Electronic Supplementary Material (ESI) for Lab on a Chip.

Electronic Supplementary Information (ESI):

Wide bandwidth power amplifier for frequency-selective insulator-based dielectrophoresis

S1. Quantifying DEP force on the oocysts from velocity tracking measurements:

For a particle accelerated under a dielectrophoretic force (F_{DEP}), based on Netwon's second law, the net force on the particle of radius: a, within a medium of viscosity: η, can be determined by tracking displacement (x) as a function of time (t):

$$F_{DEP} - 6\pi\eta a\frac{dx}{dt} = m\frac{d^2x}{dt^2} \qquad \text{(S1-1)}$$

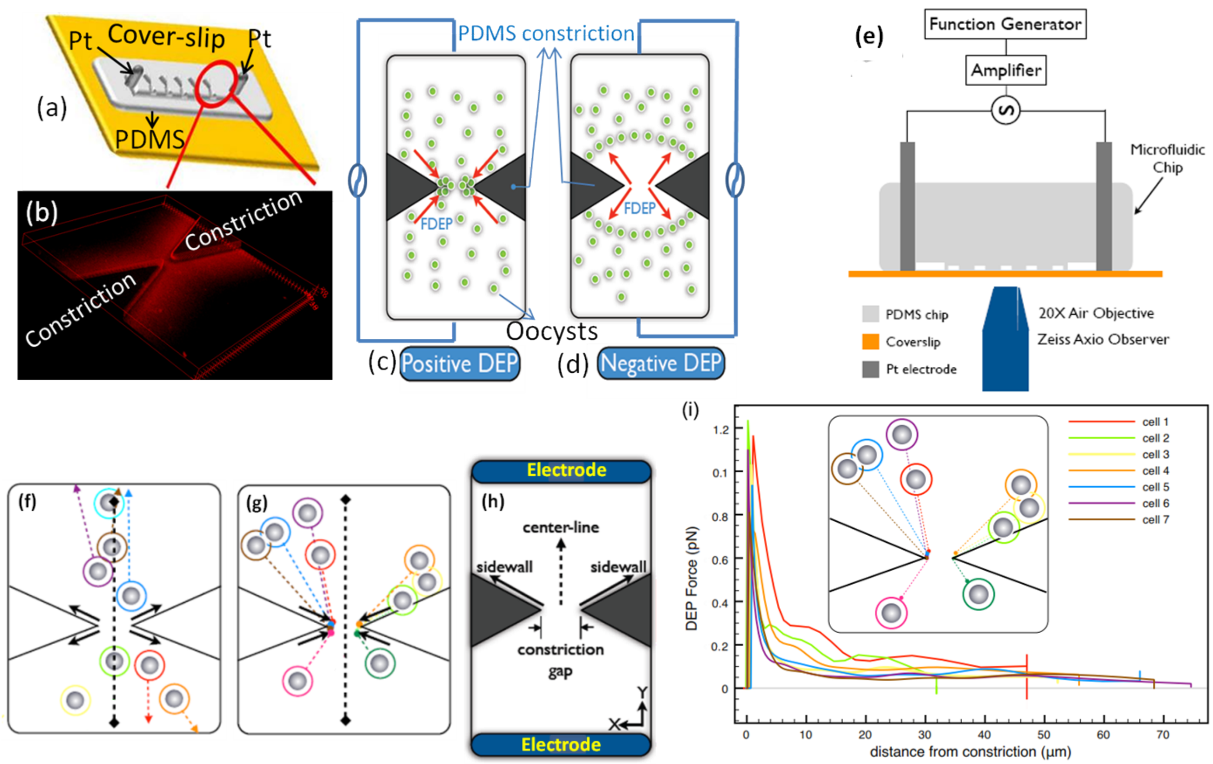

Figure S1: (a) Schematic device; (b) confocal image of constriction chip; and force directions under: (c) positive DEP (PDEP), and: (d) negative DEP (NDEP). (e) Set-up for observing DEP behavior of oocysts. Translation vectors for oocysts under: (f) NDEP; and (g) PDEP. (h) Center-line and sidewall vectors for the constriction device. (i) Typical force profiles in pN versus distance from constriction tip for untreated oocysts. There are ~25-30 data points over the constriction region and force profiles peak at 2-4 µm from constriction tip.

