‘ALL-INTO-ONE’ CONCENTRATION: CASCADE ELECTROKINETIC PARTICLE FOCUSING FOR RARE SAMPLE DETECTION

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ABSTRACT

This study presents an on-chip particle concentrator using a cascade electrokinetic flow. Suspended particles is focused three-dimensionally on a bottom surface at the center of a fluidic channel by optimized AC electroosmotic flow so that a highly-sensitive in-line surface detection such as electrochemical method or modified surface-binding is possible. Cascade configuration of electrode arrays allows 96.4 % of 2 μm particles in the channel to be concentrated at 10 × 5 μm area with a concentration factor of 700 regardless of their charge and polarizability. This cascade electrokinetic method can be useful as a preconcentrator for ultra-sensitive detection of rare samples.

KEYWORDS

AC electroosmosis, Particle concentration, Cascade electrokinetic concentrator, rare sample detection.

INTRODUCTION

An improvement of detection sensitivity in a microfluidic system is still an issue [1] for in-field sensing or point-of-care diagnostics. Strategies to improve the detection sensitivity include developing highly sensitive detection techniques or using concentration methods prior to analysis. At the same time, detection of rare samples like circulating tumor cells [2] or genetic variants of viruses requires a perfect detection without any undetectable targets, which could be a challenging task in conventional concentration techniques. This paper presents a cascade electrokinetic approach using alternating-current electroosmosis (ACEO) for a particle preconcentrator, which enables ‘all-into-one’ sheathless particle focusing with co-planar electrodes. Utilization of ACEO for particle control offers a tolerance in particle properties, electrical conductivity, permittivity, surface charge and size, because of its principle of particle transportation using the fluidic force. Additionally, our cascade method overcomes a disadvantage of conventional ACEO-based particle concentrators of the local effective field [3] due to inevitable counter flow preventing their performances.

PARTICLE CONCENTRATOR DEVICE

Figure 1 depicts a schematic of the cascade electrokinetic concentrator chip. AC electric field is applied individually to asymmetric electrode (AS) and double-gap electrode (DG). AS, located upstream, is designed to prevent particles flowing near sidewalls of a channel, and DG focused all the particles flowing above the wide electrode to the surface at the center. The microfluidic preconcentrator comprised of a glass substrate with an ITO layer for the electrodes and A PDMS channel. The channel dimensions was 500 × 50 μm. The electrode in AS has 100 μm wide trunk and branches, and 10 μm separated lines. The gaps in the branch and line were 25 μm. In DG, wide center electrode is 300 μm wide and two gaps are 25 μm. The distance between AS and DG is 2 mm, which is enough long to avoid an interaction of electric field applied to the other electrode. The surface charge, and polarization of target particles is neglected due to the use of fluidic force; this is essential dealing with unknown particles in a sample solution.

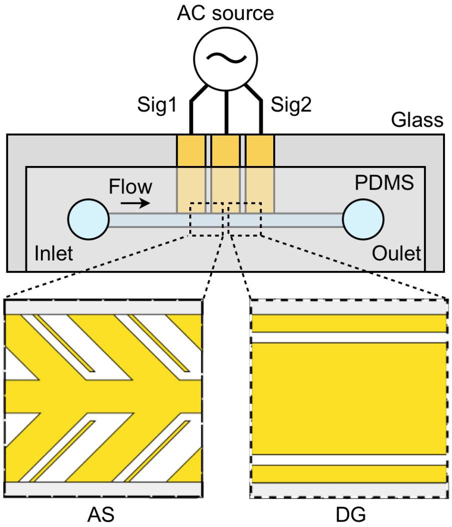

Figure 1. Schematic of cascade electrokinetic particle concentrator. Combination of alternating-current electroosmotic flows induced by asymmetric and double-gap electrodes (AS and DG) enable highly efficient concentration for all particles in a 500 μm channel.

1 or 2 μm carboxylate-modified fluorescent polystyrene particles were dispersed in KCL aqueous solution with electric conductivity of 4.4 mS/m.

