanodisk array (Fig. 5-8 f). In order to speed up the peeling of the polystyrene beads from the gold nanodisk, ultrasound was utilized (3 minutes). An atomic force microscopy (AFM) was used for the nanodisk topography characterization (Figure 5-8 k).

After the gold nanodisk array was fabricated, we shifted our attention to fabricating the IDTs: a PR layer was deposited onto the device covering the gold nanodisk array. Lithography was used to give the opening of IDTs. This was followed by metal deposition (50Å/800Å, Cr/Au) and lift-off, to produce the IDTs. Next, the polydimethylsiloxane (PDMS) microchannels were fabricated with standard soft-lithography and mold-replica techniques (refer to the full discussion
in). The PDMS channel was bonded with the SAW substrate with the channel covering the gold nanodisk array on the piezoelectric substrate (please refer to § 2.3.2 for detailed discussion on device fabrication and bonding).

It is clear from the nanosphere lithography that the diameter of the original nanobeads decides the period of the fabricated nanodisk array, and the tuned bead size after oxygen plasma etching decides the diameter of the nanodisk. Simply speaking, smaller the nanodisk, the smaller wavelength of the surface plasmon generated from the nanodisks. In order to get different resonance wavelength from the gold nanodisk array, the diameter of the gold nanodisk need to be tuned, which can be achieved by tuning the oxygen plasma etching time and power. Table 5 summarized the etching parameters in this experiment (using 320 nm nanobeads to fabricate nanodisks with diameter ~170 nm). It has to be mentioned that the parameters listed here are just for reference, which may vary a lot for different machines. We also noticed that the parameters have to be calibrated even for the same machine at different time.

Table 5 Etching parameters involved in the nanosphere lithography

<table>
<thead>
<tr>
<th></th>
<th>Flux (sccm)</th>
<th>Power (W)</th>
<th>Pressure (mTorr)</th>
<th>Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen</td>
<td>20</td>
<td>300</td>
<td>100(^a)</td>
<td>30~35</td>
</tr>
<tr>
<td>Argon</td>
<td>20</td>
<td>300</td>
<td>100(^a)</td>
<td>120~150(^b)</td>
</tr>
</tbody>
</table>

\(^a\) The pressure of the chamber can be tuned in a relatively large range (100 ~ 350 mTorr).
\(^b\) The etching time is defined as long as the metal layer was totally etched through.

§ 5.2.3 Results and discussion

In the active LSPR tuning experiment, an AC signal was generated from a signal generator (Agilent E4422B) and amplified by a power amplifier (Amplifier Research 100A250A). The output signal from the amplifier was then split into two identical signals, which
were applied to the IDTs to generate SAWs. The applied AC signal was set to be 87.332 MHz (the resonance frequency for SAWs with the wavelength of $\lambda=40 \, \mu\text{m}$ on LiNbO$_3$ substrate). The absorbance spectra of the Au nanodisks were measured for varying levels of SAW power inputs (Figure 5-9). When SAWs were absent, the LSPR exhibited a peak absorbance at a wavelength of 881 nm corresponding to $n_{\text{eff}}=1.66$ for the surrounding LCs, as previously discussed. As increasing power (from 23 dBm to 31 dBm) was applied to the device, the peak position of the LSPR decreased—a blue shift occurred. At the highest power tested (31 dBm), a 37 nm blue shift
of the LSPR peak position was measured. This active tuning of LSPR contributed to the SSAW-induced molecular realignment of LCs surrounding the Au nanodisk array: the acoustic forces originated from the SSAW-induced pressure gradients inside the LCs applied unbalanced force torques on the LC molecules ($\beta_0 = 51.3^\circ$) and realigned them with the extraordinary optical axis normal to the substrate, as in which orientation, the force torques on the LC molecules minimized and LCs reached a steady state. As can be seen from Figure 5-6 d, the minimum effective RI of the LCs is $n_{\text{eff}} = n_0 = 1.5271$, occurring when the LC molecules are balanced in the orientation.

Figure 5-10: The peak blue shift (in nm) vs. the power provided to the IDTs (in dBm). The inset figure represents the zoomed-in figure of the experimental data in Figure 5-8. The curve fitting reveals the saturation of the peak shift versus the applied power.
normal to the substrate ($\beta = 0^\circ$), in such an orientation the net force torque on a LC molecule was minimum. As the LSPR wavelength blue shifted with increasing power, the peak absorbance value also decreased a little bit due to the decreasing effective RI. This demonstrates that a high sensitivity tuning can be achieved with relatively small changes in the applied powers, making this device fairly energy efficient.

Further consideration of the dependence of the LSPR peak shift versus the applied power revealed that the sensitivity of the blue shift was inversely proportional to the applied power (Figure 5-10). A curve-fitting to the experimental data indicated that the peak shift of the Au nanodisk array saturated when power beyond 30 dBm was applied; this can be predicated by analyzing the dynamics of the SSAW-induced molecular reorientation of the LCs. As discussed in Figure 5-6, the application of SAWs to LCs will cause the realignment of the LC molecules, which can be characterized using such equations as [28, 29]:

$$\theta = \arcsin\left(\frac{v_{\text{Liquid}}}{v_{\text{Substrate}}}\right)$$  \hspace{1cm} (5-4)

$$\Delta \beta(z) = \sum_{j=1}^{n} \beta_j \sin\frac{j\pi z}{a}$$  \hspace{1cm} (5-5)

$$\beta_{eq}^j = -\frac{4a^2u_z\rho_0 K_3^2 I \sin 2\theta}{\pi^3 j^3 K_3 v^3} - \frac{4a^4 u_z^2 \rho_0^2 k^2 I^2 \sin 4\theta}{\pi^5 j^3 K_3^2 v^6} - \ldots$$  \hspace{1cm} (5-6)

$$n_{\text{eff}} = \frac{n_0 n_e}{(n_0^2 \sin^2 \beta + n_e^2 \cos^2 \beta)^{1/2}}$$  \hspace{1cm} (5-7)

where $\theta \approx 25^\circ$ is the incident angle of the acoustic force, decided by the comparison of sound velocity in LC ($v_{\text{liquid}}$) and substrate ($v_{\text{substrate}}$); $\Delta \beta$ is the orientation change of the LC molecules due to SAW, which is a function of the vertical distance away from the substrate surface, and dependent on the power intensity $I$, incident angle $\theta$ of the acoustic wave and thickness of LC layer on top of the Au nanodisk $a$. In our simplified model, the original orientation angles of the
LC molecules are viewed as $\beta_0 = 51.3^\circ$, upon applying the SSAW, the LC molecules tend to realign in the normal direction to the substrate due to the asymmetric distribution of the pressure gradients caused by the two oppositely propagating SAWs (Figure 5-6 d). With power increasing, LC molecules rotate to a smaller orientation angle $\beta$ under the applied acoustic force torque; consequently, the force torque becomes smaller as the moment arm becomes shorter. This explains the slope (sensitivity) decreasing of the fitting curve in Figure 5-10 with power increasing, implying it becomes harder to tune when the molecule get closer to the normal orientation to the substrate. Once the molecule becomes normal to the substrate, the net force torque applied to the molecule equals zero and will remain zero upon applying higher power—saturation occurs.

With the removal of the applied power, the LC molecules rotate back to their original states gradually, indicating the recovery of the effective RI, as well as the LSPR of the immersed Au nanodisk array. The response speed of the dynamic change of the LSPR to the applied power was characterized in a follow-up experiment, where a 31 dBm AC signal was periodically applied to the IDTs to generate a SSAW and the absorbance intensity of the LSPR at $\lambda = 711$ nm (where the intensity change is maximum) was recorded and plotted in Figure 5-11. It can be seen that the response time in turning the SSAW on and off is about 5.3, and 5.2 seconds, respectively. The relatively slow turning on time confirms our theoretical analysis to the SAW-induced LC realignment: the force torque applied to the molecule becomes smaller in its realignment process to the normal orientation; as a result it takes relatively long time to make the active plasmonics device stable. The recovery process, however, takes shorter time than the previous reported result in literature [27]. This occurs possibly because we use pure LCs instead of dye-doped LCs and we no longer contend with the additional deformation process of dye inside the LCs, which normally makes the recovery time longer. By increasing the power intensity, the turning on time can be further improved.
In summary, we have demonstrated an efficient acoustically driven plasmonic device. By modifying the power input to SAW generators, one can actively tune orientations of the LC molecules through SAW-induced force torques. This in turn changes the effective RI of LC and the LSPR of the immersed Au nanodisk array. The application of a 31 dBm SSAW generated from two identical IDTs aligned the LC molecules in the normal direction to the substrate (owning a minimum RI ~1.527) and resulted in a maximum blue shift (37 nm) of the LSPR of the Au nanodisk array. Upon removing the applied SSAW, the original orientations of the molecules, as well as the LSPR were recovered. Besides the good reversibility, this acousto-plasmonics device also features low power consummation, easy fabrication and amenability to miniaturization. The working mechanism proposed in this work allows us to further build devices

Figure 5-11: (a) Response of the LSPR peak shift versus time. (b) Turn on time $t_{on}$ and (c) turn off time $t_{off}$. 

