Optoelectrofluidic field separation based on light-intensity gradients

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Optoelectrofluidic field separation (OEFS) of particles under light -intensity gradient (LIG) is reported, where the LIG illumination on the photoconductive layer converts the short-ranged dielectrophoresis (DEP) force to the long-ranged one. The long-ranged DEP force can compete with the hydrodynamic force by alternating current electro-osmosis (ACEO) over the entire illumination area for realizing effective field separation of particles. In the OEFS system, the codirectional illumination and observation induce the levitation effect, compensating the attenuation of the DEP force under LIG illumination by slightly floating particles from the surface. Results of the field separation and concentration of diverse particle pairs (0.82–16 μm) are well demonstrated, and conditions determining the critical radius and effective particle manipulation are discussed. The OEFS with codirectional LIG strategy could be a promising particle manipulation method in many applications where a rapid manipulation of biological cells and particles over the entire working area are of interest. © 2010 American Institute of Physics.
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I. INTRODUCTION

Optical manipulation of biological objects has been the subject of intensive study since the introduction of the optical tweezers in 1986.¹ The noninvasive optical tweezers, which can manipulate single particles ranging in size down to tens of nanometers by using a strongly focused beam of light, have been a useful tool for many frontier researches. Advances of the optical tweezers, including three-dimensional improvements such as interferometric and holographic light spot generation,^{2–4} enabled this technique to be broadly accepted not only in the laboratory but also in the main stream of manufacturing and diagnostics.⁵

Like the optical manipulation, the electrical manipulation of particles on the basis of dielectrophoresis^{6–8} (DEP) have also drawn broad interest since microfabricated devices became widely adopted in the particle manipulation. While purely electrical DEP particle manipulation based on CMOS chip,⁹ microchannels,^{6,7,10} and integrated microsystems¹¹ have been extensively developed, optoelectronic DEP methods such as optical dielectrophoresis (ODEP),¹² the image dielectrophoresis,¹³ and the optoelectronic tweezers¹⁴ (OETs) enabled reconfigurable and scalable noninvasive particle manipulation by arbitrarily configurable electrode patterns. The computer-generated virtual electrode patterns, envisioning a laboratory-on-a-display,¹⁵ can provide unlimited user-defined manipulation strategies. Compared with the conventional metal electrodes which usually require numerous miniaturized electrodes or barriers, fabricated by MEMS technology, the optoelectronic technique, which necessitates no fixed electrodes, significantly improves flexibility in controlling bioparticles.¹⁶ In addition, the optoelectronic techniques consuming less power than optical tweezers can reduce thermal issues in handling biological cells.

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Another electrohydrodynamic particle manipulation based on the ACEO (Ref. 17) have been employed for the concentration and detection of bioparticles.¹⁸ While optical tweezers and DEP particle manipulation provide short-ranged forces that are highly dependent upon the size of particles, ACEO provides a long-ranged force with weaker dependency upon the particle size, providing effective particle manipulation over wider working areas. Furthermore, ACEO allows effective manipulation of submicron scale particles without considerable dipole-dipole (d-d) interaction, whereas the minimum particle size manipulated by the DEP force can be limited to a few microns, where the d-d interaction could additionally affect particle manipulation.¹⁹

In general, ACEO is driven by conventional metal electrodes; however, combined with the optoelectronic technique, light-actuated ACEO²⁰ was also introduced, taking advantage of arbitrarily configurable optical approaches. In the optoelectronic configurations using ac driven non-uniform electric fields, ACEO and DEP can occur at the same time, and can compete with each other according to the particle size. These two competing forces (F_{ACEO} and F_{DEP}) could allow more effective and controllable particle manipulation, where rapid separation, concentration, and patterning of micro-/nanoparticles can be especially flexible and straightforward for many biological and chemical applications.²¹

Particle manipulation based on the competing F_{ACEO} and F_{DEP} , however, is only effective at very local areas due to the fact that F_{DEP} is a short-ranged force, whereas F_{ACEO} is a long-ranged one. While F_{ACEO} and F_{DEP} can effectively compete each other at a local area where F_{DEP} is strong, only ACEO dominates at the other areas, where no competing effects are expected.