RESULTS AND DISCUSSION

The concentrating behavior of 1 μm polystyrene particles and ACEO velocity field in DG electrode geometry is shown in Figure 2. Applied AC voltage and frequency were 5 Vpp and 500 Hz, respectively. The width of the center electrode was 50 μm only in this experiment for high-resolution visualization. The velocity field normal to the substrate was obtained by lateral micro-PIV technique [4]. The particles are three-dimensionally concentrated on the center electrode within a height of approximately 5 μm. The focused location of particles corresponds to a stagnation area of two tangential ACEO flows facing each other from both gaps. The focused position of particles on center electrode is varied with applied voltage and frequency. Frequency dependence of the particle focusing position is depicted in Figure 3. The focused position was measured from the edge of the center electrode. At higher frequency than 1 kHz, two linearly-concentrated particle groups were confirmed. Particles are concentrated along the centerline of the center electrode under low frequency conditions (< 1 kHz). This is attributed to the frequency dependent velocity distribution of ACEO, in which the velocity remains further from the gap at low frequency instead of the low peak velocity.

Figure 4 shows particle count in spanwise direction. Particle size was 2 μm and count number in each case was approximately 2000. In 'base' case, there was no voltage application so that the particle distribution was almost uniform. The count rate in center and side areas are summarized in Figure 5. Center and side areas are 10 μm region at the center and 50 μm region from the sidewall, respectively. Optimized AC voltages were applied separately in AS and DG electrodes; 2,5 Vpp and 0.7 kHz for AS electrode, and 4.0 Vpp and 0.1 kHz for DG. DG pattern can collect particles very sharply toward center and side areas. Sidewall focusing of particles is inevitable in DG electrode because of outward-directed ACEO flow which transport particles to sidewall region. Thus, the effective area for particle focusing to the center area in DG is only over the center electrode. The concentrating performance is limited at most 60 % in this electrode geometry. In AS device, inward ACEO flow due to its asymmetric electric field strength occurs [5] and removal of particles flowing there and gentle collection of particles around the sidewall region toward above the center region is achieved.

Combined use of AS and DG derives advantages of both electrode pattern. As a result, cascade chip indicates high count rate at the center region with a width of 10 μm as much as 96.4 % decreasing the rate at sidewall area less

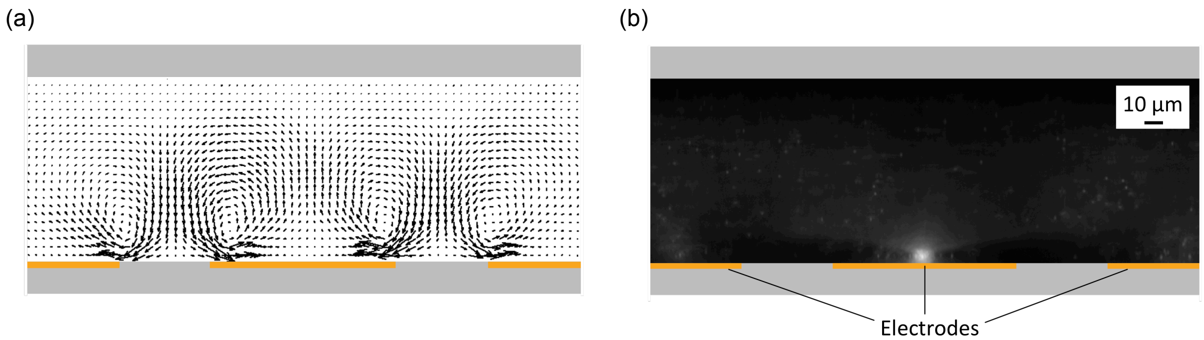

Figure 2. Concentration behavior of 1 μm particle in DG pattern. ACEO flow induced around gaps (a) concentrate particles on electrode surface (a) within 5 μm from the bottom. Narrow center electrode of 50 μm in width is used for the reason of velocity measurement with high precision.

