On utilizing alternating current-flow field effect transistor for flexibly manipulating particles in microfluidics and nanofluidics

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By imposing a biased gate voltage to a center metal strip, arbitrary symmetry breaking in induced-charge electroosmotic flow occurs on the surface of this planar gate electrode, a phenomenon termed as AC-flow field effect transistor (AC-FFET). In this work, the potential of AC-FFET with a shiftable flow stagnation line to flexibly manipulate micro-nano particle samples *in both a static and continuous flow condition* is demonstrated via theoretical analysis and experimental validation. The effect of finite Debye length of induced double-layer and applied field frequency on the manipulating flexibility factor *for static condition* is investigated, which indicates AC-FFET turns out to be more effective for achieving a position-controllable concentrating of target nano-particle samples in nanofluidics compared to the previous trial in microfluidics. Besides, a continuous microfluidics-based particle concentrator/director is developed to deal with incoming analytes *in dynamic condition*, which exploits a design of tandem electrode configuration to consecutively flow focus and divert incoming particle samples to a desired downstream branch channel, as prerequisite for a following biochemical analysis. Our physical demonstrations with AC-FFET prove valuable for innovative designs of flexible electrokinetic frameworks, which can be conveniently integrated with other microfluidic or nanofluidic components into a complete lab-on-chip diagnostic platform due to a simple electrode structure. *Published by AIP Publishing.* [<http://dx.doi.org/10.1063/1.4949771>]

I. INTRODUCTION

Lab-on-chip technologies are in urgent requirement of developing new techniques that can deal with flexible manipulation of particle samples at the micrometer and nanometer dimension.^{1–11} Induced-charge electrokinetic phenomenon occurs as a background electric field $\mathbf{E}$ gives rise to an induced double-layer (IDL) of thickness λ_D on a polarizable solid surface and in turn, causes induced-charge electroosmotic (ICEO) flow by moving this diffuse screening cloud (Fig. 1).^{12–23} ICEO has been recently recognized as a promising way to drive active microfluidic mixing,^{24–28} pumping²⁹ as well as induced-charge electrophoretic motion or interaction between polarizable colloids.^{30–33} However, studies on utilizing ICEO to flexibly manipulate biological analytes and particles samples in microfluidic or nanofluidic channels have been rarely reported.³⁴

The concept of fixed-potential ICEO was first introduced by Squires and Bazant to generate symmetry breaking in ICEO.¹⁶ In fixed-potential ICEO, the voltage of a polarizable object is

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FIG. 1. We make use of a three electrode configuration to induce AC-FFET vortex of tunable flow profiles and a resulting shiftable FSL inside the chamber of L in width and H in height and achieve adjustable particle concentrating at desired locations on the metal strip of a in half width in a static flow condition. (a) A metal strip acting as gate electrode is deposited at the center of bottom wall and imposed with an AC voltage $A_2 \cos(\omega t)$, a background electric field of voltage difference $A_1 \cos(\omega t)$ is provided by a face-to-face 3D driving electrode pair embedded on both sidewalls of the chamber. (b) and (c) Basic physics for ICEO induced particle trapping on an unbiased center gate electrode: (b) On application of an AC voltage difference to the sidewall electrode pair, ions follow the direction of initial normal field vector to the surface of blocking metal strip; (c) after a characteristic RC charging time scale $\tau_{RC} = \frac{\epsilon a}{\sigma}$ reaching a steady state, an induced charged cloud of dipolar nature is formed against this blocking surface, which fully repels the bulk field lines, leaving only tangential field component that acts on the free ionic charge to induce ICEO vortex flow in the chamber. Particle samples suspended in the liquid medium are concentrated at the FSL of ICEO flow field located at the center of strip surface. (d) As the center gate electrode is imposed with a biased AC voltage amplitude, e.g., $\bar{V}_2 > \bar{V}_1/2$, AC-FFET vortex makes the colloid trapping center shift to the left side of electrode surface with a specific horizontal coordinate x_p .

controlled by an external AC voltage source, so as to induce total ionic charge in phase with the AC background field oscillating at the same field frequency. This effect is, in essence, an AC generalization of the DC-flow field effect transistor, a phenomenon also termed as “AC-flow field effect transistor” (AC-FFET), identical to the previous work of Van Der Wouden *et al.*³⁵ Sun *et al.* have recently developed a high-flux multifunctional ionic circuit platform,³⁶ on the basis of external ion concentration polarization due to electrical field applied across an ion-selective membrane, where a gate electrode located on top of the reservoir controls the direction and magnitude of the two imposed electric fields to result in flexible ion current rectification in the output microfluidic channel. So, the same mechanism appears to be work but with DC electrokinetics through a gating ion-selective nanoporous membrane that expands the polarized layer on the gate and induces ion concentration gradient.³⁶

With a biased gate voltage, a net pumping motion of the fluid flow by AC-FFET results if the polarizable object is held fixed, as theoretically predicted by Ramos.³⁷ Later, this idea was validated experimentally by Soni *et al.*³⁸ In their pioneering work, in order to achieve unidirectional flow of conductive biological fluids in microchannels, a second AC signal was applied to a planar gate electrode, with its magnitude different from the floating potential of polarizable surface.³⁸ They identified the mechanism underlying AC-FFET based pumping as a modulation of the induced zeta potential at the solid/electrolyte interface by imposing an arbitrarily biased gate voltage.

Prompted by the capability of AC-FFET in controlling the electrokinetic fluid flow behavior, in this work, we reinvestigated the phenomenon of AC-FFET for convection and diffusion of target analytes, and achieved flexible trapping of particle samples on the polarizable surface

of a metal strip electrode of half width a by using AC-FFET convective vortex of a shiftable flow stagnation line (FSL), in both a *static* and *continuous flow* conditions (Figs. 1(d) and 2).

Since the traditional thin double-layer approximation of ICEO breaks down as the thickness of IDL becomes large,^{39,40} we developed a general physical description of AC-FFET for finite Debye length in nondimensional form.⁴¹ The thin layer approximation simplifies the theoretical analysis of AC-FFET induced particle concentrating by assuming the liquid bulk electroneutral, since the induced free charge merely exists within a small region at the electrode/liquid interface.^{42–47} In this work, we extended the previous theoretical analysis in Ref. 48 and computed

FIG. 2. A 3D schematic diagram of the proposed microfluidic particle concentrator/director for dealing with incoming analytes in *dynamic condition*. The device exploits a tandem electrode design, where two groups of three parallel electrode configuration are placed in sequence from upstream to downstream of the mainchannel, with the yellow arrow indicating the direction of axial pressure-driven Poiseuille flow. Incoming particles are first flow focused into a thin colloid line at the end of concentrating electrode by ordinary transverse ICEO flow, and subsequently, the major stream moves into a desired one of the five downstream branch outlets due to the action of asymmetric AC-FFET vortex on the directing electrode. (a) when the potential of center directing electrode is not biased, i.e., $V_2 = V_1/2$, motion trajectory of most incoming particles is eventually diverted to the middle branch outlet C; (b) as potential of directing electrode is biased approaching the driving voltage, i.e., $V_2 \Rightarrow V_1$, most incoming particles move into branch A; (c) as voltage of directing electrode is biased slightly larger than its floating potential, i.e., $V_2 > V_1/2$, most incoming particles move into branch B; (d) as voltage of directing electrode is biased slightly smaller than its floating potential, i.e., $V_2 < V_1/2$, most incoming particles move into branch D; (e) as voltage of directing electrode is biased approaching the grounded state, i.e., $V_2 \Rightarrow 0$, most incoming particles move into branch E.

the manipulating sensitivity factor k of analytes caused by AC-FFET in the case of arbitrary thickness electric double layer, i.e., no strict restrictions are imposed on the specific values of λ_D/a . In practical experiments, finite values of λ_D/a are achievable in the case of submicron metal strip immersed in aqueous suspensions (the Debye length can reach $1\ \mu\text{m}$ for DI water) or with microelectrode strip but employing nonaqueous electrolytes.