Tracking dielectrophoretic particle displacement versus time:

The set-up for imaging the dielectrophoretic translation of oocysts is shown in Figure S1a and S1e. Based on data from high frame per second (~30 fps) movies of oocyst translation under F_{DEP}, the displacement (x & y) are tracked as a function of time (t) for particles translated away from the constriction tip under negative DEP (NDEP) and towards the constriction tip under positive DEP (PDEP). For NDEP, the translation of oocysts that were originally at rest at the constriction tip prior to application of AC field at the particular frequency of interest is recorded as displacement versus time of field, onwards from the constriction tip along a particular displacement vector (Figure S1f). For PDEP, the translation of oocysts that were originally at rest in the region immediately outside of the constriction gradient prior to application of AC field at the particular frequency of interest is recorded as displacement versus time of the field, towards the constriction tip along a particular displacement vector (Figure S1g). Since the motion of particles take place in two-dimensional space, trajectories of particles encompass both X and Y coordinates, leading us to do all computation for both directions individually.

In this manner, the experimental raw data acquired in the form of video, is processed to yield a table of position versus time; i.e. (x,y,t) coordinates for the analyzed oocysts. The displacement data (x and y vectors) as a function of time is algorithmically smoothed by using a high-order polynomial fit, since the faster displacements under higher F_{DEP} require higher frame rates for accurately tracking displacement over time, versus the slower displacements. Furthermore, while the oocyst is several pixels large in the video images, the tracking only records one central pixel per frame, which leads to some degree of noise in the data, which can be smoothed out using the polynomial fit. Hence, having a larger number of displacements versus time points, as obtained with the field non-uniformity of enhanced spatial extent for the constriction device improves the accuracy of the computed DEP force data. To ensure an effective smoothing, we check for the lack of jagged features on the derivatives of Eq. (S1). As a result we obtain $v_x = dx/dt$, $v_y = dy/dt$, $a_x = d^2x/dt^2$ and $a_y = d^2y/dt^2$ for the oocysts at a particular applied field and frequency, after each of the disinfection treatments, which can be used to compute the X and Y components of F_{DEP} frequency response in the direction of the particle trajectory ("track" direction). At each point of the trajectory, the distance from the constriction (r) can be determined based on x and y coordinates: $r = \sqrt{x^2 + y^2}$ and the total DEP force based on the value of F_x and F_y at that point: $F_r = \sqrt{F_x^2 + F_y^2}$. Therefore, we can compute the Force vs. distance ($F(r)$).

Normalizing for field non-uniformities:

Within the constriction device, the profile of the electric field and hence, F_{DEP}, varies depending on the displacement vector of the oocysts. This can create a variation in F_{DEP} of up to an order of magnitude, depending on displacement direction and distance of the oocysts in relationship to the constriction tip of a given device. Hence, we normalized all the data for field differences from the velocity tracked direction (track) to that along the centerline direction (CL), by accounting for the field differences (∇E^2) between the "track" and "centerline" directions through a normalization factor: $K = \frac{\nabla E_{track}^2}{\nabla E_{CL}^2}; F_{DEP}^{CL} = \frac{F_{DEP}^{track}}{K}$

The ∇E^2 in the "track" direction is calculated by translating the measured trajectory of the oocyst to a simulation of the device in order to read the magnitude and gradient of the electric field along this vector direction. The magnitude and gradient of the electric field along the centerline direction is also available from this simulation. In this manner, by dividing the computed DEP force along the "track" direction by the field enhancement ratio K, we ensure that all the variations in DEP force can be solely attributed to variations in particle polarizability, rather than field non-uniformities due to the device device geometry. A typical set of force profile data for untreated oocysts is shown in Figure S1(i).

DEP trapping Videos: Movies (1 minute each) of pDEP trapping of *Cryptosporidium parvum* oocysts are shown as *.mov files uploaded within Electronic Supplementary Information.