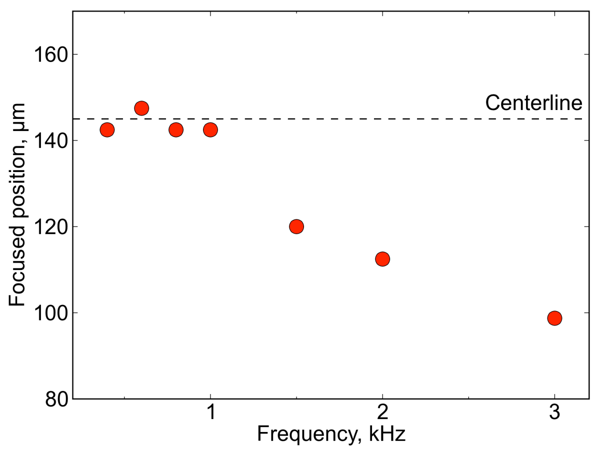

Figure 3. Frequency dependent focused position of particles in DG device. As applied frequencies decreases, the focused distance increases showing convergence at centerline of the center electrode.

than 1 %, as shown in Figure 5. Considering the vertical concentration as in Figure 2(b), the 3D concentration factor is estimated as approximately 700.

CONCLUSIONS

We have successfully developed a novel particle focusing microfluidic device using cascade ACEO method. Highly effective focusing of particles in the whole channel into a specific surface area was achieved. The cascade ACEO provides efficient sheathless concentration of particles in the microfluidic platform showing applicability for on-chip detection of rare samples in a portable device.

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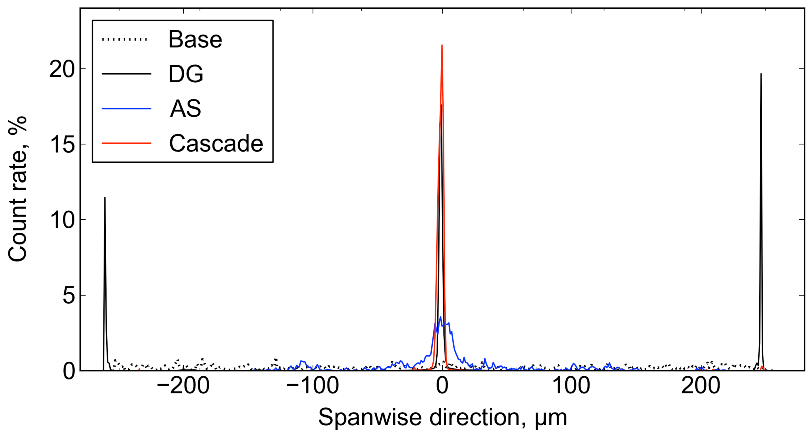

Figure 4. Spanwise distribution of particle flowing in the channel. DG yields three focused regions; center and sidewall areas. AS prevents particles flowing nearwall region. Cascade operation can concentrate most of them onto surface area at the center.

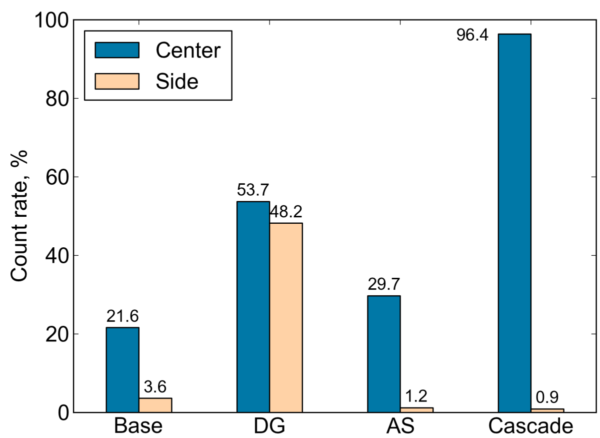

Figure 5. Evaluation of concentration performance for 2μm polystyrene particles. Center and side areas are 10 μm region at the center and 50 μm region from the sidewall, respectively. DG performance is limited by the width of center electrode. Cascade operation shows efficient concentration.