Supplementary Information

Microbe removal using a micrometer-sized optical fiber

Yao Zhang,†[a] Hongxiang Lei,†[a] Yanze Li[b] and Baojun Li[*a]

[a] *State Key Laboratory of Optoelectronic Materials and Technologies, School of Physics and Engineering, Sun Yat-Sen University, Guangzhou 510275, China. Fax: +86-20-8411 2260; Tel: +86-20-8411 0200;* [*]*E-mail: stslbj@mail.sysu.edu.cn*

[b] *State Key Laboratory of Microbial Technology, Shandong University, Jinan 250100, China*

† These authors contributed equally to this work.

1. Calculations of the asymmetry factor *J*

As schematically shown in Fig. S1, a microbe (yeast cell, regarded as a homogeneous sphere with a radius R) is suspended in water, with a monochromatic radiation along a fixed direction. For such a model, the local heat source function $Q(r,\theta)$ within or on the surface of the microbe, related to the local electric field $E(r,\theta)$, can be expressed as[1]

$$Q(r,\theta) = \frac{4\pi n_m \kappa_m I}{n_f^{\,2}\lambda}\frac{|E(r,\theta)|^2}{|E_0|^2} = \frac{n_m \kappa_m I}{n_f^{\,2}\lambda}B(r,\theta) \tag{1}$$

where

n_m: refractive index (real part) of the microbe (yeast cell),

κ_m: absorptivity (imaginary part of the refractive index) of the microbe,

n_f: refractive index of the fluid (water),

λ: wavelength of the incident radiation,

I: intensity of the incident radiation,

E_0: electric field of the incident radiation,

$B(r,\theta)$: normalized electric energy function denoted as $B(r,\theta) = |E(r,\theta)|^2/|E_0|$.

The asymmetry factor J of the energy distribution is defined as a volume integral of $Q(r,\theta)$ within and on the surface of the microbe. As ϕ is symmetrical dependent and does not contribute anything to the calculation of the asymmetry factor J, therefore, a ϕ-averaged electric energy function is used.[2] $B(r,\theta)$ averaged over ϕ is obtained as

$$B(r,\theta) = \frac{1}{2\pi}\int_0^{2\pi}\frac{|E(r,\theta,\phi)|^2}{|E_0|^2}d\phi = B(r,\theta,-) \tag{2}$$

The asymmetry factor J, which represents the direction and the magnitude of the photophoretic force, can then be expressed as

$$J = \frac{6\pi R n_{\mathrm{m}} \kappa_{\mathrm{m}}}{n_{\mathrm{f}}^{2} \lambda} \int_{0}^{R} \int_{0}^{\pi} B(r,\theta) \left(\frac{r}{R} \right)^{3} \cos\theta \sin\theta d\theta d\left(\frac{r}{R} \right). \tag{3}$$

By using the 3D FDTD simulation, the local electric field $E(r,\theta)$ within or on the surface of the microbe can be obtained for the microbes radiated by the leakage light from the fiber. The energy focusing depends on the microbe's absorptivity and refractivity. Its asymmetry can be quantified by the factor J, which is an important parameter for the photophoretic mobility of the microbes.

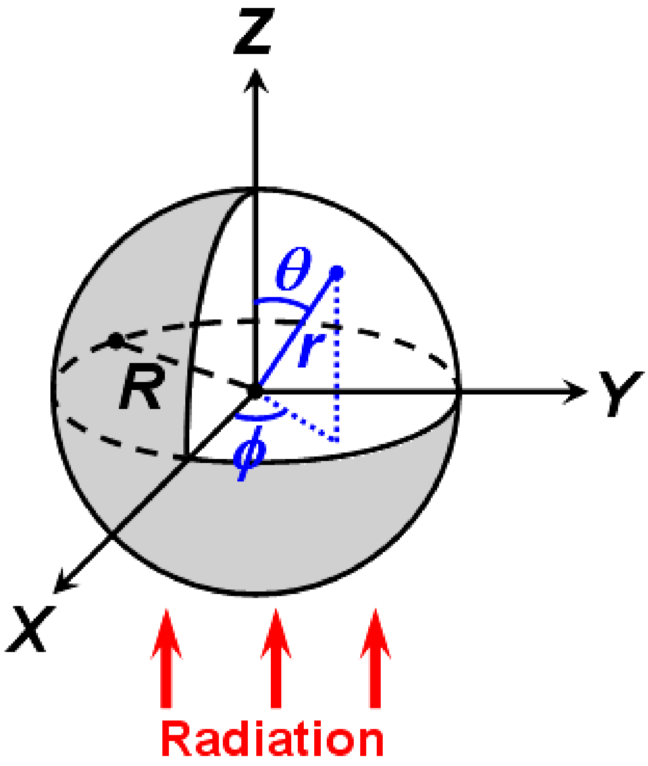

Fig. S1 Model of a microbe suspended in a fluid with a monochromatic radiation.