![Graphs showing response of LSPR peak shift versus time, turn on time $t_{on}$, and turn off time $t_{off}$]
serving as active modules such as switches, modulators and couplers in plasmonics-based applications like communications, signal processing and sensor array.

§ 5.3 SAW-induced direct active plasmonics of gold nanodisk arrays via charge/discharge process

Recently, several active plasmonic mechanisms and materials have been examined. Leroux showed that the shape and position of the LSPR of Au nanoparticles embedded in polyaniline thin films can be tuned by an electrochemical method. Wang demonstrated the electrochemical tuning of LSPR of WO3 sol-gel modified Ag nanoparticle arrays. LC’s have been broadly used in optical switches and optical modulators, particularly in LC displays, due to the large birefringence. Applications of liquid crystals for the active tuning of metal nanostructures’ LSPR have also been demonstrated using an electro-optic mechanism, in which the phase transformation of LC’s was controlled by electric signals. These mechanisms and techniques, however, all relay on the characteristics of the medium where the active plasmonics realized. The introduction of the mediums inevitably caused contamination and erosion of the metal nanostructures (i.e. electrochemical method); moreover, the energy consummation in handling the medium greatly lowers down the efficiency (i.e. electric tuning of LSPR through LC). All limitations of present mechanisms call for a novel mechanism which can directly achieve active LSPR tuning without the help of mediums. The recent achievement of charge pumping through carbon nanotube using surface acoustic wave (SAW) has shown great promise in new transistor design, quantum cryptography and metrology. The propagation of a SAW in a piezoelectric substrate generates a travelling electric field (also potential field), which directly applies to the electrons or holes and pump them through the carbon nanotube. We recognized that the coupled electric field with a SAW is ideal for active LSPR since it does not need any medium and is
applicable to virtually any metal nanostructures embedded in a piezoelectric substrate. In this chapter, we present active tuning of LSPR of gold nanodisk array utilizing surface acoustic wave (SAW). In particular, when the SAW propagated through the ordered gold nanodisk array upon a lithium niobate substrate, it induced on the array a spatially periodic positive and negative charge distribution. The positive and negative charge of gold disks led to redshift and blueshift of the LSPR, respectively. As a result, we observed a dramatic decrease of intensity with a broadening of the band width occurred when the SAW was generated. The SAW-based tuning of LSPR has potential applications in optical switches, optical displays, and high-density optical storage.

§ 5.3.1 working mechanism

Charge induced plasmonic shifts (CIPS) due to changes in free electron density of gold and silver nanoparticles have been demonstrated by various researchers recently. An increase in internal free electron density results in a blue shift of spectra and a decrease in internal free electron density results in a redshift [32, 33]. Nanoparticles, both in colloidal state and immobilized on substrate, were charged either by adding a reducing agent or by applying an electrochemical potential. For an applied electrochemical potential, the amount of charge/discharge or the number of electrons transferring in/out of the nanoparticle is proportional to the double-layer capacitance across the solid-liquid interface. The direction of the shift is controlled by the electrochemical polarization and the amount of charge is limited only by the evolution of hydrogen or oxidation of the solvent at higher potentials [32]. The charging solutions, however, causes contamination and corrosion of the nanoparticles; furthermore, the controlling of this process is inconvenient and time consuming. These disadvantages call for a clean and easy-handling method to achieve SPR tuning.
Figure 5-12 (a) Experimental setup. A white light passes through the gold nanodisks on a piezo-substrate, and the output signal is detected by a spectrometer. Two parallel IDTs on the piezo-substrate are used to generate a SSAW. (b) Top view and (c) side view of the zoom-in figure of the dotted square region in (a). The surface deformation by SSAW generates periodic distribution of positive and negative charges along the piezo-substrate and attached gold disks. As a result, the nano disks show periodic shifting of LSPRs (different colors) based on their charge density changes. (All drawings are not in scale.)

Figure 5-12 a shows the experimental setup. Gold nanoparticles are localized on the surface of a piezoelectric substrate (LiNbO$_3$), which also serves as the substrate for SAW.
Two series of IDTs (Au/Cr) are aligned parallel to each other with the gold nanoparticles between. The SAW device is fixed vertically to two aligned optical fibers, one of which guides a white light generated from a halogen lamp to stimulate the surface plasma, and the transmitted light is collected by the other fiber and guided to the spectrometer, where the spectra of the light is measured and recorded. SAW is generated and propagated along the piezo substrate when the IDTs are stimulated by the applied AC signal, which is generated by an RF signal generator and amplified by a RF amplifier. When SAW is absent, the gold nanoparticles have the same free electron density; the resulting SPRs have the same wavelengths, and the constructive interference of all SPRs results in a strong absorption peak in the transmitted white light. The SAW-induced dynamic electric potential along the substrate where the gold nanoparticles localized will cause the electron re-distribution, resulting in the free electron density change of the gold particles in the SAW field. Since the electric potential amplitude is decided by the stress (and thus the deformation) amplitude of the piezo substrate, such that the electron density change of the nanoparticles has the same period as the SAW waveform. At the pressure node of the SSAW, the vibration amplitude of SAW is maximum, resulting in the maximum electron density change; on the contrary, at the pressure anti-node, the vibration amplitude is minimum, resulting in minimum free electron density change. The re-distribution of the free electrons in the gold nanoparticles results in the blue- or red-shift of the original SPRs. Since the amounts of the free electrons changes are different for gold particles at different locations in the SSAW, the resulted blue- or red-shift are different, resulting in a broaden effect of the original SPR and the intensity of the SPR is also greatly reduced. The shift of the SPR or the intensity reduction of the SPR peak can be used as active SPR tuning like optical switch, display and data storage.
§ 5.3.2 Results and discussion

As shown in Figure 5-12 a, a halogen lamp is used to generate a white light, which is guided toward the surface of the gold nanoparticles on the SAW substrate by an optical fiber. The transmitted optical signal is collected by another fiber and guided to a spectrometer. Due to the strong absorption of the gold SPR, the transmitted optical signal shows a strong drop at the corresponding wavelength. The fabrication of the SAW substrate with integrated gold nanodisk array is exactly the same as what has been discussed in § 5.2.2. The period of the nanodisk array

![Absorbance Spectra](image_url)

*Figure 5-13* The measured absorbance spectrums of the gold nanoparticles when SAW is absent (blue curve), and applied (red curve).
is ~320 nm, exactly the diameter of the original nanobeads used in the nanosphere lithography, and the gold nanodisk diameter is ~170 nm. Figure 5-13 plotted the absorbance spectrum measured by the spectrometer, where a original peak with the absorbance intensity of ~0.6 (arbitrary unit, a.u.) was found at ~813 nm, which is the SPR wavelength of the gold nanoparticles when SAW is absent. Red curve is the absorbance spectrum measured when SAW (20 dBm, 19.5 MHz, 200 μm period of IDT) was applied, where a much smaller peak (~0.25 a.u.) was found at ~800 nm. The obvious difference of the peak intensities without and with SAW reveals that SAW has strong effect to the SPR tuning, which is believed to be caused by the redistribution of the electric charge under the SAW, and can potentially be used in active SPR switching, optical display and high density data storage.