The fundamental difference of the force-ranges between F_{ACEO} and F_{DEP} poses the major difficulty in developing the optoelectrofluidic field separation (OEFS) method that we introduce in this paper for the simultaneous separation of particles in the entire working area. In theory, applying light-intensity gradient (LIG) to a broad area can render F_{DEP} long-ranged, however, applying LIG can considerably attenuate electric field gradients compared with previous methods such as OET, whereby the attenuation of F_{DEP} is natural and inevitable.

The attenuated F_{DEP} under LIG illumination could be insufficient to effectively migrate micron scale particles. In order to compensate the attenuation of F_{DEP} under the LIG illumination, we applied the particle levitation method,²² which enables more effective particle migration with weaker F_{DEP} by slightly floating particles to reduce the friction and adhesion between a surface and particles. We found that by levitating particles, the migration of particles by F_{DEP} became sufficiently improved to be able to compete with F_{ACEO} , otherwise the migration of particles was not noticeable.

Applying the particle levitation method, which is a key contributor to the OEFS, to the optoelectrofluidic configuration requires only slight modification of the conventional optoelectrofluidic systems. The major part of the particle levitation method is related to the directionality of the illumination. In general, the direction of illumination is not a critical issue in the previous optoelectrofluidic devices, where bidirectional system configuration can be preferred presumably due to the simplicity in viewing and recording the working area. In the bidirectional configuration, the computer-generated virtual electrode patterns are projected from the downside, while the working area is observed from the upside using digital imaging devices. To the contrary, in the codirectional configuration, which is essential for the particle levitation, both the projection of electrode patterns and the observation of the working area are performed from the upside, where a beam splitter (50:50) overlaps the optical paths for the projection and the observation (Fig. 1).

Although the intensity attenuation of the projected electrode patterns caused by the beam splitter would be an intrinsic disadvantage, the OEFS with the codirectional configuration shows very effective and successful field separation of different particles, proving that the reduced friction and adhesion is especially advantageous over the attenuation of the illumination. Diverse particle manipulation strategies owing to the arbitrarily configurable virtual electrode patterns are unlimited with regard to separation, concentration, patterning, and harvest of target particles. We expect that experimental characterizations of the OEFS according to particle size, frequency, and intensity gradient can help establish particle manipulation protocols in many applications dealing with (bio-)particles.

FIG. 1. Codirectional optoelectrofluidic configuration for the OEFS. (a) Conceptual illustration of the OEFS device, where F_{DEP} and F_{ACEO} compete each other over the entire illumination area. (b) The codirectional optoelectrofluidic configuration, where the beam splitter (50:50) overlaps the optical paths for the projection (red) and the observation (blue).

II. THEORY AND METHOD

A. Device structure used in the OEFS system

In the OEFS system (Fig. 1), transparent indium tin oxide (ITO) coated glass plates were used as planar electrodes at the top and the bottom of the configuration, where the bottom electrode has a thin photoconductive layer on the top of the ITO layer. The photoconductive layer comprises a few different layers; a 180-nm-thick ITO layer, a 50-nm-thick n+doped a-Si:H, a 1- μm -thick intrinsic a-Si:H, a 20-nm-thick silicon nitride.¹⁵ A conventional projector (VPL-CX5, SONY) was

used as light source to form virtual electrode patterns. The image illuminated from the projector is collimated and focused by a set of two lenses and 10× objective lens (NA=0.25) onto the photoconductive layer. The particles used in the experiments were fluorescent polystyrene beads (Duke Scientific) dispersed in 0.1 mM NaCl electrolyte solution. The diameters of the particles were 0.82, 1, 3, 5, 7, and 16 μm .

B. System configuration of the OEFS system

In the optoelectrofluidic configuration (Fig. 1), electric field gradients applied to an aqueous electrolytic media, where particles place, are controlled by the intensity gradients of the light illumination on the photoconductive layer. As an ac electric field is applied to the system, conductivity variation of the photoconductive layer due to the nonuniform illumination causes electric field gradients over the electrolytic media. In general, since bright fields increase the conductivity of a photoconductive layer, reducing potential drop across it, the electric field above it becomes stronger. Thus, the major consideration for the OEFS system should be made with regard to (1) electrical characteristics of the media and the photoconductive layer, (2) illumination intensity, and (3) the amplitude and the frequency of the applied ac electric potential.

