Master’s Thesis

Droplet Manipulation Using an Optoelectrofluidic Device Integrated with Microchannels

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Abstract

This paper presents a new channel-integrated optoelectrofluidic device capable of generating and programmable manipulating nanoliter-size droplets suspended in a continuous oil phase based on the optically induced dielectrophoresis (DEP) in a liquid crystal display (LCD)-based optoelectronic tweezers (OET) system. Microfluidic generation as well as the optoelectrofluidic transport and merging of droplets have been performed simultaneously on a single device. In order to generate droplets, we integrated poly(dimethylsiloxane) (PDMS) microfluidic channels into a film-based optoelectrofluidic device. We selectively perforated the PDMS membrane to expose the photoconductive surface for manipulating the emerged droplets using optically induced DEP. Based on this novel optoelectrofluidic device integrated with a microfluidic channel, we could continuously generate, manipulate and merge droplets using the optically induced virtual electrodes constructed by an LCD-light pattern. Also, we have achieved multiple droplet manipulation and demonstrated merging two different droplets. This novel platform may be a widely usable for parallel and high-throughput biological and chemical applications based on the droplet-based optoelectrofluidics.
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Nomenclature

Alphabetic Letters

\( f \)
Applied AC frequency

\( f_{CM} \)
Clausius-Mossotti factor

\( r \)
Radius of a particle

\( E \)
Local electric field

\( F_{DEP} \)
Dielectrophoretic force

\( \text{Re}(f_{CM}) \)
Real part of Clausius-Mossotti factor
Greek Letters

$\varepsilon_m$ Absolute permittivity of the suspending medium

$\varepsilon_p$ Absolute permittivity of the particle

$\varepsilon_r$ Relative permittivity

$\varepsilon^*$ Complex permittivity

$\sigma$ Electrical conductivity

$\omega$ Angular frequency of AC voltage
### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>a-Si:H</td>
<td>Hydrogenated Amorphous Silicon</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
</tr>
<tr>
<td>DEP</td>
<td>Dielectrophoresis</td>
</tr>
<tr>
<td>DMD</td>
<td>Digital Micro-mirror Device</td>
</tr>
<tr>
<td>EWOD</td>
<td>Electrowetting-on-dielectric</td>
</tr>
<tr>
<td>FEOET</td>
<td>Floating Electrode Optoelectronic Tweezers</td>
</tr>
<tr>
<td>ITO</td>
<td>Indium Tin Oxide</td>
</tr>
<tr>
<td>LCD</td>
<td>Liquid Crystal Display</td>
</tr>
<tr>
<td>LOC</td>
<td>Lab-on-a-chip</td>
</tr>
<tr>
<td>NA</td>
<td>Numerical Aperture</td>
</tr>
<tr>
<td>OET</td>
<td>Optoelectronic Tweezers</td>
</tr>
<tr>
<td>OEW</td>
<td>Optoelectrowetting</td>
</tr>
<tr>
<td>PDMS</td>
<td>Poly(dimethylsiloxane)</td>
</tr>
<tr>
<td>PECVD</td>
<td>Plasma Enhanced Chemical Vapor Deposition</td>
</tr>
<tr>
<td>RIE</td>
<td>Reactive Ion Etch</td>
</tr>
<tr>
<td>SiN$_x$</td>
<td>Silicon Nitride</td>
</tr>
<tr>
<td>TFT</td>
<td>Thin Film Transistor</td>
</tr>
</tbody>
</table>
2-D

Two-dimensions
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Chapter 1 Introduction

1.1 Biological studies in microreactors

The forming and handling of confined microreactors have been increasingly important issues in the growing fields of miniaturized bio-analytical systems and lab-on-a-chip (LOC) technology [1-3]. Microreactors enable to provide the basis of an effectual way of various applications such as gene-expression analysis [4], clinical diagnostics [5], protein crystallization [6], drug discovery and high-throughput bioassays [7]. Many advantages of microreactors such as independent sample isolation [8, 9], individual control of each droplet [10, 11], eliminating cross-contamination [12] and subjecting different environmental conditions and stimuli were introduced using droplet-based microfluidics. Several examples were introduced including in vitro evolution of proteins in a microfluidic channel [13], single droplet-based enzymatic assay [14, 15], droplet trapping array for incubation and electroporation of cells in droplets [16].