![Piezo substrate diagram](image)

**Positive Charged**

**Negative Charged**

Figure 5-14 Schematic drawing of the charged gold nanoparticles inside one wavelength of a SAW. From yellow to orange, more positive charges; and from navy to blue, more negative charges.

The working mechanism of the SAW-induced active tuning of SPR, though has been discussed in early section of this chapter, is not thoroughly studied, nor verified theoretically. We
proposed a model that would be used to explain the active SPR tuning, which is based on the charge induced plasma shift theory, coupling with the electric potential field caused by the SAW on the piezo substrate. Figure 5-14 demonstrated the model we built in explaining the experimental results.

Figure 5-14 shows the particle distributions in one wavelength of a SSAW (one dimension, drawing not to scale), where the waveform is assumed to be sinusoidal. Since the size of a gold nanoparticle is much smaller than one wavelength of SAW, all the nanoparticles in one wavelength have the same statistic distribution in the quantity of free charges with time varying, so we can anticipate that the total effect of all the particles in one wavelength will generate a stable SPR peak due to the interference. Simply speaking, when SAW is absent, all gold nanoparticles have the same SPR spectrum, such that the constructive interference of all these signal generates a strong SPR peak, just as what was measured in the experiment (as shown in figure 5-13 blue curve). When SAW is applied, the piezo-substrate generates a sine wave deformation along the surface, as well as a corresponding electric potential distribution. Since the charge distribution is proportional to the potential distribution, particles at different locations are charged differently both in quantity and polarization (positive or negative), such that the SPR of individual nanoparticle shows different shift according to the original peak position, resulting in a broad distribution of the SPR wavelength. The total effect of such nanoparticles shows a broad but much lower intensity spectrum, just as what was measured in the experiment (as shown in figure 5-13 red curve).

§ 5.3.3 SAW-induced surface charge distribution on a LiNbO₃ substrate

In order to get the charge distribution along a waveform of SAW, it is necessary to calculate the SAW-induced surface potential distribution.
\[ \phi = \phi_0 e^{-al} \]  \hspace{1cm} (5-8)

\[ \alpha = 0.19 f + 0.88 f^{1.9} \left( \frac{\mu s}{\mu m} \cdot v_0 \right) \]  \hspace{1cm} (5-9)

Equation 5-8 indicates the SAW-induced electric potential field \( \phi(l) \) along the propagation line, where \( \phi_0 \) is the maximum electric potential, and \( l \) is the relative distance from the SAW source [35]. \( \alpha \) is the absorption coefficient of the substrate (LiNbO\(_3\) here), which is dependant to the working frequency, and can be expressed in Equation 5-9 (in which \( f \) are the frequencies of SAW in GHz). The maximum electric potential \( \phi_0 \) can be further expressed as [35]:

\[ |\phi_0|^2 = 2PZ_0 \]  \hspace{1cm} (5-10)

\[ Z_0 = \frac{1}{Y_0} = \frac{1}{Y_0} \frac{\lambda}{W} \]  \hspace{1cm} (5-11)

\[ K^2 \cdot \nu_0 = 2\pi C_s v_0 \]  \hspace{1cm} (5-12)

Where \( P \) is the applied power of SAW, and \( Z_0 \) is the acoustic impedance of the substrate. \( Z_0 \) can be calculated using Equation 5-11, where \( \lambda \) and \( W \) are the working wavelength of SAW and width of IDTs, respectively. \( K^2 \) is the coupling coefficient of the substrate (5.6\% for LiNbO\(_3\)). \( C_s \), \( \nu_0 \) are the characteristic capacitance and SAW velocity of the substrate.

Taking \( f = 20 \text{ MHz} \), \( \lambda = 200 \text{ um} \), \( W = 10 \text{ mm} \), and \( P = 400 \text{ mW} \) in the above equations we got:

\[ \phi = \phi_0 \cdot 10^{-\frac{\alpha l}{10}} \approx 2.063 \times 10^{-0.1l} (V) \]  \hspace{1cm} (5-13)

Adding:

\[ u_x = c_x \phi \]

\[ u_y = c_y \phi \]  \hspace{1cm} (5-14)

Taking \( c_x = 0.1 \) and \( c_y = 2.0 \), the charge distribution along the surface of the piezoelectric substrate can be calculated.
§ 5.3.4 Other concerns and control experiment

There are two other concerns about the SAW-induced active SPR tuning, which are the photoelastic and electro-opto effects given by the piezoelectric substrate used in the experiments. When a SAW propagates along the LiNbO₃ substrate, the generated surface deformation will result in refractive index modulation of the substrate, which may change the SPR of the bonded gold nanostructure. On the other hand, the combined electric field with the SAW vibration will also contribute in the refractive index change of the substrate. In order to verify that the experimental results are due to the working mechanism we proposed, these two effects were characterized and one more control experiment had been processed.

**Photoelastic effect:**

The photoelastic effect describes changes in optical properties of a transparent dielectric when it is subjected to mechanical stress. Upon exposing to a SAW, the LiNbO₃ substrate endures periodic mechanical stresses according to the waveform of the SAW. This periodic mechanical stress distribution along the substrate results in periodic refractive index change, which may contribute to the dynamic surface plasmonics tuning monitored in the experiment through two manners: (1) locally changing the resonance frequency of the surface plasmon of gold nanodisks due to the local refractive index change; (2) diffracting the incident light through the grating effect caused by the periodic change of the refractive index. Equations 5-15 and 5-16 represent the photo-elastic effect of the LiNbO₃ used in this experiment [35].

\[
\Delta \left( \frac{1}{n^2} \right) = \sum_{k, l} p_{ijkl} S_{kl}
\]  

(5-15)
\[ S_{kl} = \frac{1}{2} \left( \frac{\partial n_k}{\partial x_l} + \frac{\partial n_l}{\partial x_k} \right) \]  

(5-16)

where \( n_{ij} \) is the second rank tensor describing the refractive index of the material; \( S_{kl} \) is the second order strain tensor (actually the displacement gradient); and \( P_{ijkl} \) is the fourth-rank strain photoelastic tensor [35]. In particular, for LiNbO psychosis, the tensor \( P_{ijkl} \) can be expressed as:

\[
P_{ijkl} = \begin{bmatrix}
P_{11} & P_{12} & P_{13} & P_{14} & 0 & 0 \\
P_{12} & P_{11} & P_{13} & -P_{14} & 0 & 0 \\
P_{31} & P_{31} & P_{33} & 0 & 0 & 0 \\
P_{41} & -P_{41} & 0 & P_{44} & 0 & 0 \\
0 & 0 & 0 & 0 & P_{44} & P_{11} - P_{12} \\
0 & 0 & 0 & 0 & P_{14} & \frac{P_{11} - P_{12}}{2}
\end{bmatrix}
\]  

(5-17)

The parameters in the upper tensor are demonstrated in Table 6.

Table 6 Strain photoelastic coefficients (dimensionless) at constant electric field [36]

<table>
<thead>
<tr>
<th>( P_{11} )</th>
<th>( P_{12} )</th>
<th>( P_{13} )</th>
<th>( P_{14} )</th>
<th>( P_{31} )</th>
<th>( P_{33} )</th>
<th>( P_{41} )</th>
<th>( P_{44} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.034</td>
<td>0.072</td>
<td>0.139</td>
<td>0.066</td>
<td>0.178</td>
<td>0.060</td>
<td>0.154</td>
<td>0.30</td>
</tr>
</tbody>
</table>

Taking the parameters listed above, as well as the displacement gradients caused by SAW (Equation 5-14) into Equations 5-15 and 5-16, the photoelastic effect caused by SAW in a LiNbO₃ substrate can be calculated. Figure 5-15 indicates the refractive index change caused by the photo-elastic effect on the LiNbO₃ substrate. It can be seen that the maximum refractive index change caused by the SAW (with the same parameters as used in the active surface plasmonics experiments) is \( \sim 0.0005 \), a quantity that can change the resonance wavelength of the surface plasmon of the gold nanodisks by \( \sim 0.1 \) nm. This little refractive index change generates little effects to either the SPR shift of the bonded gold nanodisks, or light diffraction caused by the grating effect.
Electro-optic effect:

Due to its piezoelectric nature of the LiNbO3, the charge distribution along its surface results in refractive index changes. This change in the optical properties of a material in response to an electric field that varies slowly compared with the frequency of light is called electro-optic effect [37]. As what has been discussed earlier in the photo-elastic effect, this refractive index change can also contribute to the active plasmonics experimental results. Equations 5-17, 5-18, 5-19 describe the electro-optic effect-induced refractive index changes of the LiNbO3 substrate, where $E_k$ are the components of the electric field and $r_{mk}$ represents the electro-optic tensor.

$$
\Delta \left( \frac{1}{n^2_m} \right) = \sum_k r_{mk} E_k
$$  \hspace{1cm} (5-17)

$$
\begin{cases}
n_x = n_y = n_0 + n_0 r_{13} E_x / 2 \\
n_z = n_e + n_e^3 r_{33} E_z / 2
\end{cases}
$$  \hspace{1cm} (5-18)
\[
\begin{align*}
    n_x &= n_0 + n_0^3 r_{22} E_x / 2 \\
    n_y &= n_0 - n_0^3 r_{22} E_x / 2 \\
    n_z &= n_e
\end{align*}
\] (5-19)

The electro-optic tensor of LiNbO₃ \( r_{mk} \) is:

\[
r_{mk} = \begin{bmatrix}
    0 & -r_{22} & r_{13} \\
    0 & r_{22} & r_{13} \\
    0 & 0 & r_{33} \\
    0 & r_{51} & 0 \\
    r_{51} & 0 & 0 \\
    -r_{22} & 0 & 0
\end{bmatrix}
\] (5-20)

and \( r_{13} = 10 \text{ pm/V}, r_{33} = 32.2 \text{ pm/V}, r_{22} = 6.7 \text{ pm/V}, r_{51} = 32.6 \text{ pm/V} \) (for incident light with wavelength 633 nm) under constant electric field [36]. Figure 5-16 indicates the refractive index change caused by the electro-optic effect of the substrate. This effect is even smaller than the photoelastic effect, as the maximum quantity of the refractive index change is around 0.00035. Such a change in refractive index can only induce the SPR peak shift by around 0.05 nm, and will not obviously affect the SPR peak intensity as much as in the experiments.

![Figure 5-16 Electro-optic effect induced refractive index change of the substrate.](image)
Control experiment

Based on the proposed model, the charge re-distribution is caused by the electric potential re-distribution in the SAW field. If all the gold nanoparticles are electrically short-circuited, the charges will be uniformly distributed and the SPR tuning effect will vanish or significantly weaken. As a control experiment, we used the same experimental setup (as shown in figure 5-12) and sample as the tuning experiment. One drop of CaCl$_2$ solution was used to immerse all the gold nanoparticles, thus building a uniform potential field for all the particles. Figure 5-17 plotted the measured result in the control experiment, where it is clearly shown that the SPR signal kept unchanged when applying SAW capable to tune the plasmonics directly through a piezoelectric.
substrate, requires no liquid medium (LC, molecules, etc.). As a result, it will be more stable in operation with a long life time. Taking into account the nanoscale feature of the nanodisk array, this method can potentially be used in data storage and fast communication switch.

In summary, we have demonstrated, for the first time, an active tuning technique of SPR to a gold nanodisk array deposited on a solid substrate without any medium. In comparison to other technique, this method features easy fabrication and simple experiment setup, significant peak intensity change under a relatively small applied power. More importantly, this method is the first demonstration of active plasmonics on a solid substrate without any liquid medium. This makes it promising in integration with solid state electronics or optics.

Reference:


Appendix A

Manipulating acoustic signals using a phononic crystals composite

1. Motivation

We have built an acoustic tweezers technology, in which standing surface acoustic waves are successfully used to manipulate (including dynamic focusing (Chapter 2), 1D and 2D active patterning (Chapter 3), and continuously separating (Chapter 4)) microparticles within microfluidic channels, and tuning the surface plasmons through realigning the LC molecules (Chapter 5). Although dramatic reduction of power consummation has been achieved by using SAWs instead of using BAW, the attenuation of acoustic energy in fluids is still obvious. Also, SAWs generated from the IDTs change their wave fronts after long distance propagation due to the boundary effect of the piezoelectric substrate, which may potentionally affect the performance of this acoustophoresis platform, as all of the particle manipulations are based on the formation of standing waves, which are generated from the strong interference of two identical waves. In order to improve the performance and further reduce the energy consumption in our acoustic tweezers technology, it is critical to maintain the plane wave nature of the wave fronts of SAWs and confining the energy of the acoustic waves. In this chapter, we present a phononic crystal composite, which combined a series of phononic crystals with same period but different filling ratios, to direct the acoustic energy and keep the wavefronts.
2 Wide-band collimation of acoustic signal using phononic crystal composite

2.1 Introduction

Photonic crystals are periodic structures that manipulate the propagation of electromagnetic waves; much like the periodic potential in a semiconductor crystal affects the motion of electrons [1, 2]. In the last decade, photonic crystals have attracted much interest, and many interesting phenomena (such as bandgaps, negative refraction, focusing, and photon tunneling) have been observed in these structures [3–7]. Recently, it has been shown that photonic crystals can be used to achieve the collimation of electromagnetic waves at particular frequencies [8–10]. Since traditional collimation lenses made of convex and concave lenses are bulky, expensive, and hard to fabricate, photonic crystal-based collimation lenses could prove advantageous in many applications, especially in micro/nano systems where fabricating small-scale, convex or concave lenses is challenging.

The concept of collimation can be extended to phononic crystals (PC’s), which are the acoustic analogs of photonic crystals. Numerical simulation has shown that acoustic waves within a narrow band tend to be collimated or guided into the direction in which propagation is allowed [11]. Recently, Qiu et al. have numerically investigated how the resonant cavities formed by line defects in PC’s affect sound collimation and signal enhancement [12]. These methods have paved a new avenue for PC-based acoustic collimation; however, they only work within a narrow frequency band, and thus are not practical for many applications. In this letter, we present a design that is capable of achieving acoustic collimation in a wide frequency range via PC composites, a sequenced series of PC’s that have the same period but different filling ratios.
2.2 Working mechanism

The two-dimensional (2D) PC’s employed were composed of rigid steel cylinders arranged in a square lattice and immersed in water. The material parameters were $\rho=7.67 \text{ g/cm}^3$, $C_L=6.01 \text{ km/s}$ and $C_T=3.23 \text{ km/s}$ for steel; and $\rho=1.0 \text{ g/cm}^3$ and $C_L=1.49 \text{ km/s}$ for water. $\rho$ is the density, and $C_L$ and $C_T$ represent longitudinal and transverse speeds of sound, respectively. All calculations and simulations in this letter were based on the plane wave expansion (PWE) [13–16] and finite difference time domain (FDTD) methods [17, 18]. Figure A-13 a shows the calculated band diagram of two PC’s, PC1 (filling ratio FR=0.545) and PC2 (FR=0.442), using 121x121 plane waves. The normalized frequency for the first full band gap of PC1 ranged from 0.504 to 0.650, corresponding to points M1 and X2, respectively. As shown in Figure A-13 a, the band gap of PC1 in the $\Gamma X$ orientation extends from point X1 (normalized frequency=0.333) to X2. Waves in the frequency range between X1 and M1 are inhibited in the $\Gamma X$ orientation.

The ability to use flat bands to achieve collimation is realized when acoustic waves propagate perpendicularly to the equal frequency surface (EFS) of the structure. This phenomenon is described by the following equation:

$$v_g = \nabla_k [\omega(k)], \quad (A-1)$$

where $v_g$ is the group velocity, $\omega(k)$ is the angular frequency, and $k$ is the wave vector. This equation shows that PC structures demonstrate flat bands in a certain frequency region where incident waves collimate normal to the flat band (Figure A-13 b, c). As shown in Figure A-13 b, at point X1 in the first band of PC1, the curvature of the EFS is zero. This implies that X1 is at the region of maximum collimation (indicated by black arrows at the boundaries of the collimation region) where the incident waves will be directed along the $\Gamma M$ orientation. Moreover, the density of states (DOS, number of the compositions of $(k_x, k_y)$ corresponding to an angular frequency $\omega$) $k_x, k_y$ are the components of wave vector $k$ in X and Y coordinates, respectively, as
shown in Figure A-1 a) is inversely proportional to the curvature of the dispersion curve. Therefore, point $X_1$ gives the maximum DOS, and incident waves with a range of wave numbers

Figure A-1: (a) Band structure (left) and density of states (DOS, right) of square-lattice PC’s composed of steel cylinders in water with filling ratios of 0.545 (PC$_1$) and 0.442 (PC$_2$). The frequency was normalized by $2\pi C/a$, where $a$ is the lattice constant and $C$ is the sound velocity in water. (b) and (c) are the EFS of PC$_1$ and PC$_2$, respectively. The red dotted lines represent the maximum collimation points, and the arrows indicate the boundaries for the collimation region at different frequencies.
can be collimated at point $X_1$.

