Supplementary Information

Trapping and viability of swimming bacteria in an optoelectric trap

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Figure S1. The laser beam intensity profile for a REP trap. For comparison, the inset figure shows the beam intensity profile for an optical trap. A REP trap requires three orders in magnitude lower laser intensity than an optical trap. The intensity profile was calculated by $I = 2\left(P/(\pi w^2)\right) \exp(-2r^2/w^2)$, where *P* is the laser power, *w* is the beamwaist, and *r* is the radial position. In the case of optical tweezers, motile bacteria are typically trapped by laser beams focused through a high numerical aperture objective (N.A. ≈ 1.3) at powers above 25 mW,¹⁻⁴ although powers down to 5 mW have also been reported.⁵ Therefore, for calculating the beam intensity profile, a 5 mW laser and a beam waist of 261 nm are assumed for the optical trap whereas a 15 mW laser and a beam waist of 15 µm are taken for the REP trap.



Figure S2. The simulated temperature rise induced by a 15 mW laser at different axial positions in the solution during REP trapping.



Figure S3. *E. Aerogenes* cells in a REP trap after five minutes. Electric field strength was 110 kV_{pp} /m at 20 kHz, and laser beam power was kept at 20 mW. Electrical conductivity of dilute phosphate-buffered saline with and without stain was measured to be 10.0±0.2 mS/m and 15.3±0.3 mS/m, respectively.



Figure S4. The simulated temperature rise induced by a 30 mW laser at different axial positions in the solution during REP trapping.

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COMSOL simulation

For simulating electrothermal (ET) flow, we followed the procedure outlined by Green *et al.*,⁶ Loire *et al.*,⁷ and Williams.⁸ The simulation was conducted in COMSOL Multiphysics v4.4. Given the axisymmetric nature of the ET vortex, a 2-D axisymmetric model was used to conduct the simulation. Based on the experimental observations, ET flow reached steady state within a fraction of second after projecting the laser. Hence, a steady state simulation was performed. We used the Non-Isothermal Flow package for modelling the heat transfer and fluid flow. A schematic diagram illustrating simulation geometry and boundary conditions is shown in **Figure S5**. The ET flow was simulated by incorporating the ET body force in the Navier-Stokes equation.



Figure S5. Schematic diagram of the simulation geometry.

$$\rho(u \cdot \nabla)u = \nabla \cdot \left[-p\mathbf{I} + \eta \left(\nabla u + (\nabla u)^T \right) - \frac{2}{3} \eta (\nabla \cdot u) \mathbf{I} \right] + \left\langle f_{ET} \right\rangle + F_g \land * \mathsf{MERGEFORMAT} (S1)$$

where ρ and η are the density and viscosity of the solution, p is the pressure, u represents velocity. F_g is the gravitational body force and $\langle f_{ET} \rangle$ is the time averaged ET body force given by Equation S2.⁹

$$\left\langle f_{ET} \right\rangle = \frac{\varepsilon_s}{2} \left[(\alpha - \beta) \frac{\nabla T \cdot E}{1 + (\omega (\varepsilon_s / \sigma_s))^2} E^* - \frac{1}{2} \alpha |E|^2 \nabla T \right] \land \text{MERGEFORMAT (S2)}$$

Coulombic Dielectric

where α is $\varepsilon_s^{-1}(\partial \varepsilon_s / \partial T)$, and β is $\sigma_s^{-1}(\partial \sigma_s / \partial T)$, E and E^* are the applied electric field and its complex conjugate, ω is the angular frequency of the AC signal, T is the temperature of the solution and ΔT is the gradient, and ε_s and σ_s are the electrical permittivity and conductivity of the solution. The two components on the right side of Equation 1 are referred to as the Coulombic and dielectric terms;¹⁰ the Coulombic term contributes the most to ET flow, whereas the dielectric term is negligible. In Equation S2, β was measured to be 0.02 K⁻¹, and α was taken to be -0.004 K⁻¹.⁶ Equation S1 along with the continuity equation and energy equation, given by Equation S3 and Equation S4 were used to model fluid flow.

$$\nabla \cdot (\rho u) = 0 \qquad \land * \text{ MERGEFORMAT (S3)}$$
$$\rho C_{p} u \cdot \nabla T = \nabla \cdot (k_{m} \nabla T) \qquad \land * \text{ MERGEFORMAT (S4)}$$

where k_m and C_p are the conductivity and the specific heat of the solution, and *T* represents the temperature of the solution. Heat transfer in the bottom ITO layer and glass substrates was modelled using the heat conduction equation for the corresponding domains

$$k\nabla^2 T = 0$$
 * MERGEFORMAT (S5)

where depending upon the domain, k is the conductivity of ITO or glass. On the top electrode surface, the energy of the projected laser beam was absorbed by the ITO layer and dissipated as heat. As a result, heat transfer in the top ITO layer was modelled using Equations S6 and S7

$$k\nabla^2 T + G = 0$$
 * MERGEFORMAT (S6)

where G, heat generation due to laser absorption, is described by

$$G = (1 - R)\alpha \left[\frac{2P}{\pi w^2} \exp\left(-\frac{2r^2}{w^2}\right)\right] \exp\left(-\alpha z\right) \land \text{MERGEFORMAT (S7)}$$

In the above expression, *R* is the reflectance from the ITO layer, *P* is the laser power, *w* is the beam waist, and *z* and α are the thickness and absorption coefficient of the ITO layer. We performed mapped meshing to ensure a high density of elements near the axis of symmetry as the temperature gradient and ET flow are significantly smaller in the region away from the central axis. The mesh independence study was performed to make sure that results such as velocity and temperature were not dependent on mesh. We applied a convection boundary condition at the top and bottom surface of chip, and the heat transfer coefficient *h* was assumed to be 15 W/m²K. Ambient temperature T_{∞} was measured to be 20±1 °C with a thermocouple during experiments. A table consisting of other parameters related to the simulation is provided below. The computation was performed using a two-step segregated solver wherein temperature was solved initially and the obtained results from the first step were used to solve for the pressure and velocity in the next segregated step.

Table S1.

Parameter	Value	Units
Electrical conductivity of medium	10	mS/m
Permittivity of medium	708.34×10 ⁻¹²	$s^4 \cdot A^2/(m^3 \cdot kg)$
Thermal Conductivity of water at 20° C	0.60	W/(m·K)
Thermal conductivity of ITO	10.80	W/(m·K)
Thermal conductivity of glass	1.10	W/(m·K)
Heat capacity of medium	4183	J/(kg·K)
Density of medium	998.2	Kg/m ³
Dynamic viscosity of medium	1.002×10 ⁻³	$N \cdot s/m^2$
Laser Power	15 or 20	mW
Beamwaist	15.0	μm
Electric field (peak-to-peak)	1.1×10 ⁵	V/m
Electric field frequency	20	kHz



Figure S6. Effect of the REP trapping conditions on the membrane integrity of the captured bacteria over a period of 8 minutes. Laser power was kept at 20 mW.

References

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