For finite thickness IDL, we revealed that a shift of FSL towards either side of the electrode surface due to tunable symmetry breaking in total current density and electroosmotic flow pattern is responsible for the position-controllable concentrating of nanoparticle samples on a biased center gate electrode *in static condition* (Fig. 1). The *ideal trapping frequency* is around the reciprocal RC relaxation time but cannot be much higher than charge relaxation frequency of liquid bulk for finite Debye length. Interestingly, concentrating position of nanoparticle samples can be adjusted by AC-FFET with an improved flexibility k as the double-layer thickness approaches the electrode half width. This implies AC-FFET turns out to be more effective for manipulating and concentrating target nanoparticle samples in nanofluidics compared to the previous effort in microfluidics.

Though AC-FFET is flexible in particle manipulation, in most situations, a microfluidic device that is able to focus particle samples in a continuous fluid flow rather than a static condition is often of particular interest.^{49–51} By proposing a method of continuous particle concentrating and diverting, the potential of AC-FFET to flexibly guide incoming particle samples was witnessed *in dynamic condition* (Fig. 2). As compared to the prominent dielectrophoresis (DEP) flow focussing technique in microfluidics where DEP force arises from potential gradient and is short-range,^{10,52–55} since AC-FFET is electric convection phenomenon, the drag force of AC-FFET acting on incoming particle samples is long-range and is effective within the entire channel height. Consequently, the additional squeezing flow for DEP focussing is not required by AC-FFET technique, that is, our AC-FFET based concentrator needs merely single inlet for injection of particle samples, which simplifies the device design.

The device takes advantage of a tandem electrode configuration that consists of an unbiased center metal strip and a biased one placed in sequence from upstream to downstream of the mainchannel (Fig. 2), so that the incoming colloids are at first flow focused into a thin particle stream at the flow stagnation line (FSL) by conventional ICEO vortex on the concentrating electrode (the unbiased one), and trajectory of this major particle stream is subsequently diverted in a controllable manner to a desired one of the five branch channels by transverse AC-FFET vortex of tunable FSL on the directing electrode (the biased one), as shown in Fig. 2. So, we have herein developed a new active, electrokinetic microfluidic particle concentrator/director for sample pretreatment in micro-total-analysis systems.

II. METHOD

A. Theory of AC-FFET

Please refer to the supplementary material for both nondimensional finite Debye length (FDL) model and slip model of AC-FFET.⁴¹

B. Numerical simulation

We use a commercial software package, Comsol Multiphysics 5.0 that implements finite element analysis, to solve all the governing equations.

For calculating with the FDL theory, Equations (S16) and (S17) subjected to boundary condition (BC), Eqs. (S18a)–(S18d) are solved in a *coupled* manner. Once we get the solution to the free charge and electrostatic potential, Eq. (S21) subjected to BC, Eq. (S22) is solved in a *segregated* manner to obtain the flow field from ICEO. The minimum mesh size should attain as small as $\bar{\lambda}_D/50$ on the surface of gate electrode, in order to resolve the exponential decay of bipolar counter-ionic charge within the diffuse double-layer with distance from the ideally polarizable surface.

For computing with the slip model that assumes $\bar{\lambda} = 1$, Eqs. (S23)–(S25) are solved in a *segregated* manner. Eq. (S23) subjected to Eq. (S26) determines the electrostatic potential in the bulk. Then, the slip velocity Eq. (S27) is estimated on the surface of metal strip and inserted as a BC into the nondimensional Navier-Stokes equation (Eqs. (S24) and (S25)). The best mesh quality is guaranteed at the electrode corner where the minimum mesh size reaches 0.01. Tetrahedral mesh is preferred due to their high stability in 3D modeling.

On obtaining the vortex flow pattern of ICEO, either Eq. (S35) for analyte concentration or Eq. (S36) for particle motion trajectory due to the combined action of ICEO flow and buoyancy force is solved, as determined by whether the colloid diameter is below or above 1 μm . Values of various material properties for simulation are listed in Table I.

III. RESULTS AND DISCUSSION

A. ICEO induced particle concentrating in static condition

1. Frequency-dependence study

We first demonstrate theoretically that *in static condition*, nano-colloids can be trapped at the center of the blocking surface by ICEO vortex flow on application of an AC voltage signal to the sidewall driving electrode pair, while the metal strip deposited at the bottom wall floats in potential (Fig. 3). We use the FDL model to analyze this problem, the simulation parameters involved are $\bar{\lambda}_D = 0.01$, $\bar{L} = 5$, $\bar{H} = 2.5$, $\bar{V}_1 = 4$, $a = 10 \mu\text{m}$. Colloidal silica nanospheres of radius $R = 500 \text{ nm}$ and mass density $\rho_p = 2200 \text{ kg/m}^3$ suspended in aqueous solutions of $\rho_f = 1000 \text{ kg/m}^3$ are considered in current analysis. Such a parametric combination results in a nondimensional buoyancy velocity $\bar{\mathbf{u}}_b = -0.023\mathbf{e}_z$ and diffusivity $\bar{D}_p = 0.0015$.

For nanoparticle samples and an AC background field, both electrophoresis (EP) and dielectrophoresis (DEP) of analytes can be disregarded in current analysis. In stark contrast to the unidirectional EP motion in DC, the oscillating electrophoresis in AC has sufficiently small amplitude and can hence be overlooked. Unlike EP, DEP has a non-zero time average and leads to net particle displacement in AC. Even so, *particle dielectrophoretic velocity* is proportional to the *squared particle radius* and also depends on the *field gradient*. In this specific configuration, however, the small size of nanoparticle samples and uniform field distribution outside the double-layer (Fig. 4(a)) result in a negligibly small DEP force in front of ICEO flow.

Before making calculations, it is important to quantify the time required to establish the induced spatial charge, which is given by the characteristic RC time scale for thin IDL, where the liquid bulk resistance R is coupled to the diffuse-layer capacitance C on the ideally polarizable metal surface that is blocking of ionic species. This results in the nondimensional RC charging frequency $\bar{\omega}_{RC} = \bar{\lambda}_D$ derivable from the transformation relation $\omega_{RC} = \frac{\sigma \lambda_D}{\epsilon a} = \bar{\omega}_{RC} \frac{\sigma}{\epsilon}$. For finite thickness electrical double layer, this characteristic frequency grows to the reciprocal

TABLE I. Material properties used in numerical simulation.