Although acoustic collimation can be achieved through a single PC structure, such a collimation system can only work over a narrow frequency range. As the frequency deviates from point $X_1$, the contour of the EFS will change into a circular geometry, and only a small portion of the EFS depicts a near-zero curvature (Figure A-1 b, c). Such circular geometries permit only waves within a certain incident angle $\theta_C$ to be collimated, thereby limiting the use of single PC-based acoustic collimation lenses. We devised a wide-band acoustic collimation lens that is composed of a series of PCs having the same period but different filling ratios (Figure A-2).

When acoustic waves pass through the first PC ($PC_1$, FR=0.545), the incident waves within the critical angle $\theta_{C1}$ are collimated along the $\Gamma M$ orientation, and remain unchanged as they

Figure A-2: Schematic of an acoustic collimation lens comprising two PC’s of the same period but different filling ratios.
propagate through the second PC (PC₂, FR=0.442). Although not collimated by PC₁, the waves outside the critical angle $\theta_{C1}$ refract toward the center (negative refraction) [19–21] as they pass through PC₁. Following that, the refracted waves of original incident angle less than the critical angle $\theta_{C2}$ ($\theta_{C2} > \theta_{C1}$) will be collimate upon propagation through PC₂. Therefore, the PC composite (PC₁+PC₂) provides an effective means to enlarge the critical incident angle. It serves as the basis of an acoustic collimation lens that focuses waves of a wide frequency range.

To reduce the boundary effects between PC₁ and PC₂, the cylinders in both PC₁ and PC₂ were oriented in a similar fashion, and the last column of PC₁ was positioned exactly at the periodic frame of PC₂ (Figure A-2). In order to illustrate how a PC composite affects the collimation characteristics, we calculated the total critical angle (the maximum incident angle

Figure A-3: The dependence of critical angles at normalized frequency for PC₁, PC₂, and PC₁+PC₂. $\Delta f₁$, $\Delta f₂$, and $\Delta f$ are the calculated collimation regions for PC₁, PC₂, and PC₁+PC₂, respectively, assuming $\theta_c=60^\circ$.

To reduce the boundary effects between PC₁ and PC₂, the cylinders in both PC₁ and PC₂ were oriented in a similar fashion, and the last column of PC₁ was positioned exactly at the periodic frame of PC₂ (Figure A-2). In order to illustrate how a PC composite affects the collimation characteristics, we calculated the total critical angle (the maximum incident angle
within which all refracted waves are less than 5° with respect to ΓM orientation) at different frequencies for PC1, PC2, and PC1+PC2 (Figure D-15). ImageJ® was used in the calculation of the refracted angles to different incident waves. First the slope of the EFC at specific angle was calculated based on the coordinates of the points on the EFC, then the refracted angle can be calculated based on the fact that the group velocity is always perpendicular to the EFC. If this refracted angle was less than 5° with respect to the ΓM orientation, the incident angle can be further increased till the corresponding refracted angle was within 5±0.1° to the ΓM orientation. In such a way, the critical angle for waves at different frequency can be calculated. At θc=60°, the normalized frequency ranges of the collimation regions for PC1, PC2, and PC1+PC2 were calculated to be 0.336–0.357 (Δf1), 0.357–0.375 (Δf2), and 0.336–0.375 (Δf), respectively. Hence, the PC composite significantly enlarges the range of the collimation region (Δf/Δf1=185% and Δf/Δf2=220%). We anticipate that when using a series (>2) of PCs, the range of the collimation region can be further improved.

2.3 Results and discussion

To verify the calculated results based on the PWE method, we employed the FDTD method to simulate the collimation phenomena of a PC composite within the collimation region (Δf=0.336–0.375). Figure A-4 a is a schematic of the PC composite used in the FDTD simulation, with a point source placed in the center of the composite. The lattice constant a was assumed to be 8 mm, the size of the PC composite was 30a×20a, and other parameters used in the FDTD simulations were the same as those in the PWE calculations. The simulation results (Figure A-4 b–d) showed clear collimation phenomena at three different normalized frequencies (0.340, 0.355, and 0.370) within the collimation region. Quantitative analysis (Figure A-4 e) based on the FDTD simulation results indicated that for all the frequencies in the collimation range (Δf), most
acoustic waves were confined in the center region after passing through the PC composite. Thus, the FDTD simulation results coincided with the PWE calculated results and confirmed that a PC composite can significantly enlarge the collimation region and cause wide-band acoustic collimation.

Figure A-4: (a) Schematic of the PC composite used in the FDTD simulation. Simulated wave propagation inside the PC composite at a normalized frequency of (b) 0.340, (c) 0.355, and (d) 0.370. The light region and the dark one represent weak and strong amplitudes of the displacement field, respectively. (e) Simulated wave intensity at $x=30a$ along Y-coordinate indicates that most acoustic waves at frequencies within $\Delta f$ are confined in the center region after passing through the PC composite.

In conclusion, the collimation phenomena of PC composites were investigated numerically through both PWE and FDTD methods. The flat bands and the density of states near the collimation point were key factors in determining the collimation characteristics of acoustic waves. An acoustic collimation lens composed of two PC’s (steel cylinders in water) with
different filling ratios was shown to enlarge the collimation region over a normalized frequency range by a factor of 185%–220%, thereby realizing wide-band acoustic collimation. The methodology described in this letter will prove useful in applications that require confined acoustic energy flow over long operation distances, such as acoustic imaging, drug delivery, cell sonoporation and non-destructive evaluation (NDE).

2.4 Extension to photonic crystals

Due to the fact that photonic crystals are the optical analogue of phononic crystals, similar principle can also be applied to design a photonic crystal composite, which are composed of a series of photonic crystals with varying filling ratios, to collimated waves with a larger critical angle and working frequency range, in comparison to the single photonic crystal-based device. Figure A-5 a shows band diagrams for the first three TM-polarized bands of PC1 and PC2. The differences in filling fractions resulted in the slope change in dispersion curves (where a higher filling fraction resulted in a smaller slope). Both PCs demonstrated a complete band gap ranging from \( \text{M}_{11} \) to \( \text{X}_{12} \) for PC1 and \( \text{M}_{21} \) to \( \text{X}_{22} \) for PC2, with relative bandwidths (bandwidth divided by central frequency) of 29% and 31%, respectively. There was also a partial band gap in the \( \Gamma\text{X} \) orientation with the normalized frequency \( \Omega \) extending from 0.2658 to 0.3164 (corresponding to points \( \text{X}_{11} \) and \( \text{M}_{11} \)) for PC1, and from 0.2897 to 0.3405 (corresponding to points \( \text{X}_{21} \) and \( \text{M}_{21} \)) for PC2. Here \( \Omega \) is defined as \( \omega a/2\pi c \), where \( c \) is the speed of light in air. Figure A-5 b and c show the EFCs for the first band of PC1 and PC2, respectively. As the normalized frequency was increased, the EFC curvatures of both PCs turned from convex to concave. The flat regions on the EFCs, which were normal to the \( \Gamma\text{M} \) orientation, enlarged steadily with frequency and then reduced gradually after reaching their maximums (\( \Omega = 0.2864 \) for PC1 and \( \Omega = 0.2970 \) for PC2; bold solid curves). The boundaries of the longest flat regions
were indicated by the solid arrows which point along the energy-propagating direction. These maximums indicate the frequencies at which the self-collimation angle, the region where wave

![Graph showing the first three TM polarized bands of PC1 (solid) and PC2 (dashed), composed of rigid GaN cylinders in air with filling fractions 0.2513 and 0.1924, respectively. First TM-polarized EFCs of (b) PC1 and (c) PC2. The bold solid curves indicate the maximum self-collimation frequency of each PC and the dotted curves indicates the corresponding EFCs in air. The dashed and dotted arrows denote the wave vectors in PCs and air, respectively. The solid arrows indicate the boundaries of the flat band and the direction of the group velocity, and the shaded region shows the wave vectors that undergo self-collimation due to flat bands. The propagating waves within the critical angle $\theta_C$ were collimated to the $\Gamma M$ orientation. (d) The dependence of critical angles on normalized frequency for PC1, PC2, and PC1+PC2.]