The electrical characteristics of the electrolytic media and the photoconductive layer are of great importance in order to maximize the electric field gradients applied to the electrolytic media. Considering that the conductivity range of the photoconductive layer is already determined by the materials, appropriate conductivity of the electrolytic media should be determined through the impedance matching between the photoconductive layer and the electrolytic media. The electric potential applied to the electrolytic media is determined by the impedance ratio between these two layers; $V_m = V_{p.p.} [1 / (1 + Z_{pcl}/Z_m)]$, where V_m is the electric potential applied to the media (volts), $V_{p.p.}$ is the amplitude of the ac electric potential (volts), Z is the impedance $[=t/A(\sigma + j\omega\epsilon)]$ (Ω), t is the thickness (meter), σ is the conductivity (S/m), A is the area (m^2), $j = \sqrt{-1}$, ω is the frequency (1/s), and ϵ is the permittivity (F/m). Subscripts m and pcl represent the electrolytic media and the photoconductive layer, respectively. When Z_m is too high or too low compared with Z_{pcl} , conductivity changes of the photoconductive layer do not sufficiently change V_m . In order to maximize the variation of V_m , Z_m has to be similar to Z_{pcl} , where an accurate impedance of the electrolytic media can be found through the geometric mean of the minimum and the maximum impedances of the photoconductive layer. Thus, the conductivity of the electrolytic media can be determined as Eq. (1),

$$Z_m = \left(\frac{t_{pcl}}{A} \right) \sqrt{\frac{1}{(\sigma_{pcl}^{\min} + j\omega\epsilon_{pcl})(\sigma_{pcl}^{\max} + j\omega\epsilon_{pcl})}}. \quad (1)$$

The conductivity range of the hydrogenated amorphous silicon is from $\sigma_{pcl}^{\min} = 10^{-9}$ S/cm to $\sigma_{pcl}^{\max} = 10^{-5}$ S/cm with regard to the illumination intensity up to 2×10^4 lx (see Refs. 16 and 23 for the detailed conductivity curve). Before solving Eq. (1), considering that the capacitance can be negligible in low frequency ranges, the appropriate conductivity of the electrolytic media can be approximated without capacitance as Eq. (2),

$$\sigma_m \approx \left(\frac{t_m}{t_{pcl}} \right) \sqrt{\sigma_{pcl}^{\min} \sigma_{pcl}^{\max}}. \quad (2)$$

The thickness ratio of the OEFS device (t_m/t_{pcl}) is about 100 and the geometric mean conductivity of the photoconductive layer is 10^{-7} S/cm, which determines the appropriate conductivity of the electrolytic media as in the order of 10^{-5} S/cm. Molar concentration of a simple electrolytic solution such as a sodium chloride solution can be simply estimated, based on the molar conductivity (Λ) of each ion contained such as Na^+ , Cl^- , H^+ , and OH^- ; an appropriate molar concentration of the sodium chloride is around 10 mM.

C. Forces in the OEFS system and the critical radius of the particle separation

In the optoelectrofluidic configuration, F_{DEP} (Ref. 7) acts on particles in the electrical field gradients, where the velocity of particles can be determined by the Stokes drag,

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

where $f_{\text{CM}} = (\varepsilon_p^* - \varepsilon_m^*) / (\varepsilon_p^* + 2\varepsilon_m^*)$, $\varepsilon^* = \varepsilon - j\sigma/\omega$, ε_p^* is the permittivity of particle, a is the radius of particle, $\text{Re}[f_{\text{CM}}]$ is the real part of the Clausius–Mossotti (CM) factor, and E is the electric field strength,

$$U_{\text{DEP}} = \frac{a^3 \varepsilon_m}{3\eta} \text{Re}[f_{\text{CM}}] \nabla E^2, \quad (4)$$

where η is viscosity of the electrolytic media.