In order to diversify merits of microreactors, precise control [17] and independent manipulation of droplet are required [18]. These techniques allow passive droplet control [19], sorting of droplets by size [20], mixing multiple fluid components within droplets [21, 22] and synthesizing [23, 24] and
transporting solid reagents [25]. These nanoliter-sized droplets can be individually manipulated by various methods, including electrostatic forces [26], temperature control [27], acoustic wave [28], magnetism [29], optical vortex trapping [30], electrowetting-on-dielectric (EWOD) [31], dielectrophoresis (DEP) [32] and optoelectrowetting (OEW) [33, 34].

1.2 Programmable manipulation of microreactors

Programmable manipulation and transportation of microparticles in microfluidic device is central to many chemical and biomedical applications [35]. However, most of the manipulation techniques with a droplet-based microfluidic system mentioned above have faced difficulty in performing programmable and interactive manipulation of individual aqueous droplets within continuous-flow microchannel. For instance, magnetic droplet actuation has the advantage of being independent from the dielectric properties of the droplet, but requires attachment magnetic beads to the targets [36]. Also, the challenge about parallel manipulation of multiple droplets is still remained. EWOD, which has been applied in droplet-based digital microfluidics, have attracted great attention in realizing programmable and reconfigurable operations of multiple microreactors. Cho et al. reported the completion of four
fundamental fluidic operations (creating, transporting, cutting and merging) with EWOD in air environment at AC 25 V applied voltage in 2003 [37]. But this approach requires physically patterned electrodes and complex wiring arising from controlling numerically large electrode arrays, thus it is difficult to apply for disposable applications. Lorenz et al. provided a fluidic and optical platform for the on-demand generation and manipulation of single femtoliter-volume liquid droplets using optical vortex traps in 2006 [38]. Although this method is a powerful tool for trapping droplets and facilitate to integrate other microfluidic components, they have drawbacks such as less manipulation area owing to optical focusing requirements and risk of photodamage.

Dielectrophoretic droplet manipulation has the advantage of unnecessary to physical contact between the droplet and any surface and has dependence on only the dielectric parameters of the droplet. Also, any modification of target particle is not needed and parallel manipulation with larger manipulation area can be conducted. Hunt et al. showed an integrated circuit/microfluidic chip that moves droplets along programmable path using DEP in 2008 [39]. Each pixel is independently driven with a radio frequency voltage, resulting in the reduction of actuation voltage (~5 V). However, only simple and inflexible manipulation along confined path can be conducted due to limited in degree of
freedom through fixed electrode patterns. Also, scaling problems about nanoscale semiconductor fabrication technology become more severe as the droplet size scales down.

Droplet manipulation using OEW proposed an alternative approach to eliminate bottlenecks about DEP and EWOD. Chiou et al. reported on the liquid droplet actuation mechanism using light and demonstrated a 2-D droplet manipulation platform on a photosensitive surface in 2008 [40]. By scaling down the gap spacing and the size of electrode, nano-liter or smaller droplets can be freely actuated by optical illumination induced by laser beam. They achieved a relatively high transport speed about 78 mm/s for a 100 nL droplet. However, it requires high actuation voltage about 100 V and needs a complex optical structure for focusing the projected image on OEW electrodes. Also, fabrication process for thick amorphous silicon deposition is relatively difficult.

Recently, optoelectronic tweezers (OET) have emerged as a powerful optical-driven technique that inherits optical tweezers and DEP advantages [41, 42]. OET utilizes programmable virtual electrodes which are projected on the photoconductive material driven by dynamic images from display devices such as digital micro-mirror device (DMD) [41] or liquid crystal display (LCD) [43]. The virtual electrodes allow the microparticle manipulation via electrokinetic
mechanisms such as electrophoresis [44], dielectrophoresis [45] and electro-osmosis [46]. This optoelectronic principle provided several benefits: drastic reduction of optical intensities (0.01 to 1 W/cm²) from that of optical tweezers, solving disposability and interconnection issues, facilitating massive parallel manipulation, and allowing programmable and interactive manipulation using a personal computer [47]. In addition, the manipulation performance can be increased by integrating with optical component such as low numerical apertures (NA) or condenser lens [48]. By using this lens-integrated LCD-based OET system, several biological applications were successfully demonstrated including cell discrimination [49] and local alignment of swimming cells [50]. Also, experimental investigations of physical phenomena such as electrostatic particle-particle interactions [51] and nonspecific surface-particle interactions [52] were performed. Floating electrode optoelectronic tweezers (FEOET), reported by Park et al. in 2008 [53], proposed possibility of optical actuation of liquid droplets in electrically insulating media using OET device. Virtual electrodes perturb an uniform electric distribution, resulting in asymmetric electric field pattern around a droplet. However, this technique requires high voltage about 300 V and has limitation about on-demand injection due to open structure.
<table>
<thead>
<tr>
<th>Scheme of device</th>
<th>Actuation Mechanism</th>
<th>Published Year</th>
<th>Energy Source (Voltage)</th>
<th>Distinguishing Marks</th>
<th>Disadvantages</th>
</tr>
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<tr>
<td></td>
<td></td>
<td>Lab Chip (2008)</td>
<td>AC voltage (5 V)</td>
<td>High voltages are not required</td>
<td>Requirement of complex wiring</td>
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<tr>
<td></td>
<td></td>
<td>J. MEMS (2008)</td>
<td>5 mW, 532 nm laser beam (100 V)</td>
<td>Actuating electrowetting locally with desired area</td>
<td>Complicated fabrication process</td>
</tr>
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Table 1. Review of programmable liquid droplet manipulation systems.
1.3 Research Objectives