5MHz-Wideband.mov – pDEP trapping of occysts at 5 MHz using wideband amplifier

5MHz-A400DI.mov – pDEP trapping of occysts at 5 MHz using conventional amplifier

3MHz-Wideband.mov – pDEP trapping of occysts at 3 MHz using wideband amplifier

3MHz-A400DI.mov – pDEP trapping of occysts at 3 MHz using conventional amplifier

Comparisons of amplifiers:

In the Table below, the output voltage (RMS and DC offset) and the total harmonic distortion (%THD) of for both Conventional amplifier (FLC A400DI) and the wideband amplifier are compared at different frequencies.

	Frequency (MHz)	1	3	5	7	10	13	15
Conventional Amplifier	VRMS (V)	77	25	14	10	6	-	-
	DC (V)	0.3	0.3	0.5	0.9	0.7	-	-
	THD (%)	10	11	17	31	46	-	-
Wideband Amplifier	VRMS (V)	107	107	91	74	54	34	25
	DC (V)	0	0	0	0	0	0	0
	THD (%)	3	6	9	9	7	6	5

S2. Influence of harmonic distortion on dielectrophoretic force and its frequency dispersion*

Throughout this section, the* ***Bolded* *characters refer to vector parameters, while regular parameters indicates scalar parameters.*

The *Clausius–Mossotti* relation describes the DEP force (F_{DEP}) on a spherical particle of radius: *a*, in a medium of permittivity: ϵ_m, under an RMS field: E_{rms}

$$F_{DEP} = 2\pi\epsilon_m a^3 Re[K_{CM}(\omega)]\nabla E_{rms}^2 \tag{S2-1}$$

Here, K_{CM} is the *Classius-Mossoti* factor, which represents the frequency-dependent complex dielectric contrast of the particle versus the medium:

$$K_{CM}(\omega) = \frac{\epsilon_p^* - \epsilon_m^*}{\epsilon_p^* + 2\epsilon_m^*} \tag{S2-2}$$

Here, ϵ^* denotes the frequency-dependent complex permittivity which includes both permittivity (ϵ) and conductivity (σ) as $\epsilon^* = \epsilon + (\sigma/j\omega)$. Subscripts *p* and *m* denote the respective property of particle and medium, respectively.

If the Electric field $E(t)$ has a pure sinusoidal waveform with the frequency of ω_1, we have:

$$E_{rms}^2 = \frac{1}{8}E_{pp}^2 \tag{S2-3}$$

Then equation (1) can be rewritten as

$$F_{DEP} = \frac{1}{8}.2\pi\epsilon_m a^3 Re[K_{CM}(\omega_1)]\nabla E_{pp}^2 \tag{S2-4}$$

In case the applied field is not purely sinusoidal, then it comprises of higher order harmonics where their corresponding frequencies (ω_n) are integer multiples of the fundamental frequency (ω_1). Using Parseval's theorem, we can expand E_{rms} based on its orthogonal harmonics:

$$E_{rms}^2 = \frac{1}{8}\left(E_1^2 + E_2^2 + E_3^2 + \dots\right) \tag{S2-5}$$

Here, E_1 ... E_n are the peak-peak intensities of each harmonic of the electric field. However, K_{CM} may take different value at each frequency, as follows:

$$F_{DEP} = \frac{1}{8}.2\pi\epsilon_m a^3 \nabla\left(Re[K_{CM}(\omega_1)]\, E_1^2 + Re[K_{CM}(\omega_2)]\, E_2^2 + Re[K_{CM}(\omega_3)]\, E_3^2 + \dots\right) \tag{S2-6}$$

If we assume that the most significant differences occur between the first two harmonics, with all other harmonics at higher frequencies exhibiting minor differences in K_{CM} value equal to $K_{CM}(\omega_2)$ denoted as $K_{CM}(\omega_m)$, then (S2-6) can be shortened as:

$$F_{DEP} = \frac{1}{8}.2\pi\epsilon_m a^3 \nabla\left(Re\left[K_{CM}(\omega_1)\right] E_1^2 + Re\left[K_{CM}(\omega_m)\right] \underbrace{\left(E_2^2 + E_3^2 + \dots\right)}_{E_1^2.THD^2} \right) \quad \text{(S2-7)}$$

$$F_{DEP} = \frac{1}{8}.2\pi\epsilon_m a^3 Re\left[K_{CM}(\omega_1)\right] \nabla\, E_1^2.(1 + \alpha\, THD^2) \quad \text{(S2-8)}$$