Parameter	Value
Ionic diffusivity (D)	$2 \times 10^{-9} \text{ m}^2/\text{s}$
Liquid permittivity (ϵ)	$7.08 \times 10^{-10} \text{ F/m}$
Liquid conductivity (σ)	0.001 S/m for dynamic experiment
Liquid dynamic viscosity (η)	0.001 Pa-s
Liquid mass density (ρ_f)	1000 kg/m^3
Double-layer thickness ($\lambda = \sqrt{D\epsilon/\sigma}$)	37.6 nm for dynamic experiment
Particle mass density (ρ_p)	2200 kg/m^3
Particle radius (R)	500 nm/2 μm for static/dynamic condition
Thermal diffusivity of particles ($D_p = \frac{R_0 T}{6\pi\eta R N_a}$)	$4.3 \times 10^{-13} \text{ m}^2/\text{s}$ for static condition; negligibly small for dynamic condition
Ambient temperature (T)	293.15 K

FIG. 3. Silica nano-colloids are trapped at the center of ion-blocking metal strip surface with finite Debye length $\bar{\lambda}_D = 0.01$ by ICEO vortex flow in *static condition*. A surface plot of steady-state distribution of nondimensional particle concentration and an arrow plot of time-averaged ICEO flow field at different nondimensional angular field frequencies: (a) $\bar{\omega} = 0$; (b) $\bar{\omega} = \bar{\lambda}_D$; (c) $\bar{\omega} = 3\bar{\lambda}_D$; (d) $\bar{\omega} = 5\bar{\lambda}_D$; (e) $\bar{\omega} = 10\bar{\lambda}_D$; and (f) $\bar{\omega} = 50\bar{\lambda}_D$.

FIG. 4. Numerical prediction on electrode polarization and charge relaxation character in the liquid for finite thickness double-layer $\bar{\lambda}_D = 0.01$. (a) and (b) A surface plot of nondimensional free charge and arrow plot of electric field lines on the blocking electrode at different field frequencies: (a) $\bar{\omega} = 0$ for the low-frequency limit; (b) $\bar{\omega} = 1$ for the high-frequency limit where the induced charge almost vanishes. (c) and (d) A surface plot of nondimensional field intensity

$$|\bar{E}| = \sqrt{\left(\frac{\partial \bar{\phi}}{\partial x}\right)^2 + \left(\frac{\partial \bar{\phi}}{\partial y}\right)^2} \text{ with } |E| = \frac{k_B T}{e a} |\bar{E}| \text{ at distinct field frequencies: (c) } \bar{\omega} = 0; \text{ (d) } \bar{\omega} = 1.$$

charge relaxation time of liquid suspension for bulk ionic screening, $\bar{\omega}_{RC} = 1$. In fact, the characteristic IDL charging frequency cannot far exceed this, since the dielectric limit approached beyond $\omega = \frac{\sigma}{\epsilon}$ and no spatial free charge would be induced in the liquid.

A series of numerical simulations are then conducted to study the temporal-spatial distribution of particle concentration under the combined action of ICEO vortex flow, colloid gravity, and Brownian motion. The steady-state concentration distribution at $\bar{t} \geq 1000$ for distinct field frequencies, that are integer multiples of $\bar{\omega}_{RC} = \bar{\lambda}_D = 0.01$, is shown in Fig. 3.

At $\bar{\omega} = 0$ and $\bar{\omega} = \bar{\lambda}_D$ (Figs. 3(a) and 3(b)), although the colloids are collected into a thin line pattern (understandable from Fig. 2(a) observing in the x-y plane) on the blocking metal strip due to the action of a symmetric ICEO vortex flow, the concentrating efficiency is not ideal at all. Lots of particles are quite uniformly distributed within a large circular region on top of the blocking surface, in that a linear ICEO slip profile within thin layer approximation induces a strong upward fluidic drag.⁴⁸

With frequency to $\bar{\omega} = 3\bar{\lambda}_D$, the ICEO flow velocity decreases due to a charge relaxation process, giving it a chance for the downward buoyancy force to effectively counteract the upward ICEO flow component, hence more stable particle trapping takes place on the gate electrode with the maximum concentration attaining 139 (Fig. 3(c)) as compared to a much lower concentrating performance at lower frequencies (Figs. 3(a) and 3(b)). In the meantime, the aggregation pattern of nano-colloid widens slightly, since the transverse ICEO convective flow acting as the main driving force for particle trapping decays and exhibits a nonlinear slip profile above the electrode surface.⁴⁸

On increasing frequency to $\bar{\omega} = 5\bar{\lambda}_D$, the span of collection pattern further extends, while the trapping performance enhances with a maximum concentration reaching to 290, due to a complicated interplay among the ICEO flow field of an elaborate nonlinear slip profile, downward buoyancy force and thermal diffusion (Fig. 3(d)).

As field frequency increases up to $\bar{\omega} = 10\bar{\lambda}_D$, ICEO diminishes rapidly due to a paucity in electrode polarization, resulting in a severe degradation of particle trapping performance in terms of a widened collection pattern and decreased concentration value (Fig. 3(e)) compared to that at $\bar{\omega} = 5\bar{\lambda}_D$ (Fig. 3(d)). At $\bar{\omega} = 50\bar{\lambda}_D$ approaching the reciprocal charge relaxation time of electrolyte bulk, the onset of bulk ionic screening makes sedimentation effect the dominating factor for $\bar{\lambda}_D = 0.01$, so that particle concentrating process would no longer take place effectively (Fig. 3(f)).

On the basis of above analysis, for obtaining a fine pattern of particle collection as well as attaining a high concentrating performance, we prefer to use three times the RC charging frequency $\bar{\omega} = 3\bar{\lambda}_D$ to actuate the ICEO flow and achieve efficient particle trapping. In other words, given a specific electrode configuration, an arbitrary double-layer thickness, and an AC voltage amplitude, there is an *ideal trapping frequency* of particle samples for ICEO convective flow above the blocking electrode, if considering the requirement of vertical force equilibrium $\bar{u}_z + \bar{u}_b = 0$ at the colloid trapping center and a sufficient driving force $\bar{u}_x$ along the horizontal direction at the same time.

2. Charge relaxation in the liquid for finite Debye length

The induced ionic charge and electric field are shown in Fig. 4 as potential of the center metal strip is unbiased. In DC limit, the dipolar free charge $\rho = -\epsilon \nabla^2 \phi$ of scale $|\bar{\rho}| = |\frac{\bar{V}_T \bar{x}}{L}| \leq 0.8$ accumulated in the diffuse double-layer screens the bipolar free surface charge $\sigma_f = -\epsilon \frac{\partial \phi}{\partial n}$ of counter polarity induced at the metal surface (Fig. 1(c)), which makes the blocking strip behave as an insulator beyond the distance scale of $10 \bar{\lambda}_D$ (Fig. 4(a)). Fluid flow is then induced, but with zero net horizontal flow component, resulting in particle trapping at the center of strip surface (Figs. 3(a)–3(d)).

At frequency much higher than $\bar{\omega}_{RC}$, the diffuse screening cloud shrinks due to charge relaxation, leaving only a bit of spatial charge in the vicinity of corner field singularity, so that the metal strip recovers to inherent role of an ideal conductor with the induced surface charge

dominating (Fig. 4(b)). Consequently, ICEO decays thoroughly and is no longer able to efficiently transport the particle samples to the central trapping region (Figs. 3(e) and 3(f)).

There is strong normal field intensity within the double-layer at low field frequencies, the average scale of which is given by $|\bar{E}_{ave}| = |\frac{\bar{V}_1 \bar{x}}{L \bar{\lambda}_D}| \leq 80$ within thin IDL approximation due to occurrence of complete ionic charge screening. Though both of them are on the same order of magnitude, $|\bar{E}_{ave}|$ is slightly smaller than the maximum field strength predicted with the FDL model (133 in Fig. 4(c)), since the corner field singularity around the electrode edge within the diffuse double-layer can be fully captured by FDL approach, while the slip model merely presents the average value.