This work aims to propose a new optoelectrofluidic platform integrated with microchannels to continuously generating and manipulating droplets based on optically induced DEP force using an LCD light pattern on a single device. We have been utilized a lab-on-a-display, which is a type of optoelectrofluidic platform applying an LCD as an optical component for projecting dynamic image to construct virtual electrode. To enhance the higher manipulation performance, we used the LCD-based OET system integrated with condenser lens.

In this study, the fabrication method of OET device integrated with a selectively perforated microchannel was first introduced. In order to evaluate the feasibility of manipulating of droplets in this device, simulation studies for polarizability parameter and electric field distribution were performed. We demonstrated parallel transporting and merging water droplets suspended in the oil phase through optically induced DEP. We have also measured the droplet velocities according to their sizes and several bias voltage conditions.

1.4 Thesis Outlines

The thesis consists of five chapters. In Chapter 1, backgrounds and research
objectives are mentioned. Chapter 2 describes the theory of dielectrophoresis. Chapter 3 describes the device design, microfabrication process, material preparation and experimental setups. Chapter 4 deals with results and discussion. The last chapter is conclusions of this thesis.
Chapter 2 Concept and Theory

2.1 Concept

In this paper, we developed an optoelectrofluidic platform integrated with microchannel. The schematic view of the channel-integrated optoelectrofluidic device is shown in Figure 1. This device composed of a photoconductive and a fluidic layer including ground electrode and poly(dimethylsiloxane) (PDMS) fluidic channel. The fluidic layer consisted of two microfluidic regions; one for continuous emerging water droplets in oil phase and the other for manipulating droplets based on optically induced DEP. When water droplets are generated from the T-shaped focusing channel, then they flow through the main channel and reached at manipulation region. With the application of voltage between the photoconductive and the ground layer, the projected dynamic image from LCD becomes the virtual electrode to form a non-uniform electric field in the manipulation region. As a result, we can perform DEP manipulation of the water droplets in the oil phase.
Figure 1. Schematic diagram of the optoelectrofluidic device integrated with a microfluidic channel. PDMS microfluidic microchannels were integrated between a photoconductive layer and an ITO-coated film as a ground layer. This device consisted of two microfluidic regions; one for continuously emerging water droplets and the other for manipulating droplets based on optically induced DEP.
2.2 Dielectrophoresis

Dielectrophoresis (DEP) is a kind of AC electrokinetic phenomenon under a spatially inhomogeneous electric field driven by interaction of an induced dipole moment with the applied electric field, resulting in the migration of a dielectric microparticle. The magnitude and direction of the DEP force depends on the volume of the particles, dielectric properties of suspension media and particle, the electrode configurations, and the applied electric field. The DEP force, \( F_{\text{DEP}} \), acting on the dielectric particles suspended in a dielectric medium, is defined as below [54]:

\[
F_{\text{DEP}} = 2\pi r^3 \varepsilon_m \Re[f_{CM} \nabla E^2] \quad (1)
\]

where \( r \) is the radius of the particles; \( \varepsilon_m = \varepsilon_0 \varepsilon_r \) is the permittivity of the suspending medium, where \( \varepsilon_r \) is the relative permittivity of the fluid and \( \varepsilon_0 \) is the permittivity of free space; \( E \) is the local electric field; and \( \nabla \) is the del vector operator. \( \Re[f_{CM}] \) is the real part of the Clausius-Mossotti factor which is described as below:
\[ f_{CM} = \frac{\varepsilon_p^* - \varepsilon_m^*}{\varepsilon_p^* + 2\varepsilon_m^*} \]  

(2)

where \( \varepsilon_p^* \) and \( \varepsilon_m^* \) are the complex permittivities of the particle and medium, respectively, and

\[ \varepsilon^* = \varepsilon - \frac{\sigma}{\omega} j \]  

(3)

where \( \sigma \) is the conductivity; \( \varepsilon \) is the permittivity; \( \omega \) is the angular frequency (\( = 2\pi f \), where \( f \) is the applied frequency); and \( j = \sqrt{-1} \).