Particles having lower permittivity than water such as polystyrene beads are attracted to dark sides by negative DEP (nDEP), while some of biological particles such as yeast cells having higher permittivity than water could be attracted to bright sides by positive DEP, especially when the frequency is sufficiently high.

Besides, the nonuniform conductivity distribution over the photoconductive layer induces nonuniform charging of counterions in diffuse layer on the surface, which induces electric fields along the diffuse layer. Then, the surface charge is subjected to the tangential electric fields, producing a time-averaged flow and a hydrodynamic force, F_{ACEO} ,

$$U_{\text{slip}} = -\frac{\varepsilon_m}{2\eta} \langle E_t \zeta \rangle, \quad (5)$$

where E_t is the tangential electric fields, ζ is the zeta potential, and $\langle \rangle$ is the mathematical symbol for the time-averaging,

$$F_{\text{ACEO}} = -3\pi a \varepsilon_m \langle E_t \zeta \rangle. \quad (6)$$

When the polarity alternates under ac electric potentials, the polarity of the surface charge and the direction of the electric fields both alternate, producing consistent flow direction toward bright sides in the optoelectrofluidic systems. This electrohydrodynamic flow can be categorized as ACEO since it occurs on the electrode surface where ac electric potentials are applied.

In addition to the flows by ACEO, electrothermal flows²⁴ and natural convection could exist, where the direction of these flows is the same as that of ACEO, posing difficulties in experimentally separating contribution of these flows. Although experimental measurements would be needed for more complete verification, we exclude these flows based on the numerical analyses which confirm that these flows are negligible.

F_{ACEO} is proportional to particle size, while F_{DEP} is proportional to particle volume. Accordingly, the direction of the net force ($\vec{F}_{\text{net}} = \vec{F}_{\text{ACEO}} + \vec{F}_{\text{DEP}}$) is strongly dependent on the particle size. Given that F_{ACEO} and F_{DEP} are dominant in the OEFS system, the critical radius (a_c) can be found as Eq. (7), where the net force becomes zero. Larger particles than the critical radius will migrate toward dark sides and vice versa,

$$a_c = \sqrt{\left| \frac{-1.5 \langle E_t \zeta \rangle}{\text{Re}[f_{\text{CM}}] \nabla E^2} \right|}. \quad (7)$$

The critical radius is determined by the major three factors such as ζ , E_t , and ∇E^2 , where $\text{Re}[f_{\text{CM}}]$ is generally accepted as constant (≈ -0.5) for insulating beads in the low frequency regime (≤ 100 kHz).⁷ However, the CM factor cannot be simply approximated as a constant for diverse noninsulating particles such as biological ones, wherein the CM factor should be accurately assessed case by case. Equation (7) indicates that in addition to the intensity gradient of the

FIG. 2. A trend of the critical radius with regard to the frequency and the intensity gradient. (a) When the frequency is lowered, the F_{ACEO} becomes stronger, where F_{net} finds new balance (F_{net}') as the arrows direct. Thus, the critical radius increases as the frequency decreases. (b) When the intensity gradient is increased, both F_{ACEO} and F_{DEP} become stronger. In this case the new F_{net} found as the arrows indicate shows that the critical radius decreases. In the OEFS system, larger particles than the critical radius migrate to dark sides and vice versa. Thus, the changes of the critical radius should be clearly understood according to the control parameter such as the frequency and the amplitude of the ac electric fields and the intensity gradient of the illumination source.

illumination, control parameters such as the amplitude and the frequency (ω) of the applied ac electric potentials can change the critical radius.

First, in the OEFS system, appropriate amplitude of the ac electric potential is usually set as a constant during the particle manipulation. The amplitude, which directly affects ∇E^2 and E_r , is important in balancing F_{ACEO} and F_{DEP} . Appropriate amplitude is usually found according to the specific conditions, where the most effective particle separation is to be performed. Although these two forces become stronger, as the amplitude increases, the F_{DEP} is more affected by it compared with the F_{ACEO} .