With increasing frequency to the inverse charge relaxation time of the bulk $\bar{\omega} = 1$, however, charge relaxation in the liquid makes negligibly small field intensity distributed along the electrode surface inside the IDL, and there is only an evident field source at the electrode corner (Fig. 4(d)), which agrees qualitatively with the numerical prediction on volumetric charge distribution in Fig. 4(b).

B. AC-FFET induced flexible particle concentrating in static condition

1. Shifting the particle trapping center on a biased center gate electrode

The above analysis is focused on the situation with an unbiased center gate electrode, where the electrode polarization is symmetric and free ionic charge in the liquid is strictly dipolar, resulting in the FSL constantly fixed at the center of blocking electrode surface. We then impose a second AC voltage to the gate electrode, so as to make the charge distribution not exactly dipolar and therefore generate controllable symmetry breaking in vortex pattern of ICEO convection, inducing AC-FFET streaming flow. Simulation parameters keep the same with Section III A, and the *ideal trapping frequency* $\bar{\omega} = 3\bar{\lambda}_D$ as found previously is used in this section for studying position-controllable particle concentrating on a biased center gate electrode (Fig. 5).

For $\bar{V}_2 = \bar{V}_1/2 = 2$, symmetric ICEO vortex flow originated from the dipolar ionic charge within double-layer of arbitrary thickness makes particles trapped at the center of blocking electrode (Fig. 5(e)). For $\bar{V}_2 > \bar{V}_1/2$, however, left-right symmetry in field intensity is broken, which induces more intense total current density $\mathbf{J}_{total} = \sigma \mathbf{E} + \frac{\partial \mathbf{E}}{\partial t} - D \nabla \rho$ in the right inter-electrode gap, resulting in a more dominating ICEO vortex on the right side of electrode surface (Figs. 5(a) and 5(c)). As a consequence, FSL where particles are stably trapped shifts to the left side, as shown in Figs. 5(a) and 5(c). And vice versa, for $\bar{V}_2 < \bar{V}_1/2$, particle concentrating center shifts to the right side due to the dominating counterclockwise whirlpool on the left side, as shown in Figs. 5(b) and 5(d). So, once the gate voltage amplitude deviates from the natural floating potential $\bar{V}_2 \neq \bar{V}_1/2$, arbitrary symmetry breaking in the ICEO flow pattern and particle trapping position can be induced by adjusting the specific voltage deviation $\frac{\Delta \bar{V}_2}{\bar{V}_1}$, which is multiplied by the manipulating flexibility factor k to finally decide the specific concentrating location $\bar{x}_p = k \frac{\Delta \bar{V}_2}{\bar{V}_1}$ (Fig. 1(d)).

2. The concept of linear manipulating sensitivity

In Fig. 5(f), the simulation result of $\bar{x}_p$ as a function of the gate voltage follows flawlessly a linear variation trend, namely, $\bar{x}_p = k \frac{\Delta \bar{V}_2}{\bar{V}_1}$ with k being a constant slope for $\bar{\lambda}_D = 0.01$ and $\bar{\omega} = 3\bar{\lambda}_D$, so that the definition of linear manipulating sensitivity k in Eq. (S30) may be appropriate. We then prove how general this phenomenon is.

From Fig. S2 and Table S1,⁴¹ the nondimensional particle trapping position $\bar{x}_p$ and biased gate voltage $\frac{\Delta \bar{V}_2}{\bar{V}_1}$ show a linear relation with different values of slope k at three characteristic field frequencies $\bar{\omega} = 0, \bar{\lambda}_D$, and $5\bar{\lambda}_D$ for various Debye length $10^{-4} \leq \bar{\lambda}_D \leq 10$, which indicates introducing the concept of linear sensitivity is indeed justifiable from a physical perspective, since the slope k , that is the ratio of $\bar{x}_p$ to $\frac{\Delta \bar{V}_2}{\bar{V}_1}$, keeps constant for arbitrary double-layer thickness $\bar{\lambda}_D$ and fixed field frequency $\bar{\omega}$. As a consequence, the linear manipulating sensitivity k is

FIG. 5. For electrical double layer of finite thickness $\bar{\lambda}_D = 0.01$, silica nano-colloids can be trapped by AC-FFET at an arbitrary position on the surface of a blocking gate electrode imposed with an AC voltage of biased amplitude $\bar{V}_2$ and fixed field frequency $\bar{\omega} = 3\bar{\lambda}_D$. Nanoparticles are trapped at: (a) $\bar{x} = -0.417$ (the left side of electrode surface) for $\bar{V}_2 = 2.8$; (b) $\bar{x} = 0.417$ (right side) for $\bar{V}_2 = 1.2$; (c) $\bar{x} = -0.202$ (left side) for $\bar{V}_2 = 2.4$; (d) $\bar{x} = 0.202$ (right side) for $\bar{V}_2 = 1.6$; (e) $\bar{x} = 0$ (center) for $\bar{V}_2 = 2 = \bar{V}_1/2$. (f) Horizontal position of particle trapping center $\bar{x}_p$ as a function of the biased voltage $\frac{\Delta V_2}{V_1}$, together with the linear fitting data of slope $k = \partial \bar{x}_p / \partial (\Delta V_2/V_1) = -0.417L$.

a good indicator for evaluating the flexibility degree in adjusting the concentrating location of particle samples on the blocking electrode by AC-FFET.

3. Effect of finite Debye length on manipulating flexibility of AC-FFET

As shown in Fig. 6, the linear manipulating sensitivity k is a function of both double-layer thickness and applied field frequency. Though ICEO flow velocity decreases as $\bar{\omega}$ increases from 0 to $5\bar{\lambda}_D$ due to ionic charge relaxation in the liquid, or as the Debye length becomes

FIG. 6. Effect of double-layer thickness $\bar{\lambda}_D$ on manipulating sensitivity factor k of AC-FFET at three distinct field frequencies $\bar{\omega} = 0, \bar{\lambda}_D$ and $5\bar{\lambda}_D$.

larger, we concern the sensitivity factor k most, since the kinetic energy can be enhanced by just raising the background field intensity.

To exactly calculate the value of k , the height of particle concentrating location has to be confirmed. For $\bar{\lambda}_D \leq 0.1$, we find the height of particles trapping center is in the order of $z = \bar{\lambda}_D$. For $0.1 \leq \bar{\lambda}_D \leq 10$, however, though the charged region and vortex flow extend far into the bulk, FSL is still close to the electrode surface, with a distance in the order of $z = 0.1$ (results not shown).

For various Debye length, the normalized sensitivity $-k/\bar{L}$ is a decreasing function of field frequency. For thin layer approximation $\bar{\lambda}_D \leq 10^{-4}$, the normalized sensitivity is largest and equals 1 in DC limit where the ICEO flow is also maximized, in good accordance with the analytical solution Eq. (S29),⁴¹ and decreases to 0.423 with increasing frequency to $\bar{\omega} = 5 \bar{\lambda}_D$. Beyond the thin double-layer limit, $-k/\bar{L}$ increases monotonously with increasing $\bar{\lambda}_D$ from 0.01 to 10 at the intermediate frequency $\bar{\omega} = \bar{\lambda}_D$. At $\bar{\omega} = 0$ and $5\bar{\lambda}_D$, the overall variation trend of $-k/\bar{L}$ still keeps growing with finite Debye length, though there are some local fluctuations (Fig. 6).

The normalized sensitivity reaches a plateau of 2 at $\bar{\lambda}_D = 10$ for both DC limit and $\bar{\omega} = \bar{\lambda}_D$, and $-k/\bar{L} = 1.654$ for $\bar{\omega} = 5 \bar{\lambda}_D$. That is, the normalized sensitivity at different frequencies not only increases but also further approaches one other as well with expanding nondimensional double-layer thickness.