Notably, the direction of DEP is determined by \( \text{Re}[f_{CM}] \) which can have a value between +1.0 and -0.5. A positive value for \( \text{Re}[f_{CM}] \), which means that the particle is more polarizable than the medium, produces a positive DEP force that leads the particle to move toward the region of the maximum electric field. On the other hand, when this value is negative, where the medium is more polarizable than the particle, the particles migrate in the opposite direction due to negative DEP force (Figure 2).
Figure 2. Movements of microparticles under dielectrophoretic regime. For negative dielectrophoresis, particle is pulled towards the local minimum of the electric field. For positive dielectrophoresis, particle is pulled to the maximum of the electric field.
Chapter 3 Materials and methods

3.1 Materials

Hexadecane (Sigma-Aldrich Co., St Louis, MO) was used as the continuous oil phase mixed with 0.5 % (w/w) Span 80 (Sorbitan monooleate, Aldrich) for efficient emerging of droplets. Red and blue food dye (Kemide Co., Jeonju, Korea) diluted with deionized water were prepared to create dispersed water phase.

3.2 Channel design and fabrication

The width of the water and oil channels were 60 and 80 μm, respectively. The height of the channel was 68 μm. We designed that the dimension of manipulation region was 15 mm × 3 mm for decreasing flow rate. After moving into an enlarged manipulation region, the droplets were recovered into their spherical shapes. The height of the manipulation region was 125 μm (Figure 3).
Figure 3. Microchannel design of the channel-integrated optoelectrofluidic device and enlarged view of focusing channel for droplet generating. Generated droplets from focusing channel were recovered their spherical shapes at enlarged manipulation region.

The photoconductive layer was comprised of four layers: 1) a 180 nm-thick ITO layer, 2) a 50-nm-thick $n^+$ doped hydrogenated amorphous silicon ($n^+$ a-Si:H) layer, 3) a 1 μm-thick intrinsic hydrogenated amorphous silicon layer (intrinsic a-Si:H), and 4) a 20 nm-thick silicon nitride ($\text{SiN}_x$) layer. The ITO-coated glass substrates (Samsung-Corning Precision Glass, Asan, Korea) were
prepared and a triple layer of n+ a-Si : H, intrinsic a-Si : H and SiNₓ was consecutively deposited by plasma enhanced chemical vapor deposition (PECVD) onto the substrate. Afterward, some regions were etched by reactive ion etch (RIE) for electric connections. A wire was connected after dicing the fabricated device into 37.5 mm × 25.0 mm sections. Finally, a 30 nm thick film of 0.5 % Teflon AF 1060 (DuPont, Wilmington, DE) diluted in Fluorinert FC-40 was spin-coated and baked for 2 h at 200 °C to make the surface hydrophobic (Figure 4).

**Figure 4.** Fabrication processes of photoconductive layer. Triple layer including n' doped a-Si, intrinsic a-Si and silicon nitride was deposited by PECVD onto ITO-coated glass substrate. For electric connections, some regions were etched by RIE.
The transparent ITO-coated film was prepared as the conductive layer for ground electrode. The ground layer with microfluidic channel was fabricated from PDMS silicone elastomer (Sylgard 184, Dow corning, MI) and ITO-coated film using conventional photolithographic technique for low-cost and disposability. The microfluidic channel was fabricated by spin coating PDMS (850 rpm for 30 s) onto a photoresist mold fabricated on a silicon wafer with negative photoresist SU-8 2025 (MicroChem Co., MA). In order to increase the viscosity, the prepolymer of PDMS (10:1 mixing ratio) were stored at the room temperature for 2 h before spin coating. To make a manipulation region, we selectively perforated the PDMS membrane by gas-flow using a 30-gauge syringe needle connected to an air compressor. After curing on a hot plate at 75 °C for 1 h, the PDMS replica peeled from the mold and bonded to an ITO-coated film as a ground layer. The bonding process was performed after oxygen plasma (200 mTorr, 1 min, 200 W) treatment by an expanded plasma cleaner (PDC-002, Harrick Science, Ossing, NY). Since this treatment oxidizes the surface to become hydrophilic, we stored the device in a convection oven at 65 °C for 24 h to recover hydrophobic nature of the microchannel. After punching the ground layer to make tube holes, a 30 nm thick Teflon was then spin-coated and baked for 4 h at 100 °C (Figure 5).
**Figure 5.** Fabrication processes for the optoelectrofluidic device integrated with microchannels. Two separated microfluidic regions were perfectly constructed by selectively perforated PDMS membrane.