Figure A-5: (a) First three TM polarized bands of PC1 (solid) and PC2 (dashed), composed of rigid GaN cylinders in air with filling fractions 0.2513 and 0.1924, respectively. First TM-polarized EFCs of (b) PC1 and (c) PC2. The bold solid curves indicate the maximum self-collimation frequency of each PC and the dotted curves indicates the corresponding EFCs in air. The dashed and dotted arrows denote the wave vectors in PCs and air, respectively. The solid arrows indicate the boundaries of the flat band and the direction of the group velocity, and the shaded region shows the wave vectors that undergo self-collimation due to flat bands. The propagating waves within the critical angle $\theta_C$ were collimated to the $\Gamma M$ orientation. (d) The dependence of critical angles on normalized frequency for PC1, PC2, and PC1+PC2.
vectors (dashed arrows) undergo self-collimation along the ΓM orientation, was largest (shaded regions). By considering the conservation of the transverse momentum at the input boundary [22], the construction lines (solid lines) were obtained by connecting the boundaries of the longest flat regions to the EFC of air (dotted curves) along the ΓM orientation. The dotted arrows indicate the wavevectors corresponding to the largest incident angle that can be self-collimated by PCs in air. Within the critical angles \( \theta_{c1} \) and \( \theta_{c2} \) (corresponding respectively to PC\(_1\) and PC\(_2\)), all incident waves were self-collimated.

To apply the similar working principle to photonic crystals, a 2D PC composite consisted of two 2D PCs (PC\(_1\) and PC\(_2\) in Sec. II) is proposed in Figure A-6 b. The cylinders in PC\(_1\) and PC\(_2\) were oriented in a similar fashion, and the first columns of the subsequent PC (PC\(_2\)) were positioned exactly at the periodic frame of the previous PC (PC\(_1\)). A point source was placed in the center of the structure. For the emitted electromagnetic waves with different frequencies, two cases were involved: (1) when waves passed through the first PC (PC\(_1\)) at frequencies near the maximum self-collimation frequency of PC\(_1\) (\( \Omega_{m1}=0.2864 \)), the incident waves within the critical angle \( \theta_{c1} \) of PC\(_1\) were self-collimated along the ΓM orientation (blue dashed arrows in case (1) of Figure A-6 b), and remained self-collimated (along ΓM orientation) as they propagated in PC\(_2\) (blue dotted arrows) because the ΓM orientation is perpendicular to the EFCs of PC\(_2\). Since the critical angle of PC\(_2\) (\( \theta_{c2} \)) was smaller than \( \theta_{c1} \) in this frequency range, PC\(_1\) dominates the EM collimation behavior, and the function of PC\(_2\) was to retain the self-collimated beam. (2) When electromagnetic waves were emitted at frequencies near the maximum self-collimation frequency of PC\(_2\) (\( \Omega_{m2}=0.2970 \), \( \theta_{c2} > \theta_{c1} \) in this case), few of the waves were guided by PC\(_1\) along the ΓM orientation due to its small critical angle \( \theta_{c1} \) (blue dashed arrows in case (2) of Figure A-6 b). The waves outside the critical angle \( \theta_{c1} \) were subject to negative refraction as they passed through PC\(_1\) toward the center of the self-collimated beam, due to the concave-like EFC (red dashed arrows).
Although not self-collimated by PC1, the incident waves with angles less than the critical angle $\theta_{c2}$ of PC2 ($\theta_{c2} > \theta_{c1}$) were subject to self-collimation upon propagating through PC2 (red dotted arrows). In this case, PC2 was the major contributor to self-collimation, and the function of PC1 was to confine the out-spreading energy to the center of the self-collimated beam. The PC composite thereby enlarged the self-collimation frequency bands by combining those of two
single-PC structures. As shown in Figure A-5 d, for example, the PC composite significantly enlarges the collimation region by \( \Delta f / \Delta f_1 = 267\% \) and \( \Delta f / \Delta f_2 = 178\% \) at \( \theta_C = 25^\circ \). Such a PC composite (PC\(_1\)+PC\(_2\)) may serve as the basis of an optical collimation lens that focuses waves of a wide frequency range; this idea can be extended to PC composites with more than two PCs.

In order to illustrate how a PC composite affects self-collimation, we simulated by a FDTD method the electromagnetic wave propagation phenomena within two single PC structures (PC\(_1\) and PC\(_2\)) and a PC composite (PC\(_1\)+PC\(_2\)). FDTD methods provide the time-domain solutions of Maxwell’s equations by computing the electromagnetic energy in discrete computational grids as functions of time [23]. As shown in Figure A-6 a and b, our simulation domain consisted of a rectangular area (60\(d \times 40d \) normalized units, where \( d \) is the distance between layers) filled with air and GaN cylinders distributed periodically with a lattice constant \( a \). The simulation domain was discretized into 20 grids per \( d \). The other parameters used in the FDTD simulations were the same as those in the PWE calculations. The entire structure was surrounded by Berenger’s perfectly matching layers (PML) at the boundaries to avoid reflections in the simulation domain [24]. A narrow-band Gaussian source of TM polarization \( (E_x, E_y, \text{ and } H_z) \) was placed at the center of the simulation domain and the propagation of electromagnetic energy was monitored. To implement the FDTD method, we used the MEEP FDTD package, which features sub-pixel smoothing for increased accuracy [25]. Computations were performed on a high-performance computer that had quad-core 2.6 GHz AMD Opteron processors and 32 GB of ECC RAM.

Two working bands \( \Delta \Omega_1 (\Omega = 0.2758–0.2970) \) and \( \Delta \Omega_2 (\Omega = 0.2828–0.3111) \) were chosen to simulate the single PC structures, PC\(_1\) (maximum self-collimation point \( \Omega_{m1} = 0.2864 \)) and PC\(_2\) (\( \Omega_{m2} = 0.2970 \)). A larger band \( \Delta \Omega_{1+2} (\Omega = 0.2758–0.3111) \) was used for the simulation of the PC composite (PC\(_1\)+PC\(_2\)). A line receiver of length 24\(d \) was placed at the right edge of the simulation domain, parallel to the y-coordinate, in order to measure the electromagnetic wave transmittance. Figure A-7 depicts the simulated wave propagation results of PC\(_1\) (31 layers thick in the x-
coordinate) for different normalized frequencies. As shown in Figure A-7 a, electromagnetic waves at the maximum self-collimation point ($\Omega_m=0.2864$) were collimated along the $\Gamma\text{M}$ orientation after passing through the PC structure. The wavefronts were parallel to each other, indicating collimation. However, as the frequency deviated from the maximum self-collimation point, only a small portion of the EFC had near-zero curvature, indicating that self-collimation was reduced (Figure A-19 b, c). While the field intensity along the y-coordinate of non-

Figure A-7: Simulated electromagnetic wave propagation of the PC$_1$ (31-layer thick in x-coordinate) at a normalized frequency of (a) $\Omega=\omega a/2\pi c=0.2864$, (b) $\Omega=0.2758$, and (c) $\Omega=0.2970$. (d) Wave intensity along y-coordinate measured by the line receiver.
collimated waves had multiple peaks (since the wavefronts were spherical), well-collimated waves had one single peak. The field intensity along the y-coordinate measured by the line receiver at different frequencies (Figure A-7 d) shows that a small deviation in frequency (less than 2% from $\Omega_{m1}$) from the maximum self-collimation point greatly reduced the collimation.