Second, the frequency of the ac electric fields is an effective parameter on the critical radius since it can strongly affect ζ and E_r ; $\text{Re}[f_{CM}]$ should be also considered as one of the effective parameters for biological particles. Given that the frequency of the ac electric fields does not significantly affect ∇E^2 , the critical radius of insulating particles will increase by lowering the frequency (from 100 to 10 kHz) due to the increment of the time-averaged product of ζ and E_r , as shown in Fig. 2(a). This can be interpreted that F_{ACEO} becomes stronger as the frequency decreases while F_{DEP} is not significantly affected by the frequency for insulating particles. The effect of the frequency on the critical radius of biological particles is difficult to find simple rules due to the complex behavior of these particles.^{25,26}

Finally, the intensity gradient of the illumination is the major control parameter in the OEFS system, whose analyses are, however, somewhat complicated. In order to simplify the illumination control, the span of the LIG (λ_{LIG} , distance between adjacent brightest and darkest points of the LIG) is controlled, while the maximum and the minimum illumination intensities are not changed. When the illumination intensity is increased by reducing the λ_{LIG} , F_{DEP} become stronger than F_{ACEO} , although the two forces are all reinforced. Experimental measurements also showed that increasing intensity gradient reduces the critical radius, which is in good agreement with Fig. 2(b). Thus, according to the electrical properties and the size of particles the control parameters should be properly controlled for the effective field separation.

D. Levitation effects in the OEFS system

In the codirectional optoelectrofluidic configuration, the upside light illumination causing lens and shadow effects locally changes the illumination intensity underneath of particles. Translucent beads working like a lens focus bright spot on the center of the underneath region, while the boundary becomes darker. Because the transmittance is not 100%, additional shadowing effect will make the overall brightness of that region reduced. This bright and dark local illumination

FIG. 3. Levitation of particles by localized F_{DEP} . (a) Lens and shadow effects underneath the particle locally distort electric fields producing a localized F_{DEP} against gravity. (b) As the particle floats as high as the radius of the particle, gravity and F_{DEP} are balanced. Thus, the levitation height is limited to the order of the particle size. (c) Unlike the codirectional configuration, the electric fields around particles are not significantly distorted in the bidirectional configuration, where the light is illuminated from the downside. Thus, F_{DEP} is not enough to sufficiently levitate particles, where considerable reduction of the friction and the adhesion is difficult to occur.

distributions distort the electric fields near particles, causing localized F_{DEP} to push particles against gravity [Fig. 3(a)]. The numerical analyses show that local F_{DEP} is strong enough to overcome gravity, enabling particle to levitate. The DEP levitation force is strongest, when the particle sits on the surface. However it significantly languishes, when levitation height is approximately as high as the particle radius [Fig. 3(b)], where gravity and F_{DEP} become balanced. Thus, the levitation effect is only localized and does not allow particles to completely float away from the bottom surface. Without the lens and shadow effects like in the bidirectional optoelectrofluidic configuration, the localized F_{DEP} is not strong enough to overcome gravity, where the levitation effect is difficult to occur [Fig. 3(c)]. The levitation effect is an important factor in realizing OEFS with LIG strategy in that the attenuation of F_{DEP} can be largely compensated by reducing the friction and the energy barrier of the adhesion between the surface and particles.

III. RESULTS AND DISCUSSION

A. Application of LIG to the field separation of particles

Particle separation results using a vertical LIG pattern with bright center were compared with those using a simple bright and dark bar patterns in Fig. 4. The dark and bright bar patterns in Fig. 4(a), where F_{DEP} is limited near the electrodes, leave particles in the middle of the dark and the bright electrode patterns. This is because the F_{DEP} in the middle is insufficient to attract particles against the opposite F_{ACEO} . However, the LIG electrode pattern in Fig. 4(b) leaves no particles in the middle because consistent F_{DEP} is applied to the entire LIG illumination area, leaving no stagnation points in the region. Thus, the short-ranged F_{DEP} can become long-ranged.