In order to bond hydrophobic-coated fluidic layer to photoconductive layer, we prepared microfluidic assembler that enables reversible bonding. To achieve uniformly pressing between two layers, we attached acryl plate below upper assembler plate. Thick PDMS slab was bonded to upper side of ITO-coated film by plasma treatment for simple tubing. Leak-proof sealing was completed by screw-fastening. After experiment, the photoconductive layer could be recycled (Figure 6).
Figure 6. Schematic diagram of microfluidic assembler for reversible bonding of hydrophobic-coated fluidic layer to photoconductive layer. Leak-proof sealing was completed by screw-fastening.
3.3 Experimental setup

Figure 7 shows the experimental setup for OET system, based on an upright microscope (Zeiss Axioskop 40; Carl Zeiss, Germany) integrated with a condenser lens (NA = 0.9). Optical patterns were generated by a 0.7 in polysilicon active-matrix TFT LCD module (16 mm × 12 mm image area, 800 × 600 pixel array with 14 μm pixel pitch) from conventional projector (CP-S225; Hitachi, Japan) and drawn by using standard presentation software (Microsoft PowerPoint™) on a computer. The dimensions of module were 27 mm in length, 23 mm in width, and 5 mm in thickness. The LCD module was operated by the LCD driver circuit of the projector. A condenser lens, which is located between the OET device and the LCD module, plays a role in condensing and focusing the light passed through LCD module positioned above light source into a photoconductive layer of OET device. The electric field with 100 kHz frequency and several voltage produced from a function generator (AFG310; Tektronix, OR) was applied to virtual electrodes. The motions of droplets were observed and recorded using microscope with a CCD camera (DS-U1; Nikon Instruments Inc., NY) connected to a personal computer. In order to quantify the velocity data of droplets, we used an image analyzing program (i-Solution; IMT, Korea). We measured maximum moving
velocity of the droplets, which are following the scanning virtual electrodes. All fluids were introduced into the microfluidic system via the syringe pumps (Pump 11 Pico Plus; Harvard Apparatus, Inc., Holliston, MA).

**Figure 7.** Schematic diagram of experimental setup of channel-integrated optoelectrofluidic platform for droplet emerging and manipulation.
Chapter 4 Results and Discussion

4.1 Simulation of Clausius-Mossotti factors

To figure out the DEP characteristics of water droplets in oil phase under the application of AC voltage, we calculated the real part of CM factors from different oil materials (hexadecane, diethylene glycol, glycerin and silicon oil) according to the AC frequency (Figure 8). This simulation was calculated by using equation (2). The electrical relative permittivity and conductivity of DI is 78 and $2.3 \times 10^{-4}$ S/m, respectively. The electrical relative permittivity and conductivity of several oil materials are represented at Table 2. At the frequency range below 10 kHz, the real part of CM factors was almost one, which means that strong positive DEP forces would act on the water droplets. Especially, in the case of hexadecane, the water droplets show positive DEP motions in broader frequency range with higher velocity than others.
Table 2. Simulation conditions for frequency-dependent real part of Clausius–Mossotti factors for different oil materials.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Electrical Relative Permittivity</th>
<th>Conductivity [S/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hexadecane</td>
<td>2.05</td>
<td>$0.02 \times 10^{-6}$</td>
</tr>
<tr>
<td>Diethylene Glycol</td>
<td>31.69</td>
<td>$0.42 \times 10^{-6}$</td>
</tr>
<tr>
<td>Glycerin</td>
<td>47.0</td>
<td>$6.4 \times 10^{-6}$</td>
</tr>
<tr>
<td>Silicon Oil</td>
<td>4.4</td>
<td>$2.67 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

Figure 8. Simulated results for frequency-dependent real part of Clausius–Mossotti factors for different oil materials. The water droplets in hexadecane medium would show positive DEP motions in broader frequency range with higher velocity than others.
4.2 Simulation of electric field distribution

In order to understand the DEP response of droplets due to the strength and spatial change of the electric field, we simulated the electric field strength in the manipulation region using commercial CFD solver (CFD-ACE; CFD Research Corporation, Huntsville, AL). Figure 9 stands for the case that the illumination region was 200 μm. We regarded the illuminated region and non-illuminated region of photoconductive layer as a conductor and insulator, respectively. The voltage applied across the illuminated area of photoconductive layer and ground layer was assumed to have a value of 30 V at 100 kHz.