2. Variation of *J* with the increase of the distance to the fiber

The value of J is mainly determined by the electric field distributions near the microbe, and strongly related to the field profiles of the radiation from the fiber.[3] Actually, the value of J becomes larger when the cross-section of the radiation field profile is close to the one of a plane wave, while becomes smaller when it closes to the one of a spherical wave. As shown in Fig. S2, with the increase of the distance d from the microbe to the fiber, the cross-section of the radiation field profile deforms from a spherical wave to a plane wave. As examples, the 3D FDTD simulated electric field amplitude distributions around two yeast cells (5-μm diameter) with different distances (d_1 = 10 μm and d_2 = 50 μm) are obtained and shown in Fig. S2. For comparison, the power of the incident radiation is set to be the same for the simulations with distances d_1 and d_2. It can be seen that the radiation focusing of the yeast cell with d_2 = 50 μm is much stronger than that by the yeast cell with d_1 = 10 μm, leading to a larger J value for the yeast cell farther to the fiber. According to the electric field amplitude obtained from the simulations, the J values for the two yeast cells were calculated as J = 0.011 and J = 0.045 for the yeast cell with d_1 = 10 μm and d_2 = 50 μm, respectively. The results indicate that with the increase of the distance d, the value of J keeps increasing due to the profile deformation of the radiation from the fiber.

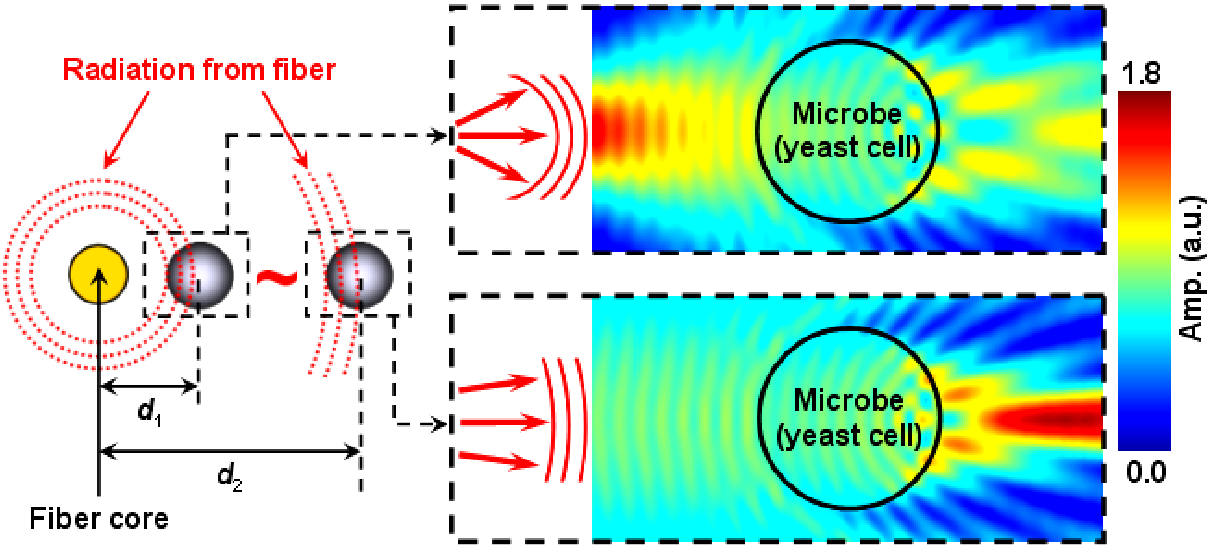

Fig. S2 Schematic of the field profiles of the radiation from the fiber and the 3D FDTD simulated electric field amplitude distributions around two yeast cells with different distances (d_1 = 10 μm and d_2 = 50 μm). The dashed red lines denote the cross-section of the field profile radiated from the fiber. The diameters of the fiber and the yeast cells in the 3D FDTD simulations are 3.4 μm and 5 μm, respectively.