The arbitrarily configurable virtual electrode patterns are not limited. The field separation of particles using circular LIG electrode patterns is shown in Fig. 5. When the circular LIG electrode pattern with the bright center was applied to the field containing small and large particles, field separation of particles was well shown that small particles concentrated at the center region, while large particles distributed along the perimeter [Fig. 5(a)]. When the opposite LIG circle was

FIG. 4. (a) Comparison of particle separation between bright and dark bar patterns and (b) LIG pattern with bright center; 820 nm and 16 μm particles were used. (a) When dark and bright bar patterns were applied, large particles moved to dark side in about 10 s. However, some particles were trapped in the middle, where the significantly reduced F_{DEP} could not overcome the steady flows by ACEO. Sufficient separation of small particles took about 92 s. Separation results were well demonstrated after removing the virtual electrode patterns. (b) The separation of big particles by DEP under LIG electrode patterns took slightly longer time compared with bar patterns. However, there left no particles in the middle, proving that the short-ranged F_{DEP} became long-ranged covering the entire LIG illumination area. In addition, the separation of small particles seemed to take less time and more amounts of particles were gathered. Thus, the overall separation performance of the LIG strategy is better than that of the bar pattern strategy. The repulsive d-d interaction limited to closely gather large particles by DEP.

applied to the field, the opposite separation clearly occurred [Fig. 5(b)]. These results prove that the long-ranged F_{DEP} effectively competes with F_{ACEO} over the entire illumination region under LIG illumination.

B. Field separation according to the frequency of the applied ac electric field

As expected in the analyses of forces in the optoelectrofluidic system, F_{ACEO} and F_{DEP} can be controlled by changing the frequency, the amplitude of the applied ac electric potential, and the intensity gradient of illumination. Appropriate values are chosen according to the properties of particles such as size and permittivity.

The frequency range was from 10 to 100 kHz, where frequencies lower than 10 kHz easily caused electrolysis under 20 V_{p.p.} ac potentials and those higher than 100 kHz were difficult to produce sufficient ACEO for separation. The effect of frequencies on F_{DEP} was negligible in this frequency range since the CM factor is almost a constant.^{7,23} As shown in Fig. 6, the field

FIG. 5. Separation of particles using two opposite circular LIG patterns; 820 nm and 16 μm particles were used. (a) Initially, bright center circular LIG pattern was applied to the field, where small and large particles were mixed. The separation of large particles by DEP to the dark perimeter took about 14 s, whereas small particles were more slowly separated to the bright center. (b) When the opposite LIG pattern was applied to the previously separated field, the opposite results clearly occurred. Similar times were taken to migrate particles to opposite places. The repulsive d-d interaction was also well shown for the large particles, limiting to closely gather large particles by DEP.

FIG. 6. Particle field separation according to the frequencies of 10, 50, and 100 kHz. Large particles gathered at the dark side were 16 μm in diameter, while small particles sizing from 820 nm to 8 μm were separated to the bright center. Migration of large particles was not considerably affected by the frequency, showing the variation of the CM factor in these frequency ranges is negligible. However, the migration of small particles was found to be largely affected by the frequency. The amount of separated small particles was significantly reduced, as the frequency was increased. It was also found that gathering large particles (5 and 8 μm) in the bright center by ACEO was increasingly limited presumably due to the repulsive d-d interaction.

separation results were consistent with the theory that the migration of large particle to the dark side was not considerably affected by the frequencies. On the contrary, as expected that ACEO is directly affected by the frequency, migration of small particles to the bright center was noticeably reduced as the frequency was increased from 10 to 100 kHz.

The d-d interaction between relatively larger particles was well shown. The d-d interaction is a short-ranged force and quickly decays to the radial direction ($\sim 1/r^4$). When particles are closely

		nDEP dominant (A-type particle)					
		G1	G2	G3	G4	G5	
		Size	1 μm	3 μm	5 μm	8 μm	16 μm
ACEO dominant (B-type particle)	0.82 nm	1:0.82
	1 μm	-	3:1
	3 μm	-	-
	5 μm	-	-	-
	8 μm		-	-	-

FIG. 7. Size combination matrix of the separable particle pairs in the OEFS system. The frequency was fixed at 10 kHz, while the intensity gradient of the LIG illumination was controlled to produce effective separation of each pair. The intensities of the brightest and the darkest parts were fixed, while the size of the LIG pattern was controlled for the variation of the LIG.

placed, the repulsive d-d interaction limits the minimum distance among particles. For large particles, especially bigger than 3 μm , the repulsive d-d interaction is considerable. As shown in Fig. 6, coarsely distributed particles at the bright center become evident, when particles of 5 and 8 μm in diameter are concentrated at the bright center.