Consequently, as the Debye length of IDL λ_D becomes comparable with the electrode half width a , the concentrating position of particle samples can be tuned with a much higher flexibility by AC-FFET. This suggests us that it is more superior to use submicron or even nanometer sized metal strip of a slight gate voltage deviation to trap nanoparticle samples on its blocking surface in nanofluidics compared to the previous trial in microfluidics.

C. A continuous microfluidic particle concentrator/director for handling incoming analytes in dynamic condition

1. Overview of the tandem electrode configuration

In this section, we develop a design of tandem electrode configuration to flexibly concentrate and direct incoming colloidal streams in a *continuous fluid flow* (Fig. 2). In this microfluidic device, two sets of three parallel electrode configuration are placed in series in the main-channel of height $H = 100 \mu\text{m}$ ($\bar{H} = 1.66$) bifurcating into five downstream branch channels (Fig. 2). The six branch channels are linked to six respective reservoirs-the inlet and five outlets A–E (Fig. 8(a)). The reservoirs are all 6 mm in height and 3 mm in radius, leading to a volumetric capacity of approximately $170 \mu\text{l}$. Under such capacity, steady axial flow can be driven for about 20 min inside the main channel by the liquid level difference.

Specifically, for each electrode group, a driving electrode pair of planar metal strip with nondimensional width $\bar{W}_e = 0.5$ is arranged at the bottom wall of the mainchannel. 2D coplanar electrodes rather than 3D sidewall electrodes were chosen here for fabrication convenience. Besides, in the inter-electrode gap area with a nondimensional span $\bar{G} = 3.66$, a center gate electrode of half width $a = 60 \mu\text{m}$ is disposed along the longitudinal direction of mainchannel. The length of all the metal strip electrodes is $\bar{L} = 66.66$, and the nearest spacing between the two groups of electrode is $\bar{G}_2 = \bar{G} = 3.66$ as well.

KCl electrolyte of conductivity $\sigma = 0.001 \text{ S/m}$ suspended with colloidal silica microspheres of radius in $2 \mu\text{m}$ was injected through the channel by using a microsyringe, resulting in a double-layer thickness $\lambda_D = 37.6 \text{ nm}$ ($\bar{\lambda}_D = 0.000627$). AC voltage difference of amplitude $V_1 = 2.5 \text{ V}$ ($\bar{V}_1 = 100$) and field frequency $f = 100 \text{ Hz}$ ($\bar{\omega} = 0.000445$) slightly below the inverse RC relaxation time ($\bar{\omega} < \bar{\lambda}_D$) was applied to the two pairs of driving electrode (Fig. 2), leading to nondimensional buoyancy velocity $\bar{u}_b = -0.0019$ and thermal diffusivity $\bar{D}_p = 3.2 \times 10^{-7}$. The pressure difference between the inlet and five different outlets induces a steady convective flow along the longitudinal direction with an approximate inlet flow velocity $u_{in} = 200 \mu\text{m/s}$ ($\bar{u}_{in} = 0.0364$), which transports the incoming colloidal silica microspheres from the upstream inlet to the five downstream branch channels.

As for the two center metal strip electrodes, the one positioned near the inlet floats in potential (floating electrode), i.e., $\overline{V}_2 = \overline{V}_1/2 = 50$, while the other adjacent to the five outlets is imposed with an AC voltage of arbitrary amplitude $0 \leq \overline{V}_2 \leq 100$ and the same field frequency $f = 100$ Hz (gate electrode), as shown in Fig. 2. Transverse ICEO vortex of symmetric flow profile is hence induced in the x-z plane above the surface of floating electrode with unbiased gate voltage and gives rise to continuous-flow focusing of incoming particles with finite gravity. Therefore, a thin colloid stream is formed at the end of the floating electrode by ICEO convection, which is then transported downstream by the incoming Poiseuille flow, and experiences transverse AC-FFET vortex of adjustable flow profile induced on the gate electrode by varying the specific gate voltage amplitude $\overline{V}_2$, resulting in an effective diversion of the trajectory of the major particle line to any one of the five downstream branch channels.

So, the core idea of such a series connection design for the two center metal strips is crystal clear. At first, the floating electrode with symmetric ICEO flow field achieves a flow focus process of the incoming particle samples and acts as an efficient particle concentrator. Subsequently, the gate electrode with AC-FFET vortex of tunable flow profile makes the thin particle stream formed move into a desired downstream outlet and acts as the role of a microfluidic particle director. For such, this device design is in fact a continuous microfluidics-based particle *concentrator/director*. And we named the floating and gate electrode as the concentrating and directing electrode, respectively, due to their unique contribution to the device function (Fig. 2).

2. Chip fabrication

Fabrication process of the microfluidic particle concentrator/director on the whole consists of three steps: ITO electrodes patterning, SU8 mold fabrication, and PDMS channel polymerization, as well as alignment and bonding.

First, we employ transparent thin-film ITO as the metal electrode material for clear observation of particle behaviors in the channel, and the two groups of electrode and ITO leads for external wire connection were patterned in one step by corroding the ITO material coated on a glass substrate. Glass slides coated with a conducting ITO film (6.5–6.8 Ω sheet resistance, 220 ± 30 nm thick ITO film, 80% in transmittance) are purchased from Kaivo Optoelectronic Technology (Zhuhai, China). The ITO substrate is washed with ethanol and acetone two times, rinsed with DI water, and dried at 100°C for 20 min (Fig. 7(a)). Positive AZ4620 photoresist was first spin-coated onto the ITO thin film (Fig. 7(b)), followed by soft bake at 100°C for 9 min. AZ resist film was then exposed to UV light under a 3500-dpi photo mask of the desired electrode geometry (Fig. 7(c)), followed by post-exposure bake at 110°C for 9 min. After the hard bake, a resist layer is obtained (Fig. 7(d)) by developing the photoresist in the special AZ developer solution. Subsequently, we submerge the glass slide with patterned resist layer in 60% volume fraction HCL aqueous solution for 30 min to chemically etch off the ITO material in direct contact with the solvent. Then, the remaining photoresist is removed with acetone (Fig. 7(e)).

Second, PDMS channel of 100 μm in height was fabricated using the standard soft-lithographic technique, with SU8 photoresist pattern (SU8–2050) as the mold. To ensure the desired geometrical features and height of the microfluidic channels, fabrication of SU-8 mold is a key step. Negative SU8–2050 photoresist was first spin-coated onto a silicon wafer, with 500 rpm for 10 s at the first stage and 1500 rpm for 30 s at the second stage, yielding a uniform thickness of 100 μm , followed by an eight-step soft bake (60°C for 10 min, 65°C for 10 min, 70°C for 10 min, 75°C for 10 min, 80°C for 10 min, 85°C for 10 min, 90°C for 10 min, and 95°C for 1 h) to evaporate the resist solvent and densify the film. Next, the SU8 photoresist film was exposed to UV light under a 3500-dpi mask of desired channel geometry (Fig. 7(f)), followed by 20-min relaxation and then eight-step post-exposure hard bake (60°C for 5 min, 65°C for 5 min, 70°C for 5 min, 75°C for 5 min, 80°C for 5 min, 85°C for 5 min, 90°C for 5 min, and 95°C for 30 min). The photoresist was then developed for 10 min, forming the expected SU8 mold of correct channel pattern for PDMS polymerization (Figs. 7(g)–7(i)). The mold was positioned in a culture dish and covered with the PDMS mixture of prepolymer and

FIG. 7. Fabrication process of the microdevice: (a) the ITO thin film-coated glass slide cleaned; (b) the positive AZ4620 photoresist spin-coated on the sample wafer; (c) UV light exposure; (d) Development; (e) chemical etching of ITO material; (f) and (g) SU8 resist layer patterned; (h) PDMS channel polymerized with SU8 resist pattern as a mold; (i) PDMS structure stripped off; (j) alignment and bonding of PDMS channel and ITO substrate.

curing agent with a mass ratio of 10:1. The liquid PDMS was then cured in the vacuum chamber at 70 °C for 2 h. Once cured, PDMS with the channel portion was cut out and six holes of 6 mm in diameter were punched in predesigned areas to serve as the one-inlet or five-outlets fluid reservoirs, as shown in Fig. 8(a).