3. Evaluation of heating effect of water

The heating effect of water by 1.55 μm light induces a temperature gradient near the fiber. Generally, this temperature gradient generates a thermophoretic force that drives the yeast cells to move toward the colder region (i.e. away from the fiber). However, in this work, due to the low power consumption (less than 50 mW) in the 3.4-μm-diameter fiber, the temperature gradient is relatively small and the range of the temperature gradient is rather limited. According to the 3D FDTD simulations on the electric field at P_{in} = 200 mW (the maximum laser power applied in the experiments), distributions of power flow S along the radial direction of the fiber can be obtained. Therefore, the temperature variation ΔT around the fiber can be expressed as[4]

$$\Delta T = \eta S\tau/(c\rho d), \tag{4}$$

where d = 125 μm is the depth of water, $c = 4.2 \times 10^3$ J/(kg·K) is the heat capacity of water, $\rho = 1 \times 10^3$ kg/m^3 is the density of water, $\eta = 1 - e^{-\alpha d}$ = 12.7% is the ratio of light absorbed by water ($\alpha = 10.9$ cm^{-1} is the absorption coefficient of water at 1.55 μm), $\tau = d^2/\kappa = 0.11$ s is thermal relaxation time ($\kappa = 1.4 \times 10^{-3}$ cm^2/s is the thermal diffusivity of water). By using Eq. (4), temperature variations ΔT were calculated. The simulated S and calculated ΔT along the radial direction (X direction) of the fiber are shown in Fig. S3. It can be seen that the temperature variation ΔT at the fiber surface (X = 0 μm) is 0.66 K. The temperature gradient is less than 1 K/μm along the X direction for $X \leq 1$ μm. Moreover, it can be seen that ΔT is almost zero for $X > 1$ μm, indicating that ΔT or the temperature gradient is extremely small in the yeast cell accumulation region with a distance of larger than 24 μm to the fiber. Therefore, although a small temperature gradient was induced near the fiber surface, the heating effect of water by 1.55 μm light is ignorable in the yeast cell trapping process.

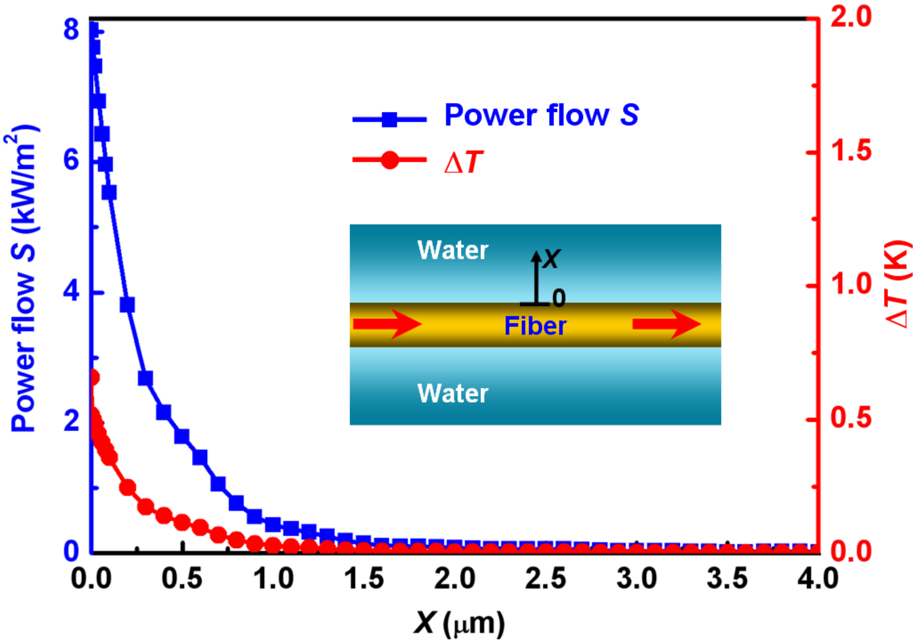

Fig. S3 Power flow S and temperature variation ΔT in the radial direction of the fiber at P_{in} = 200 mW. The inset is the schematic of the fiber immersed in water, indicating the radial direction (X direction) for calculation.

References

1. C. Y. Soong, W. K. Li, C. H. Liu and P. Y. Tzeng, *Opt. Express*, 2010, **18**, 2168.
2. W. M. Greene, R. E. Spjut, E. Bar-Ziv, A. F. Sarofim and J. P. Longwell, *J. Soc. Opt. Am. B*, 1985, **2**, 998.
3. H. Lei, Y. Zhang, X. Li and B. Li, *Lab Chip*, 2011, **11**, 2241.
4. H. Xin, H. Lei, Y. Zhang, X. Li and B. Li, *Opt. Express*, 2011, **19**, 2711.