In addition, the repulsive d-d interaction among relatively large particles (5 and 8 μm) at the bright center becomes apparently bigger, as the frequency increases from 10 to 100 kHz, degrading separation efficiency. Given that F_{DEP} is not affected by the frequency and the magnitude of the d-d interaction would not considerably change, the reduced F_{ACEO} at high frequencies can be attributed to the frequency dependence of the particle repulsion.

C. Performance of field separation by intensity gradient of the illumination

The OEFS system based on the two competing F_{ACEO} and F_{DEP} inherently has the size limitation of separable particles; in the OEFS system, F_{DEP} acting on particles smaller than a few micrometers significantly attenuates, whereas F_{ACEO} is still effective for submicron-sized particles. Thus, assessing the separable size limit is important in characterizing the OEFS system.

The size combination matrix in Fig. 7 visualizes the possible size combination of the separable particle pairs in the OEFS system. The field separation was controlled by the intensity gradient of the illumination with the constant frequency and amplitude: 10 kHz and 20 $V_{\text{p.p.}}$, respectively. The particle pairs with significant size differences such as particles of 16 and 1 μm (symbolized as 16:1 afterward) were easily separable. As the size difference became reduced,

separation became increasingly difficult. Although the size difference is the major factor determining the separation limit, the repulsive d-d interaction should be also considered. In the size combination matrix, pairs having small size difference are placed along the diagonal. Interestingly, among the difficult pairs having small size differences ($\sim 2\text{--}3\ \mu\text{m}$), the field separation was not equally difficult. Among these pairs, relatively small particle pairs such as 3:0.82 were more clearly separated than bigger pairs such as 5:3 and 8:5, although the size differences among these pairs were very similar. These were mainly caused by the repulsive d-d interaction, which poses difficulties in closely packing large particles. In addition, the repulsive d-d interaction degrades separation efficiency. The size combination matrix well demonstrates that the effect of the repulsive d-d interaction is not limited to particle pairs having small size differences, but it is universal throughout other pairs having large size differences, where particles bigger than $3\ \mu\text{m}$ are forced to the bright side by F_{ACEO} .

The separation result of 3:0.82 indicates that the minimum size of particles manipulated by the F_{DEP} in the OEFS system is smaller than $3\ \mu\text{m}$ and the F_{ACEO} effectively migrates submicron scale particles too. This is owing to the particle levitation effect in the OEFS system in that F_{DEP} and F_{ACEO} in the OEFS configuration are not significantly compromised by the conversion of F_{DEP} to the long-ranged force under LIG.

IV. CONCLUSIONS

The OEFS system introduced in this paper utilizes LIG electrode patterns to convert the short-ranged F_{DEP} to the long-ranged one, whereby the F_{DEP} can compete with the F_{ACEO} over the entire illumination area for realizing an effective field separation of particles. In addition, the application of the codirectional illumination strategy inducing the levitation effect provides solution for the attenuation of F_{DEP} under LIG illumination. Thus, the codirectional illumination of the LIG electrode patterns is the key feature of the OEFS system. In addition, most of optoelectronic techniques utilizing DEP would take advantage of the levitation effect by applying the codirectional illumination strategy to improve the sensitivity of the system or to extend the effective range of the DEP force.

Experimental investigation based on the developed OEFS system showed that microparticles ranging from $820\ \text{nm}$ to $16\ \mu\text{m}$ are well separable and manipulatable by controlling the frequency and the intensity gradient of the illumination.

Now that diverse photoconductive layers such as phototransistor-based ones having higher conductivity are within reach,²³ allowing researches to overcome the low conductivity limitation of the previous photoconductive layers based on the hydrogenated amorphous silicon. Combined with these diverse photoconductivity layers, the OEFS system with codirectional LIG strategy could be used in many applications, where a rapid manipulation of diverse particles over the entire working area is of interest. Furthermore, the arbitrarily configurable virtual electrode patterns will provide unlimited user-defined electrode patterns for highly adaptive particle manipulation strategies including separation, concentration, patterning, and harvest.