Here, α is the ratio of $Re[K_{CM}]$ at the frequencies of higher order harmonics versus fundamental harmonic ($\propto\ = \frac{Re\left[K_{CM}(\omega_m)\right]}{Re\left[K_{CM}(\omega_1)\right]}$)

The Peak-to-Peak amplitude of fundamental harmonic is not generally equal to the Peak-to-Peak amplitude of a signal. To better understand the effect of distortion on DEP force, we would like to compare the DEP force with the so-called *Ideal* DEP force (F_{Ideal}) from a sinusoidal field with the same Peak-to-Peak amplitude to the original signal:

$$F_{Ideal} = \frac{1}{8}.2\pi\epsilon_m a^3 Re\left[K_{CM}(\omega_1)\right] \nabla E_{pp}^{\ 2} \quad \text{(S2-9)}$$

The DEP force (F_{DEP}) and the Ideal DEP Force (F_{Ideal}) can be related together by comparing equation (S2-8) and (S2-9):

$$F_{DEP} = \left(1 + \alpha\, THD^2\right) \frac{\nabla\, E_1^2}{\nabla\, E_{pp}^{\ 2}} F_{Ideal} \quad \text{(S2-10)}$$

The distribution of Electric field throughout the microfluidic device is determined by the device geometry. The E-field is linearly proportional to the applied voltage, though at each point it has different intensity. Therefore, at each point inside the device, the E-field intensity can be expressed as:

$$|E\ (x,y,z,t)| = f(x,y,z).V(t) \quad \text{(S2-11)}$$

Where $V(t)$ is the Electric potential (Voltage) applied across the device and $f(x,y,z)$ is a function of location. Now, we apply the definition of gradient to the squared of E-field intensity:

$$\nabla|E\ (x,y,z,t)|^2 = \nabla\left(f(x,y,z)V(t)\right)^2 = \underbrace{\left(\frac{\partial\left(f(x,y,z)^2\right)}{\partial x}\hat{x} + \frac{\partial\left(f(x,y,z)^2\right)}{\partial y}\hat{y} + \frac{\partial\left(f(x,y,z)^2\right)}{\partial z}\hat{z}\right)}_{h(x,y,z) = \nabla f(x,y,z)^2} .\, V(t)^2$$

(S2-12)

It confirms that at each point, the magnitude of $\nabla|E|^2$ (i.e. ∇E^2) is proportional to V^2 with a new factor ($h(x,y,z)$) which only depends on the location.

$$\nabla E^2 = V^2 . h(x,y,z) \tag{S2-13}$$

Using (S2-13), the ratio of gradient terms ($\nabla E_1^2 / \nabla E_{pp}^2$) in (S2-10) can be replaced with their corresponding applied electric potentials:

$$\frac{\nabla E_1^2}{\nabla E_{pp}^2} = \frac{V_1^2 .\ h(x,y,z)}{V_{pp}^2 .\ h(x,y,z)} = \left(\frac{V_1}{V_{pp}}\right)^2 \tag{S2-14}$$

Here, V_{pp} and V_1 are the Peak-to-Peak amplitudes of the applied electric potential and its fundamental harmonic, respectively.

Finally, by substituting (S2-14) into (S2-10), we obtain (Eq. (6) of manuscript):

$$F_{DEP} = (1 + \alpha\, THD^2)\left(\frac{V_1}{V_{pp}}\right)^2 F_{Ideal} \tag{S2-15}$$

In special case where all harmonics, including the fundamental harmonic, lie in the pDEP region and have the same K_{CM}, we have ($\alpha = 1$) and (S2-15) can be simplified to (Eq. (5) of manuscript):

$$F_{DEP} = (1 + THD^2)\left(\frac{V_1}{V_{pp}}\right)^2 F_{Ideal} \tag{S2-16}$$