FIG. 8. (a) A photograph of the continuous microfluidic particle concentrator/director. (b)-(d) Fabricated ITO electrode strips at different positions of the device channel: (b) at the upstream inlet, (c) around the gap between the concentrating and directing electrode, (d) at the mainchannel/branch outlets junction. The distinct outlet channel geometry appearing in (d) is made unintentionally due to microfabrication inaccuracy at the sharp corners between adjacent branches, and is found to exert no substantial influence on the specific device function.

At last, PDMS channel and glass slide with the pattern of metal strip electrodes were aligned with great care under an optical microscope and then bonded together in a reversible manner by using oxygen plasma treatment (Fig. 7(j)). The microfluidic device for switchable particle concentrating *in dynamic condition* is shown in Fig. 8(a), and the fabricated ITO electrode strips are shown in Figs. 8(b)–8(d).

3. Experimental method

A commercial multi-phase function generator (TGA12104, TTI, UK) was employed to produce sinusoidal AC voltage signals $V_1 \cos(\omega t)$ and $V_2 \cos(\omega t)$, which were imposed to the driving electrode pair and the directing electrode via ITO leads, respectively (Fig. 2). Here, $V_1 = 2.5$ V, $0 \leq V_2 \leq 2.5$ V and $f = 100$ Hz, as stated previously. Waveform of all the applied voltages was monitored in real time by a digital oscilloscope (TDS2024, Tektronix).

After introducing the colloidal suspension into the mainchannel and switching on the AC voltages required for flexible particle manipulation, we observed the movement of silica particles of $4 \mu\text{m}$ in diameter under an optical microscope (BX53, Olympus). In the meantime, a high-speed CCD camera (RETIGA2000R, Qimaging) was utilized to record consecutive frame images of the experimental observations.

4. Numerical prediction of the device function

Since the nondimensional Debye length $\bar{\lambda}_D = 0.000627$ is much smaller than 1, it is reasonable to calculate ICEO flow field using the thin layer approximation. Besides, considering a negligibly small particle diffusivity, we make use of the kinematic equation Eq. (S36) to keep track of the transient particle motion trajectory.⁴¹

a. Continuously concentrating and directing particles into the middle branch. To capture correctly the dynamic behavior of incoming colloids during the trajectory simulation, 72 ideal point particles are released with zero initial velocity from the inlet plane where they distribute uniformly. According to Eq. (S36),⁴¹ as they are transported forward by the axial Poiseuille flow, particles are simultaneously swept to the centerline of the concentrating electrode positioned on the bottom wall by the unbiased electroosmotic vortex. Besides, the downward buoyancy force also plays an important part in maintaining a vertical force balance at the trapping region on the floating electrode. As a result, the incoming wide colloid stream becomes thinner and thinner as particles go downstream (Fig. 9(a)), and effectively squeezes into a fine line pattern at the end of the first strip (Fig. 9(c)). Since the gate voltage is unbiased as well ($\bar{V}_2 = \bar{V}_1 / 2 = 50$), the thin particle line keeps moving straight forward with the axial Poiseuille flow on the directing electrode, with its trajectory not yet perturbed by the symmetric ICEO vortex (Fig. 12(c)). Eventually, this major thin colloid line consisting of 50 particles moves into the middle branch outlet C, as shown in Figs. 12(c) and 2(a).

By imposing similar BCs with Eqs. (S26) and (S27) on the driving electrode pair,⁴¹ we take into account electrode polarization and electroosmotic convection there as well. While the major colloid line passes by both the center strips (Fig. 9(c)), AC electroosmotic (ACEO) vortex induces a similar flow focusing process of incoming particles on the driving electrodes (Fig. 9(a)), so that there is an additional thin particle line consisting of 11 particles in the vicinity of each side-wall sailing downstream along the driving electrodes (Fig. 9(c)). The two minor particle streams focused by ACEO eventually move into branch A and E, respectively, exerting an adverse influence on continuous particle concentrating into a desired branch (Fig. 12(c)).

b. Continuously concentrating and directing particles into a side branch. As discussed in Section III C 1, the original purpose of arranging the directing electrode is to deviate the trajectory of thin colloid stream formed at the end of concentrating electrode from the centerline, leading to an effective particle director. However, to generate controllable symmetry breaking in ICEO vortex or to actuate AC-FFET flow on the directing electrode, it has to be imposed

FIG. 9. As both center metal strips including the concentrating and directing electrode float in potential, i.e., $\overline{V}_2 = \overline{V}_1/2 = 50$, most incoming particles are flow focused and finally move into the middle branch C (Fig. 12(c)). A volume plot of nondimensional particle trajectories in steady state for $\bar{t} = 10000$ at different part of the mainchannel: (a) theory on the concentrating electrode; (b) experiment on the concentrating electrode; (c) theory around the gap region between the two groups of electrode; (d) experiment in the gap area. The intended branch is highlighted in red.

with an arbitrarily biased gate voltage, so that the incoming colloid samples may finally move into one of the side branches rather than the middle outlet (Figs. 12(a), 12(b), 12(d), and 12(e)).

In order to dynamically guide the major colloid stream to one of the branches on the right side (observed from the upstream, Figs. 2(b) and 2(c) and Figs. 12(a) and 12(b)), FSL should shift to the same side as well in analogy with the static ICEO trapping case (observed from the backside, Figs. 5(a) and 5(c)). Inspired by the previous theoretical justification of AC-FFET in static condition, a gate voltage larger than the floating potential was imposed to the directing electrode, i.e., $\overline{V}_2 > 50$. Under this condition, AC-FFET vortex has a FSL on the right side of the directing electrode surface. Due to a combined action of the asymmetric transverse AC-FFET vortex and axial pressure driven Poiseuille flow above the directing electrode, motion locus of the major particle line becomes a curved one there and deviates to the right side (Figs. 10(a) and 10(c)). At last, most incoming particle samples move into one of the right branches B or A, as determined by the specific magnitude of the gate voltage $\overline{V}_2$ (Figs. 12(b) and 12(a) or Figs. 2(c) and 2(b)). The larger the gate voltage is, the greater the particle line trajectory deviates towards the right side, which is more likely to make particles move into branch A in the end.