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- ¹ A. Ashkin, J. M. Dziedzic, J. E. Bjorkholm, and S. Chu, *Opt. Lett.* **11**, 288 (1986).
- ² M. P. MacDonald, L. Paterson, K. Volke-Sepulveda, J. Arlt, W. Sibbett, and K. Dholakia, *Science* **296**, 1101 (2002).
- ³ M. P. MacDonald, G. C. Spalding, and K. Dholakia, *Nature (London)* **426**, 421 (2003).
- ⁴ W. Hossack, E. Theofanidou, J. Crain, K. Heggarty, and M. Birch, *Opt. Express* **11**, 2053 (2003).
- ⁵ D. G. Grier, *Nature (London)* **424**, 810 (2003).
- ⁶ K. H. Kang, X. Xuan, Y. Kang, and D. Li, *J. Appl. Phys.* **99**, 064702 (2006).
- ⁷ K. H. Kang, Y. Kang, X. Xuan, and D. Li, *Electrophoresis* **27**, 694 (2006).
- ⁸ K. H. Kang and D. Li, *Langmuir* **22**, 1602 (2006).
- ⁹ N. Manaresi, A. Romani, G. Medoro, L. Altomare, A. Leonardi, M. Tartagni, and R. Guerrieri, *IEEE J. Solid-State Circuits* **38**, 2297 (2003).
- ¹⁰ M. Yamada and M. Seki, *Lab Chip* **5**, 1233 (2005).

- ¹¹E. T. Lagally, S.-H. Lee, and H. T. Soh, *Lab Chip* **5**, 1053 (2005).
- ¹²Y.-S. Lu, Y.-P. Huang, J. A. Yeh, and C. Lee, Proceedings of the Second Asian and Pacific Rim Symposium on Biophotonics, 2004, pp. 238–239.
- ¹³Y.-S. Lu, Y.-P. Huang, J. A. Yeh, C. Lee, and Y.-H. Chang, *Opt. Quantum Electron.* **37**, 1385 (2005).
- ¹⁴P. Y. Chiou, A. T. Ohta, and M. C. Wu, *Nature (London)* **436**, 370 (2005).
- ¹⁵W. Choi, S.-H. Kim, J. Jang, and J.-K. Park, *Microfluid. Nanofluid.* **3**, 217 (2007).
- ¹⁶H. Hwang, D.-H. Lee, W. Choi, and J.-K. Park, *Biomicrofluidics* **3**, 014103 (2009).
- ¹⁷A. González, A. Ramos, N. G. Green, A. Castellanos, and H. Morgan, *Phys. Rev. E* **61**, 4019 (2000).
- ¹⁸J. Wu, Y. Ben, D. Battigelli, and H.-C. Chang, *Ind. Eng. Chem. Res.* **44**, 2815 (2005).
- ¹⁹H. Hwang, J.-J. Kim, and J.-K. Park, *J. Phys. Chem. B* **112**, 9903 (2008).
- ²⁰P.-Y. Chiou, A. T. Ohta, A. Jamshidi, H.-Y. Hsu, and M. C. Wu, *J. Microelectromech. Syst.* **17**, 525 (2008).
- ²¹H. Hwang and J.-K. Park, *Lab Chip* **9**, 199 (2009).
- ²²K. V. I. S. Kaler and T. B. Jones, *Biophys. J.* **57**, 173 (1990).
- ²³H.-y. Hsu, A. T. Ohta, P.-Y. Chiou, A. Jamshidi, S. L. Neale, and M. C. Wu, *Lab Chip* **10**, 165 (2010).
- ²⁴H. Lee, S. Yun, S. H. Ko, and K. H. Kang, *Biomicrofluidics* **3**, 044113 (2009).
- ²⁵G. Fuhr and P. I. Kuzmin, *Biophys. J.* **50**, 789 (1986).
- ²⁶T. L. Mahaworasilpa, H. G. L. Costera, and E. P. George, *Biochim. Biophys. Acta* **1193**, 118 (1994).