Figure A-8: Simulated electromagnetic wave propagation of the PC$_2$ (31 layers thick in the x-coordinate) at a normalized frequency of (a) $\Omega=0.2970$, (b) $\Omega=0.2828$, and (c) $\Omega=0.3111$. (d) Wave intensity along y-coordinate measured by the line receiver.
The simulated wave propagation results of the 31 layer-thick, single PC\textsubscript{2} structure (Figure A-20) are similar to those of PC\textsubscript{1}. Electromagnetic waves at the maximum self-collimation point ($\Omega_{m2}=0.2970$) were well-collimated along the $\Gamma\text{-}\text{M}$ orientation (Figure A-8 a). However, once the frequency deviated from the maximum self-collimation point (less than 2.5% from $\Omega_{m2}$), the collimation was greatly reduced (Figure A-8 b, c, d). Based on Figure A-7 and A-8, the collimation effect of a single PC structure is limited to a small range (the frequency must be within ±2.5% of the maximum self-collimation point). We expected that a much-wider collimation range could be achieved by a PC composite structure. The simulated electromagnetic wave propagation results of a PC composite (PC\textsubscript{1}+PC\textsubscript{2}, arranged as shown in Figure A-6 b; PC\textsubscript{1} has 17 layers in the center and PC\textsubscript{2} has 7 layers at each side) are shown in Figure A-9. The simulated results exhibit excellent collimation for a large frequency range ($\Omega=0.2758–0.3111$). Quantitative analysis (Figure A-9 e) based on the FDTD simulated results indicated that for all the frequencies within $\Delta\Omega_{1+2}$, most waves were collimated and confined in the center region after they passed through the PC composite. In a PC composite, the transmittance is mainly dependent on the refractive index mismatch between PC\textsubscript{1} and PC\textsubscript{2}. The effective refractive index of the PC structure is dependent on the filling fraction and arrangement of the inclusions in the background material [26], which are similar for the PC\textsubscript{1} and PC\textsubscript{2} as they have the same arrangement and slightly different filling fractions. Furthermore, the arrangement of the PC composite (filling ratio of inclusions decreases when apart from center of the structure, so does the refractive index) creates a pressure-release process when waves pass through the composite, the loss in transmittance was thus minimized. As a result, the transmittance in the PC composite was expected to be similar as the single PC-based collimation lens, which coincides with the observations among Figures A-7–9. The FDTD-simulated results indicate that in comparison to single PC structures, a PC composite greatly enlarges the collimating region; this finding was confirmed by the PWE method. By using a series of PCs (more than two), the collimation region
can be further enlarged.

In summary, by properly arranging a series of photonic/phononic crystals in a composite, one can greatly improve the performance in optical/acoustic signal manipulation, especially on
the small scales. Such composites can be used in a series of applications where the high intensity optical/acoustic signals are required, such as optical/acoustic imaging, light-emitting diodes, biosensors, waveguides, ultrasound enhanced drug delivery, cell sonoporation and non-destructive evaluation (NDE).

References


Appendix B

Surface Plasmon Tweezers-induced Nanoparticle Patterning in Microfluidics

1. Introduction

Despite the promising achievements of the acoustic tweezers in manipulating microparticles in microfluidic channels (described in Chapters 2, 3, 4), it is still challenging for acoustic tweezers to manipulate particles less than 500 nm. Due to the fact that acoustic forces are proportional to the volume of particles, when particles come to nanometer scale, acoustic powers have to be increased dramatically to generate enough acoustic forces in manipulating the nanoparticles. However, the increased acoustic power will result in obvious thermal effect, which may damage the nanoparticles. So we have to seek alternative method which can be effective in nanoparticle manipulation, as dynamic manipulation of nanoparticles in microfluidics plays a key role in a series of bio- and chemical- applications. Although a bunch of techniques are available in manipulating objects in microfluidics (e.g. hydrodynamic, electrostatic, electrophoresis, acoustic, etc.) [1–3], most of which are ineffective in manipulating objects in nanometer scale. Here we report on dynamic patterning of nanoparticles in microfluidic channels using patterned surface plasmon polaritons (SPP) from a gold thin film with highly ordered nanohole arrays.

SPPs are confined evanescent waves at the interface of materials with opposite dielectric constants [4]. Such surface plasmon polaritons (SPP) at metal/dielectric interfaces are potentially an ideal candidate for applications where classical optics is fundamentally restricted, e.g. trapping and patterning of nanoparticles in microfluidics, as the dispersion of SPP is highly tied on the nature of the adjacent dielectric. Conventional optical trapping uses optical gradient forces originated from a highly focused laser beam to confine particles at the beam focus [4], such that
the minimum particle size that can be effectively manipulated is strictly limited by the diffraction limitation. Furthermore, the high laser intensity (~$10^9$ W m$^{-2}$) requirement to fulfill the momentum conversion for particle trapping makes it impractical for particle manipulation in large region. The confinement of SPPs to the interface provides an alternative method for overcoming the diffraction limit to realize the planar manipulation of objects in nanoscale. In addition to the lightning-rod effect and resonant buildup, the electric field of SPP can be greatly enhanced at corners or edges of metallic patterns [5], thus minimizing the laser intensity requirement. Here we report a novel design of dynamic patterning of nanoparticles using the constructive interference of SPPs launched on a gold thin film with nanohole arrays.

2. Working mechanism

Figure B-1 schematically demonstrates the working mechanism of the SPP-based nanoparticles patterning technique. A gold thin film with nanohole arrays is formed on a glass substrate. A laser beam incident upon the gold thin film from the glass side produces SPPs around the nanoholes with their intensities decaying exponentially from the centers of the holes [5, 6]. The SPPs converts to propagation waves in the nearby nanoparticles and thereby photon scattering occurs through multiple internal reflections [7], and the photon scattering applies unbalanced forces to the particles, pushing them away from the center of the hole where the SPP intensity is highest. For a highly ordered array of nanoholes, the constructive interference of SPPs from neighboring holes leads to a periodic lateral distribution of SPP intensities. Such a SPP distribution builds up a series of trapping wells, where the intensity gradient of SPP is minimal. Nanoparticles will be transported along the intensity gradient and trapped in these trapping wells as the net force is minimal there. This nanoparticles trapping in ordered trapping wells comprises the patterning of nanoparticles. The performance of the patterning technique is strictly dependent
on the SPP gradient instead of the intensity, which implies a potential reduction of the required laser intensities. Furthermore, while SPPs decay exponentially in the perpendicular direction to the substrate within 100 nm, they can propagate in a long distance (~1mm) along the substrate. As a result, this SPP-based technique can actively pattern massive nanoparticles in large areas and confine all of these nanoparticles on the substrate.

Figure B-1 Schematic illustration of the device’s operation mechanism: (a) a patterned gold thin film (30 nm of thickness, with periodic close-packed nano holes) is deposited on a glass substrate. Nanobeads exposed to the gold thin film will be trapped in the holes due to the hydrodynamic effect. (b) A laser beam impinges onto the glass substrate from bottom, and the SPP are launched around the nano holes. The SPPs apply unbalanced forces to the nearby particles (based on their original positions) by photon scattering (through multiple internal reflections, shown in black arrows inside beads), pushing them away from hole center. In a nano hole array, nano particles are balanced when the net force exerted from the surrounding holes are equal to zero, thus achieving the patterning. (All drawings are not in scale)
3. Device fabrication and characterization

Figure B-2 Fabrication process of the gold thin film with nano hole array: left, front view; right, top view. From top to bottom: formation of self-assembly-monolayer (SAM) of polystyrene beads on glass substrate; reactive-ion-etching (RIE) tuning the size of beads; gold deposition in an e-beam evaporator; removing of beads [4]. Bottom left, SEM image of the nanohole array; bottom right, AFM image of the nanohole array.
In order to get ordered distribution of SPP intensity, a gold thin film with highly ordered nanohole array is adopted [8]. Figure B-2 illustrates the fabrication process. Firstly, a drop of polymtylene beads (970 nm in diameter) solution was put on a glass substrate (which is totally cleaned). After the evaporation of the solvent, the beads formed a self-assembly-monolayer (SAM) on the glass substrate (Figure B-2). The glass substrate with the SAM layer was then processed with an oxygen reactive-ion-etching (RIE) to tune the bead size to the desired parameter (the size of the hole diameter). A 30 nm gold thin film was deposited on the the glass substrate in an e-beam evaporator, with the beads as protection mask. Then a lift-off process is used to remove the polystyrene beads and attached gold film, thus obtaining a gold thin film with highly ordered nanohole arrays on the glass substrate. The topography characterization (SEM figure in Figure B-2) of the fabricated nanohole array reveals the holes to be in a close-packed geometry, with the period of 970 nm (the same as the diameter of polystyrene beads). The hole diameter is ~800 nm, which can be continuously tuned by changing the etching time in RIE. At last, A PDMS-based microchannel, fabricated using the standard soft-lithography and mold-replica technique, is bonded to the glass substrate to obtain the desired device.