It is important to note that the electric field gradient was relatively stronger at the region around the edges of illuminated area, resulting in stronger DEP force than elsewhere. Therefore, we could predict that the droplets would move to the edge of illuminated area under positive DEP regime. The gradient of electric field squared was in the range $\sim 4 \times 10^{11} \text{ V}^2/\text{m}^2$. 
**Figure 9.** Simulated electric field distribution within the manipulation region induced by virtual electrode formed by light pattern under the voltage of 30 V at 100 kHz.

### 4.3 Water droplet generation in the focusing channel

Figure 10(a) shows the generation of water droplets in the focusing channel with respect to the flow rate ratio of water to oil phase (Qₘ/Qₒ). The volume of water droplet was increased as the flow rate of the water phase (Qₘ) increased when flow rate of oil (Qₒ) was fixed (20, 40, 60 and 80 µL/h), as in Figure 10(b). The droplet sizes continuously increased as the flow rate of water phase increased. Especially, a rate of increase was relatively large when the oil flow rate was lower (20 µL/h).
Figure 10. (a) Microscopic view of generation water droplets at focusing channel for different flow rates of water and oil phases. (Scale bar: 100 µm) (b) Plot of the water droplet volume as the ratio of $Q_w$ and $Q_o$ increases at the flow rate of the water phase 20, 40, 60 and 80 µL/h.
4.4 Optoelectrofluidic droplet manipulation using a light source

In order to examine optically induced DEP response to water droplet, we demonstrated optoelectrofluidic droplet manipulation by scanning optical lines (Figure 11). We created the optical line using patterned Au sputter-coated glass slide. The width of line pattern was 80 μm. When we illuminate light onto optical mask using the downside illumination with high intensity, the virtual electrodes can be created at only non-patterned region. Thus, we can generate light image pattern using light source. When the voltage was applied, the water droplets with diameter of 100 μm were moved to the light pattern by optically induced positive DEP. The applied voltage was 33 V bias at 100 kHz. Some large droplets were attached to the bottom layer by surface-particle electrostatic interactions.

Figure 12 shows the optoelectrofluidic trapping and merging of droplets in the continuous flow under on/off electrical control. Before applying voltage, water droplets were moved along the flow direction. With the application of voltage, the water droplets were rapidly merged with neighbors and trapped on the light pattern. Other droplets of tiny volume were not trapped and passed the virtual DEP walls along the fluid flows due to the weak DEP forces. After
turning off the voltage, the trapped droplet was moved in the flow direction again. The applied voltage was 33 V bias at 100 kHz.

**Figure 11.** Example of optoelectrofluidic droplet manipulation by scanning optical lines from left to right. The light pattern was generated by light source directly. 100-μm-diameter droplets were moved to the light pattern by optically induced positive DEP under the condition of 33 V bias at 100 kHz.
Figure 12. Example of optoelectrofluidic droplet trapping and merging in the continuous flow under on/off electrical control. The voltage conditions we applied were 33 V bias at 100 kHz.
4.5 Droplet manipulation using an LCD-light pattern

The water droplet velocities as a function of the applied voltage for different droplet volumes (0.59, 2.09 and 3.02 nL) are shown in Figure 13. Droplet shows faster motion as applied voltage increases due to stronger DEP forces. However, when the applied voltage was higher than 40 V, droplet absorptions were appeared because of electrostatic force, resulting in decreased droplet velocity. Also, due to friction force induced by gap spacing between fluidic and photoconductive layer, the droplet velocity was decreased as volume increases.

![Figure 13](image_url)

**Figure 13.** Plot of droplet velocities depending on the applied voltage with different droplet volumes.
We have successfully performed manipulation of a single water droplet in oil phase using optically-induced positive DEP based on LCD OET system (Figure 14). We can transport target droplet by manipulating of optically induced virtual electrode which was made by user. The 80-μm-diameter water droplet was transported to the illuminated (red) area of the square-shaped LCD light pattern. As the pattern was moved, the droplet was followed to the light pattern. This droplet was manipulated under the applied voltage of 27 V at 100 kHz.