In such a circumstance where voltage of the directing electrode is biased, particles are not only flow focused into a thin colloid line at the centerline of concentrating electrode, but also the trajectory of major stream is deviated slightly to the right side at the end of concentrating electrode (Figs. 10(a) and 10(c)). Surprisingly, this kind of deviation enlarges with increasing gate voltage of the directing electrode. Since the two center metal strips are placed in close

FIG. 10. As voltage amplitude of the directing electrode is biased larger than its floating potential, most incoming particles are flow focused and finally move into one of the branches on the right side (Figs. 12(b) and 12(a)). (a) and (b) A volume plot of steady-state particle trajectories that finally enter branch B around the gap region for $\overline{V}_2 = 70$: (a) theory; (b) experiment. (c) and (d) On nondimensional particle trajectories that finally enter branch A for $\overline{V}_2 = 90$.

proximity with a small spacing $\overline{G}_2 = 3.66$, biased voltage of the directing electrode can exert an effect on the electric field distribution outside the diffuse double-layer around the concentrating electrode, rendering the ICEO flow profile at the end of the floating electrode asymmetric to some extent as well.

Making a comparison between the symmetric (Fig. 9) and biased cases (Fig. 10), only if the directing electrode is imposed with a biased voltage, slight deviation of particle trajectory can occur at the end of concentrating electrode, and is along the same direction as that caused by AC-FFET above the directing electrode (Figs. 10(a) and 10(c)). Considering its sufficiently small contribution to change in particle line trajectory compared to AC-FFET, however, we still deem the concentrating electrode mainly plays the role of flow focusing particles, and the directing electrode helps to divert the trajectory of the major colloid line to one desired branch channel.

And vice versa, as shown in Figs. 2(d) and 2(e) and Fig. 11, as a gate voltage amplitude smaller than the floating potential was imposed to the directing electrode, i.e., $\overline{V}_2 < 50$, all the antisymmetric phenomena with respect to Figs. 2(c) and 2(b) and Fig. 10 took place and hence the particle line trajectory deviates in the opposite direction, in that FSL now shifts to the left side of directing electrode surface rather than the right side. As a result, the incoming particle samples ultimately move into one of branches on the left side, D or E, which corresponds to an applied gate voltage of $\overline{V}_2 = 30$ or 10, respectively, as shown in Figs. 12(d) and 12(e) or Figs. 2(d) and 2(e).

As noted previously, a major colloid line, whose trajectory is adjustable by tuning the ICEO flow field, is invariably accompanied by two minor particle lines focused by ACEO along

FIG. 11. As voltage amplitude of the directing electrode is biased smaller than its floating potential, most incoming particles are flow focused and finally move into one of the branches on the left side (Figs. 12(d) and 12(e)). (a) and (b) A volume plot of steady-state particle trajectories that finally enter branch D around the gap area for $\overline{V}_2 = 30$: (a) theory; (b) experiment. (c) and (d) On particle trajectories that finally enter branch E for $\overline{V}_2 = 10$.

the driving electrodes. Although we concern most the importance of ICEO in the device function, performance of this particle director is indeed lowered to a certain extent due to a negative effect of ACEO. However, since we reasonably divide the functional area in sequence into focusing region (floating electrode) and directing region (gate electrode) from upstream to downstream of the tandem electrode design, current microfluidic device realizes an eligible particle concentrator/director.

5. Experimental validation of the device function

In this section, we validate the device function by observing particle dynamic behaviors in practical experiment. Turning off all the AC voltage sources, implying in the absence of electroosmotic vortex on the metal strips, the axial Poiseuille flow transported the incoming particle samples downstream, and they passed by the five branch outlets uniformly, without apparent concentrating phenomenon occurring (Fig. 13(a)).

On the contrary, once the two pairs of driving electrode were actuated by an appropriate AC voltage signal of $V_1 = 2.5$ V and $f = 100$ Hz, while the directing electrode floated in potential ($V_2 = 1.25$ V), the incoming silica beads underwent a continuous flow focusing process on the concentrating electrode due to symmetric ICEO convective vortex (Fig. 9(b)). The particle stream focused by ICEO gradually becomes thinner as the beads float downstream (Fig. 9(b)), squeezing into a fine line pattern in the gap area (Fig. 9(d)), and eventually the major colloid line moves into the middle branch C (Fig. 13(d)), which is in qualitative agreement with our theoretical prediction on the incoming particle trajectory in Fig. 12(c). That is, under such a

FIG. 12. Simulation results of incoming particle trajectories in the vicinity of the outlets, as different gate voltage amplitude $\overline{V}_2$ is applied to the directing electrode for fixed driving voltage amplitude $\overline{V}_1 = 100$, (a) $\overline{V}_2 = 90$, (b) $\overline{V}_2 = 70$, (c) $\overline{V}_2 = 50$, (d) $\overline{V}_2 = 30$, and (e) $\overline{V}_2 = 10$.

condition with an unbiased directing electrode, the device merely realizes the function of an analyte concentrator.

If gate voltage of the directing electrode deviates sufficiently from its floating potential, a microfluidic particle director can be anticipated, and is able to induce expected transverse concentration gradient of incoming analytes at the branch outlets. As $V_2 > V_1/2$, the major colloid stream formed by symmetric ICEO flow at the end of concentrating electrode was deviated towards the right side by asymmetric AC-FFET vortex on the directing electrode (Figs. 10(b) and 10(d)), so as to finally move into one of the right branches, outlet A for $V_2 = 2.25$ V (Fig. 13(b)) or B for $V_2 = 1.75$ V (Fig. 13(c)), which is in good accordance with the numerical prediction in Figs. 12(a) and 12(b). And vice versa, when $V_2 < V_1/2$, since FSL shifts to the left side of electrode surface, the major particle line now deviates in the opposite direction (Figs. 11(b) and 11(d)), and the biased AC-FFET micro-vortex diverts the motion trajectory of most incoming colloids to one of the left branches, viz., outlet D for $V_2 = 0.75$ V (Fig. 13(e)) or E for $V_2 = 0.25$ V (Fig. 13(f)), which agrees well with theoretical result exhibited in Figs. 12(d) and 12(e).

It is noteworthy that the number of particles adhering to the driving electrodes is quite limited and even reaches saturation after a time. That is to say, will repeat experiments, the particles become dislodged, and the channel won't become blocked, as shown in the supporting movie.⁴¹ After running for some time, since particle electrokinetic adhesion phenomenon is

FIG. 13. Experimental validation of performance of the microfluidic particle director at the mainchannel/branch channel junction, with yellow arrow indicating the Poiseuille flow direction, (a) with all of the AC voltages switched off ($V_1 = V_2 = 0$), (b)–(f) as different gate voltage amplitude V_2 is applied to the directing electrode for fixed driving voltage amplitude $V_1 = 2.5$ V, (b) $V_2 = 2.25$ V, (c) $V_2 = 1.75$ V, (d) $V_2 = 1.25$ V = $V_1/2$, (e) $V_2 = 0.75$ V, and (f) $V_2 = 0.25$ V. The particle focusing efficiency for any intended branch channel is the same and achieves approximately 70% according to theoretical prediction.

saturated, we can safely ignore its effect on long-term operation, implying our device can be used for continuous separation.

However, particle leakage into both side branches was observed in experiments (Fig. 13), which agrees well with the theoretical prediction considering the adverse effect of ACEO converging stagnation flow on the driving electrodes (Fig. 12).

As a result, to analyze the focusing efficiency η_X for an intended branch outlet X, we need take into account particles that come out of the correct outlet N_X and those that go into other outlets $N_{total} - N_X$

$$\eta_X = \frac{N_X}{N_{total}} \times 100\%. \quad (1)$$

Here, N_X represents the number of particles focused by ICEO and AC-FFET on the gate electrode that finally move into the intended branch X as the major thin particle stream, and N_{total} the total number of particles moving into the five outlets. Since particle leakage into the side branches is severest due to the action of ACEO on the driving electrode, we deem that $N_{total} - N_X$ equals the number of particles focused by ACEO on the driving electrodes that finally move into the side branches A and E as two minor thin particle streams.