4. Experimental setup

The final device is then mounted on an inverted fluorescent microscope, with a 60X objective lens monitoring the beads behavior inside the container (Figure B-3). An excitation laser beam (488 nm) is expended and collimated to impinge upon the gold nanohole arrays from the bottom. Solutions of fluorescent polystyrene beads with different diameters are injected to the PDMS-based container to immerse the gold nanohole arrays. The excited fluorescent light from the nanobeads pass through a dichroic mirror and recorded by a CCD camera, where the live-
videos and stable images of the dynamic patterning of nanoparticles under the SPP excitation were recorded.

5. Results and discussion

In order to get theoretical explanations for this patterning technique, a calculation is processed to plot the SPP intensity and gradient distribution along the gold thin film with nanohole arrays. When a laser impinges upon a nanohole in a uniform metal film, the lateral distribution of the generated SPP can be well described using a dipolar form [5]:

$$ E_x(r, \theta) = E_0 \cos^2(\theta) \exp(-r / \delta) \cos(\omega t - 2\pi r / \lambda_{spp})\sqrt{r} $$(B-1)

where $\lambda_{spp}$, $\delta$ are the wavelength and propagation distance of the SPP, respectively. They are defined as:

Figure B-3 Experimental setup: a laser diode is used to generate 488 nm laser, followed by the beam expansion and collimation by lens, which is bent up by a mirror and incident normally to the sample (mounted on a microscope).
Figure B-4 Simulation of the surface plasmon polaron around a single nanohole (a) and a nanohole array (b) on a thin gold film. (a), a lateral polarized incident beam impinges upon a nanohole to generate a SPP distribution around the hole. The electric field of such a SPP distribution is shown (middle). The intensity of such a SPP decays exponentially apart from the center of the hole (bottom). (b) a non-polarized incident beam stimulates SPP around each hole in an array, and the interference among the SPPs of the nearby nanoholes results in a periodic distribution of the electric field (middle and bottom).
in which $\varepsilon_m$ is the dielectric constant of metal and $\lambda_{in}$ is the wavelength of incident laser. The
SPP intensity around the nanohole on the gold thin film is then calculated taking into account $E_x$ along with the corresponding $E_y$. In such a way, the SPP filed intensity of a gold nanohole array, as well as the positions where the nanobeads would be trapped, can be predicted. The simulation results were demonstrated in Figure B-4, where the electric fields around a nanohole and an array of nanoholes have been depicted. It is clearly seen from the simulation result that the electric field of the SPP around a nanohole decays exponentially apart from the center of the hole. As a result, the nanobeads near the hole center will be pushed away from the center (where the SPP intensity is maximum), as the SPPs applied unbalanced forces to the nearby nanobeads through the multiple internal photon reflection. The radiation force generated from the intensity gradient pushes the nanoparticles to the lower intensity direction. Taking into account the symmetric geometry of the nanohole array, the minimum SPP intensity localized periodically inbetween the nanohole array. As a result, the particles will be trapped at the positions in between the nanoholes, where both the intensity and the intensity gradient are minimal. Seen from Figure B-4 b, the dotted circles are in a hexagonal shape, implying the nanobeads will be patterned in a hexagonal geometry.

Figure B-5 demonstrates the patterning results when applying a laser beam with the intensity of $2 \times 10^5$ W m$^{-2}$ (50 mW on 500 μm x 500 μm area) on 300 nm polystyrene beads. The AFM characterization of the surface morphology of the gold thin film reveals that nanoparticles are well-patterned in a hexagonal shape under the SPP excitation, while a control experiment under the same working situations without laser incidence shows apparently different results- the particles are trapped inside the nanoholes such that their patterning shows a close-packed
The trapping of nanoparticles in nanoholes is attributed to hydrodynamic effects. By comparing the relative positions of patterned nanoparticles to the nanohole array in the gold thin film, we conclude that the nanoparticles are patterned around the geometric centers of triangles by three neighboring holes, where the SPP intensity gradients are believed to be nominal.

Figure B-5 Experimental results showing the SPP-induced nanoparticle patterning. (a) AFM characterization of the surface of a gold nanohole array, indicating the nanoparticles and their arrangement in a hexagonal geometry. (c) AFM characterization of the patterning result occurred on a nanohole array with smaller hole diameter than that was used in (a). (b) and (d) are the zoomed-in figures of the circled regions in (a) and (c), respectively.
As the boundary of a nanohole is 30nm in height, far less than the radius of the nanoparticles used in experiment, the minimal parallel force to release the particle from the nanohole is calculated to be 5.3e-18 N (Figure B-6). Under 50 mW incident laser beam, the particle with diameter of 300 nm moved at an average speed of 2 um/s. The necessary force to move this particle at such a speed in a viscous medium can be calculated based on the Stokes formula,

$$f = 6 \cdot \pi \cdot \eta \cdot r \cdot v = 5.7e^{-15}(N)$$  \hspace{1cm} (B-6)

where $\eta = 1e^{-3} \text{pa \cdot s}$, is the viscosity of water, and $r, v$ are the radius and velocity of the particle, respectively. This force is $\sim 1000$ times larger than the necessary force to release the nanoparticle from a nanohole. In general, we believe the radiation force from SPP dominates the nanoparticle patterning process in this work.

Figure B-6 Effect of viscous force on the immobilization of nanobeads in a nanohole. B: Buoyant force; G: Gravity and f: viscous force.
6. Conclusion

To our knowledge, this is the first demonstration of dynamic patterning of nanoparticles in microfluidics using SPP. The simple fabrication process is inexpensive and attractive for practical applications. The introduction of nanohole arrays in the gold thin film not only generates a well-patterned SPP distribution, but also enhances the SPP intensity and lowers the laser intensity to $1/10,000$ of that used in conventional optical tweezers—a viable alternative for the manipulation of nanoparticles [6]. Less energy consumption implies less damage to the targeted nanoparticles, making our technique promising for numerous biomedical applications that entail the manipulation and patterning of nanoscale biomaterials.

References


VITA

Jinjie Shi was born in Yexian county, Henan province of China. He got B.S. and M.S. in the major of microelectronics from Peking University, Beijing, China, in 2002 and 2005, respectively. He then joined the STMicroelectronics Co. as a business development assistant manager in 2005. He began to pursue his PhD in the Pennsylvania State University in 2006. His research interests mainly focus on 1) creating a new class of Nano-Electro-Mechanical Systems (NEMS) and nanophotonic devices using acoustic waves, 2) microfluidics, 3) optofluidics and 4) metamaterials. Within two and a half years, he has already published five first-author, three non-first-author journal papers, and has seven more manuscripts (all first-author) that have been submitted or are ready to be submitted soon for journal publications. He has presented seven papers on conference proceedings. In addition, he is in a process of applying for three patents based on his research findings in micro/nano technology. His research bridges the traditional engineering discipline with the emerging bionanotechnology, and has already created great interest from multiple communities (engineering, biology, applied physics, materials, and chemistry). His work has been highlighted in both public media (US News, Wired Science and Nanotech Web) and professional publications (Cover images on journals Applied Physics Letters, Lab on a Chip). He has won the Grand Prize at the 2008 ESM Today Graduate Research Symposium, the Sabih and Guler Hayek Graduate Scholarship (2008, 2009) in Engineering Science and Mechanics, and the 2009 Penn State Alumni Association Dissertation Award (the most prestigious award for Penn State graduate students).