Parallel manipulation process is an advantageous function for large-scale droplet manipulation. We have also demonstrated the multiple droplet transportation using multiple virtual electrodes created by LCD-light patterns. As shown Figure 15, three droplets that trapped by three virtual electrodes are followed the trace of the moving electrodes during 112 seconds. One droplet was transported in lower direction, while other droplets were moved in upper direction and merged together.
**Figure 14.** Snapshots of optically induced DEP movement of single water droplet in oil phase using LCD-light pattern. This droplet was manipulated under the voltage of 27 V at 100 kHz.
Figure 15. Snapshots of parallel transporting and merging water droplets in oil medium based on optically induced positive DEP under the voltage of 27 V at 100 kHz. Three droplets were guided by three LCD light patterns.

4.6 Manipulation of two different droplets

We demonstrated simple example of merging two different droplets using LCD-light patterns. First, we designed microchannel with two focusing channels for introducing four fluids including two different samples (red and blue dye) and two oil phases (hexadecane) (Figure 16). The width of the water and oil channels were 60 and 80 μm, respectively. The height of the emerging and manipulation region were 68 and 125 μm, respectively. Red and blue dyed
droplet was generated from each focusing channel. Some emerged droplets were moved into manipulation region with 4000 μm of diameter and the rest of the droplets were bypassed into a waste outlet. As shown Figure 17, red droplet was transported and merged to blue droplet by two LCD light patterns in the manipulation region.

![Diagram of microchannel for transporting and merging droplets](image)

**Figure 16.** The layout of the microchannel for transporting and merging two different droplets.
Figure 17. Snapshots of transporting and merging two different droplets based on optically induced positive DEP under a voltage of 30 V at 100 kHz.
Chapter 5 Conclusions

We have developed a new optoelectrofluidic platform for continuously generating and manipulating droplets by integrating microfluidic channel. Microchannel fabricated by selectively perforated PDMS membrane for continuous droplet generation was integrated with an OET device. Using this fabrication process including gas-flowing, we could successfully construct two separated microfluidic regions; droplet emerging region and manipulation region. We devised a T-junction in a microfluidic channel of emerging region for continuous droplet generation. Water droplets with various sizes were generated by changing the flow rate ratio of water to oil phase. The height of manipulation region can be varied by the spin-coating rate of the PDMS prepolymer. In this experiment, we decided the height of emerging region and manipulation region on 68 and 125 μm, respectively. In order to make hydrophobic coating on fluidic and photoconductive layer for prevention absorption problem, we coated thin Teflon AF membrane onto each layer. Reversible bonding was achieved by microfluidic assembler for leak-proof sealing and recycling photoconductive layer.
We conducted the simulation of frequency-dependent CM factors from different oil materials and electric field distribution to further clarify the feasibility of manipulating droplets in this platform. Especially, the water droplet in hexadecane medium has higher value of real part of CM factor in broader frequency range. Electric field simulation in the manipulation region by CFD solver shows that DEP forces acted on a droplet at the edge region of virtual electrode would be stronger.

We first demonstrated optoelectrofluidic water droplet manipulation using scanning optical lines. 100-μm-diameter droplets were moved to light pattern by optically induced positive DEP. Also, optoelectrofluidic trapping and merging of droplets was demonstrated in the continuous flow under on/off electrical control. We have demonstrated droplet operation functions including droplet transportation, multidroplet manipulation and merging using LCD-light patterns under the condition of 27 V bias at 100 kHz. We could manipulate 0.59 nL volume droplets with 97 μm/s average velocity using optically induced DEP.

Several dimensions of device may have an effect on optoelectrofluidic droplet manipulation. For the most part, the gap spacing between the photoconductive and the ground layer is significant, for increasing spatial
electric field gradient. If this gap spacing is too high, droplets of tiny volume will be not trapped and manipulated by the virtual electrodes. However, there will be a trade-off between gap spacing and droplet velocity. Small gap spacing would prevent freely manipulate droplets due to surface-droplet electrostatic interactions. This problem would be solved by scaling down dimensions of microchannel for decreasing droplet volume.