According to simulation results, $N_X = 50$ and $N_{total} = 72$, particle focusing efficiency for any intended branch channel achieves approximately 70%, implying 70% of incoming particle samples finally come out of the correct outlet, while other 30% go into other outlets (mainly ACEO induced particle leakage into the side branches). Indeed, the directing efficiency is not ideal at present. However, measures can be taken to improve the concentrating performance, e.g., using 3D sidewall driving electrodes rather than 2D coplanar ones, which cancels the adverse effect of ACEO.

6. Discussion on focusing particles of non-uniform size

Biological analytes are usually non-uniform in size, which complicates the AC-FFET-based particle manipulation. We consider the convective velocity of bioparticles u_p under the combined action of ICEO vortical flow field u and downward particle buoyancy force F_b

$$u_p = u + u_b = u + \frac{F_b}{6\pi\eta R} = u - \frac{2R^2(\rho_p - \rho_f)g}{9\eta} e_z. \quad (2)$$

For analytical purpose, we decompose the total particle velocity into horizontal x and vertical z components

$$\mathbf{u}_{px} = \mathbf{u}_x, \quad (3a)$$

$$\mathbf{u}_{pz} = \mathbf{u}_z - \frac{2R^2(\rho_p - \rho_f)g}{9\eta} \mathbf{e}_z. \quad (3b)$$

For spherical samples, the non-uniformity in particle radius R does not affect the horizontal electroosmotic convection $\mathbf{u}_{px}$, while the downward buoyancy velocity $|\mathbf{u}_b| = -\frac{2R^2(\rho_p - \rho_f)g}{9\eta}$ is proportional to the radius squared. So, there are two different situations that we need take into account.

On one hand, if the fluctuation of particle radius is not large enough, implying the downward $|\mathbf{u}_b|$ of the smallest particle is still sufficiently large to overcome the upward ICEO flow component to achieve stable particle trapping on the gate electrode, all the incoming particles of varying size experience similar motion trajectory, while with different stagnation height. Theoretically, larger particles stagnate at a higher position from the electrode surface, since greater upward fluidic drag is required to balance the larger downward buoyancy force of larger particles and upward ICEO flow component increases gradually with distance from the electrode surface.

On another hand, if the fluctuation of particle radius is sufficiently large, e.g., the nominal particle diameter is $4\ \mu\text{m}$, while actually the distribution is within the range $1\text{--}8\ \mu\text{m}$. Then, there is a problem to stably trap the smallest bioparticles at the FSL. First, the horizontal electroosmotic flow component transports all the incoming particles of varying size to the FSL on the gate electrode. However, the buoyancy force of $1\ \mu\text{m}$ particle is merely $1/16$ of $4\ \mu\text{m}$ standard sample and may be too small to overcome the strong upward ICEO flow component at the original voltage amplitude and field frequency, and $1\ \mu\text{m}$ particles rotate with ICEO vortices and fail to become trapped at the electrode surface, resulting in a failure in AC-FFET flow focusing. So, in order for AC-FFET concentrating to be effective for smallest biological samples, the applied voltage and frequency must be readjusted and optimized.

As for the $8\ \mu\text{m}$ (largest) particles, since the mere upward fluidic drag cannot balance the large downward buoyancy force, particles may sedimentate onto the gate electrode surface and suffer from a normal support force and resulting wall friction force on the channel bottom. So, due to the action of the wall friction force, the largest particles are transported quite slowly towards the downstream branch channels by the axial Poiseuille flow, which increases the time required for flow focusing, but no apparent reduction in concentrating performance can be expected. For such, AC-FFET flow focusing is effective for large particles.

On the basis of above analysis, as we deal with biological analytes of non-uniform size, the most important issue is to reduce the upward ICEO flow component, to enable a stable trapping of smallest particle samples of small buoyancy velocity in the vicinity of FSL. This is usually accomplished by appropriately adjusting the applied driving voltage amplitude V_1 and/or the field frequency f . A reduction in driving voltage suppresses the ICEO bulk flow, in both horizontal and vertical directions. Besides, increasing the field frequency is an alternative way to achieve the same goal, due to frequency-dependent electrochemical ion relaxation. That is, *either lowering the driving voltage amplitude or slightly increasing the field frequency* can effectively reduce the upward ICEO flow component $\mathbf{u}_z$, giving it a chance for the small buoyancy velocity of smallest particle samples to dominate in the vertical direction, resulting in successful AC-FFET flow focusing of incoming biological analytes of varying size.

IV. CONCLUSION

In this study, from both theoretical and experimental perspectives, we propose to utilize AC-FFET as a versatile means for flexibly manipulating micro-nano particle samples based on its shiftable FSL, in either a *static* or *continuous flow* condition. We started from deriving a general physical description of AC-FFET for finite Debye length of diffuse double-layer, identifying the physics behind AC-FFET induced particle concentrating: a requirement of the vertical

force equilibrium at the FSL where colloids are trapped (excluding the DC limit where a strong upward fluidic drag makes particle focusing erratic) and a sufficiently large horizontal electroosmotic convection (excluding the high frequency limit where charge relaxation in the liquid occurs), leading to an *ideal trapping frequency* around the characteristic inverse double-layer relaxation time for a given electrode configuration, an arbitrary Debye length and AC voltage amplitude. Most importantly, even for finite thickness double-layer, AC-FFET is able to adjust the concentrating position of analytes on a biased center gate electrode *in static condition* by generating arbitrary symmetry breaking in total current density and electroosmotic flow pattern.

Since a linear relation between the horizontal position of particle trapping center and biased gate voltage is general for various Debye lengths at distinct characteristic field frequencies, the definition of a linear manipulating sensitivity k is physically justifiable, and is a good indicator for appraising the flexibility in manipulating the target analytes on the blocking gate electrode by AC-FFET. Furthermore, by calculating the value of k at different double-layer thickness and field frequency, it was discovered that the trapping center of nanoparticle samples can be more flexibly tuned by AC-FFET as the double-layer thickness approaches the electrode half width. The finite values of Debye length are attainable in the case of a nanometer or submicron metal strip submerged in low-conductivity or even semi-insulating liquids, and the characteristic charging frequencies are, in general, not high due to a low liquid conductivity and the resulting thick double layer.

At last, a method of continuous particle concentrating and diverting, that exploits a design of tandem electrode configuration, was developed to deal with incoming analytes *in dynamic condition*. Since the functional area of the device was reasonably divided in sequence into two separate regions, including the concentrating and directing electrode, the incoming particle samples was first flow focused into a thin colloid line at the end of concentrating electrode by symmetric transverse ICEO vortex, sailing downstream with the incoming Poiseuille flow, and the trajectory of major particle stream can be flexibly diverted to one desired branch of the five outlets due to the action of AC-FFET vortex of tunable flow profile on the directing electrode. A good agreement between experimental observation and theoretical prediction of dynamic particle behaviors based on thin double-layer approximation indicates that, a clear division of the tandem design into the two separate regions with their respective functions makes the device become an eligible continuous microfluidics-based particle concentrator/director, which has potential to produce arbitrary transverse concentration gradient of incoming analytes, as prerequisite for a subsequent analysis.

In near future, AC-FFET would serve as a valuable manipulation tool of biological analytes and micro-nano particle samples in the interdisciplinary research field of electrokinetics, electrochemistry, and micro-/nano- fluidics.

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