This novel channel-integrated optoelectrofluidic platform based on LCD-OET system can have the potential for parallel and high-throughput biological and chemical applications based on the droplet-based optoelectrofluidics. Due to low complexity of optical components, it is easy to integrate with other additional optical or microfluidic components and can serve as an important tool for programmable bioassays.
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본 연구에서는 미세 물방울을 자유자재로 구동하기 위한 미세채널이 집적된 새
로운 광전기유체 (Optoelectrofluidic) 플랫폼을 제안하였다. 최근 미세유체 기술 중에
서 생물학적 샘플의 정교하고 독립적인 구동을 위한 미세물방울 기술이 중요하게
대두되고 있으며, 특히 2차원적으로 프로그램화 가능한 (programmable) 물방울 제어
기술을 이용하여 다양한 환경 하에서 다양한 생성시료의 혼합, 측정, 배열화 등에
적용한 예가 보고되었다. 그러나 기존의 유전영동 (dielectrophoresis)이나 전기습윤
(electrowetting-on-dielectric, EWOD)과 같은 기술의 경우 고정된 전극이 포함된 소자
를 제작하기 위한 복잡한 공정 및 배선작업이 필요하며, 광학 소자를 이용하는 경
우 레이저 등을 구동하기 위한 복잡한 장치 구성이 필요하고 높은 광학 및 전기적
에너지에 따른 광손상 (photodamage)이 우려된다. 그러므로 간단한 광학 장치를 이
용하여 비교적 낮은 전기적 에너지로 미세 물방울을 구동할 수 있는 기술이 필요
하였다.

본 연구에서는 복잡한 광학 장치가 필요없는 집광렌즈가 집적된 액정 디스플레이
(liquid crystal display, LCD) 기반의 광전자접계 장치를 이용하여 저전압에서 물방
울의 프로그램화 구동을 수행하였다. 특히, 미세 물방울의 높도 및 크기 조절이 가
능한 미세유체 채널을 광전기유체 장치에 집적함으로써 단일 광전기유체 장치 내
에서 미세 유체 기반의 연속적인 미세 물방울 생성과 광전자접계를 이용한 구동이
가능하도록 하였다. 물방울 구동의 원리는 디스플레이 영상을 광전도성 층에 조사함으로써 형성되는 가상 전극을 이용하여 불균일한 전기장을 발생시킨 뒤, 이를 이용하여 유전영동을 유도하는 것이다. 본 플랫폼에서는 빛에 의해 유도된 양의 유전영동에 의해 물방울을 조작할 수 있다.

미세유체 채널이 집적된 광전자잡게 장치는 광전도성층과 접지층 사이에 폴리디메틸실록산 (polydimethylsiloxane, PDMS) 박막이 집적된 형태이며 이를 집적하기 위해 질소 기체에 의한 선택적 친공 기법을 이용하였다. 이와 같은 공정 방법에 의해 미세 물방울 형성 영역과 광전자적 구동 영역을 완벽하게 분리할 수 있다. 광전도성층과 미세 채널이 포함된 접지층에 각각 표면처리하여 소수화한 뒤, 미세 조립기 (microfluidic assembler)를 이용하여 가역 결합을 유도하였다.

영상에 의한 가상 전극으로 형성되는 전기장의 기울기 및 유전영동력을 시뮬레이션을 통해 확인한 결과 hexadecane을 매질로 하는 물방울이 상대적으로 높은 유전영동력을 받으며 양의 유전영동에 의해 가상 전극의 가장자리 부근으로 음직임을 예상하였다. 유체의 속도를 변화시킴으로써 연속적으로 생성되는 물방울의 부위를 측정하였다. 생성된 단일 물방울을 LCD 영상을 이용하여 프로그램화 구동을 수행하였으며, 다수의 물방울을 동시에 구동 및 합체하는 실험도 수행하였다. 인가한 전압이 높을수록 구동 속도가 빠름을 확인하였으나 특정 전압 이상의 고전압을 가하는 경우에는 물방울의 표면 흡착 현상에 의해 속도가 감소하거나 전기분해 (electrolysis) 현상이 일어나는 것을 확인하였다.
본 연구에서 제안한 미세유체 채널이 집적된 광전기유체소자를 이용한 미세 물방울 조작 기술은 기존의 물방울 조작 기술에 비해 단순하고 사용하기에 편리한 구조를 제공함으로써 생물학적 응용 및 분석 분야에 이용될 수 있을 것이다. 특히 대면적이지 다수의 물방울을 동시에 구동할 수 있다는 장점은 미세 물방울 기반의 초고속 스크리닝 (high-throughput screening)에 기여할 수 있을 것이라 기대한다. 또한 영상 장치에 의해 형성된 가상 전극을 이용한 광전자적 구동원리는 자동화된 세포 분석 실험에 응용될 수 있을 것이다.