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New Opto-Plasmonic Tweezers for Manipulation and Rotation of Biological Cells – Design and Fabrication

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***Abstract*—Opto-Plasmonic Tweezers are proposed as a new optical manipulator and rotator for biological cells. The approach utilizes polarized light to excite localized surface plasmon resonance (LSPR) on an array of Au nanostructure. Large dielectrophoretic trapping force is expected to be induced by the highly non-uniform scattering field from the resonant oscillating dipoles. Fine orientation control of the cells can be realized by tuning the polarization state of the input light.**

I. Introduction

THIRTY years ago, neurophysiology was revolutionized by the invention of a way to record the electric ionic channel across a membrane [1]. This so-called patch-clamp technique allows the statistical analysis of the current flowing through a single channel, which yields more valuable information than simply measuring the current flowing through a large ensemble of channels. The cell biology is undergoing a similar transformation, with the development of tool for non-invasive manipulation of single biological cells. The tool allows individual cells, cellular components, and synthetic marker particles treated with biochemical tags to be collected, separated, concentrated, and transported without damage to the objects themselves. Among various non-invasive manipulation mechanisms, a particularly desirable one is to control the orientation of biological cells, in addition to trapping and moving them. Such capability opens the door for building structured biomaterials for potential application in constructing bio-films and human tissue engineering.

In the past, dielectrophoresis (DEP) and electro-rotation have been the most widely employed methods for manipulation and rotation of biological cells [2]. However, such approaches often require micro-fabrication for the fixed electrodes, the manipulation area is constrained and the resolution of orientation control is limited. Optical tweezers utilizing radiation pressure from photons is another important tool to manipulate and rotate biological cells [3]. The disadvantage of optical tweezers lies in the required high optical intensity to generate enough force and torque, which makes photodamage to biological cells a concern [4].

We propose a new approach for manipulation and rotation of single biological cells that utilizes polarized light to excite resonant oscillating dipoles on the surface of Au nanostructure. Advantages of this approach include fine orientation control and low optical intensity requirement. In this paper, we focus on theoretical analysis that explores light-induced dielectrophoretic force and associated torque to determine the trapping and rotation behavior. Section II-A illustrates the principle of the approach, and Section II-B describes the LSPR properties of the Au nanostructure. Section III-A details the distribution of scattering field induced by LSPR, and Section III-B performs the analysis of light-induced dielectrophoretic force, focusing on simulation of the 3D trapping trajectory for a spherical object. In section III-C, the model is further expanded to non-spherical object and *L. monocytogenes* is used as a model system to study the associated light-induced dielectrophoretic torque and explain the mechanism for orientation control. The self-assembly fabrication process for the Au nanostructure and the characterization results are presented in Section IV.

II. Principle of the Opto-Plasmonic Tweezers

A. System Configuration

Fig. 1 shows the schematic drawing of the proposed opto-plasmonic tweezers. Biological cells are suspended in a solution. The light source, with its polarization adjusted by a fine polarization controller, has an electric field component and is focused on the Au nanostructure. This electric field oscillates in time with frequency of the incident light, and induces the free electrons in Au to move and form oscillating dipole moments. With proper frequency, resonant oscillation of electrons can be induced and the localized surface plasmon resonance is formed. The direction of the oscillating dipoles is parallel to the polarization direction of the light. These dipoles radiate and create a patterned radiation electric field that manipulates the biological cells through DEP.

B. LSPR of the Au nanostructure

Localized surface plasmons are charge density oscillations confined to Au nanostructures. Excitation of localized surface plasmons by an electric field at the resonant wavelength, results in strong scattering light and enhancement of the local electromagnetic field [5]. The resonant wavelength is sensitive to the size, size distribution and shape of the nanostructures. Fig. 2 shows simulation results using Mie theory for the extinction, scattering and absorption spectrum of Au nanospheres with 150 nm diameter.

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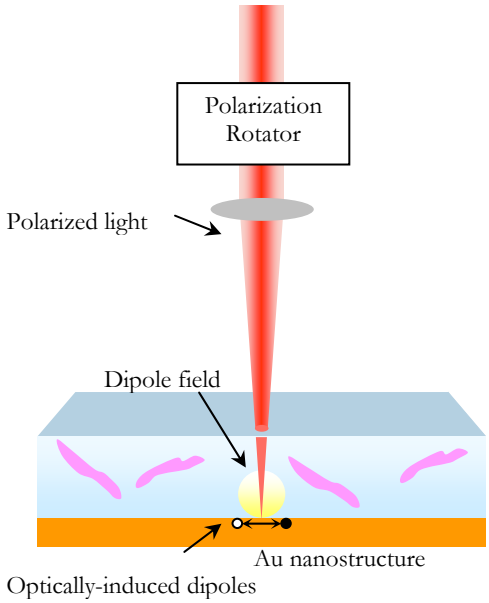


Fig.1 Schematic drawing of the opto-plasmonic tweezers.

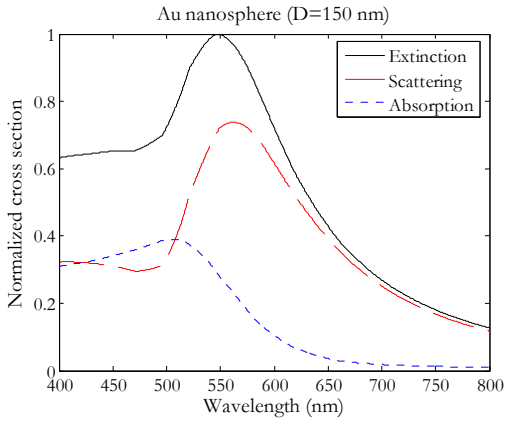


Fig.2 Extinction, scattering and absorption spectrum for the 150 nm diameter nanosphere.

III. Modeling for Spherical Objects

The incident light, with well-defined polarization, has an electric-field component $\vec{E}_0$. This electric field oscillates in time with the frequency of incident light, and has a time dependence of $e^{-j\omega t}$. The magnitude of the electric field is related to the intensity of the focused light I by,

$$E_0 = \sqrt{2\eta_1 I} \tag{1}$$

where η_1 is the impedance of the liquid solution.

Solving for the induced motion of the oscillating electrons under this electrical field using Newton's law, the total dipole momentum of the oscillating electron can be described by,

$$P = \int A \cdot n \cdot dp = \frac{4Anq^2 n_1}{m\omega\alpha\sqrt{n_1^2\omega^2 + \omega_p^2 - \omega^2}}\sqrt{2\eta_1 I} \tag{2}$$

where q and m are the charge and mass for a single electron respectively, n_1 is the refractive index of the solution, ω is the angular frequency of the incident light, ω_p is the plasma frequency of Au, and α is the attenuation coefficient of the incident light in Au. A is the area of the light spot, assuming uniform intensity, and n is the free electron density of Au.

The resonant dipole moments are known as Hertzian dipoles, since its magnitude is much smaller than the radiated wavelength of the radiation field. The direction of the Hertzian dipoles is parallel to the electric-field polarization of the light. They radiate the same way as oscillating charges, and create a patterned radiation field [6]:

$$E = \frac{k^2 P}{4\pi\varepsilon_1 r}\sin\theta \exp i\omega(t - r/c) \tag{3}$$

where k is the wave number, ε_1 is the dielectric constant of the liquid solution, r is the radial distance from the center of light spot, and θ is the longitudinal angle from the axis of dipole.

The DEP force induced by the non-uniform field E on a dielectric spherical object is given by [2],

$$\vec{F}_{DEP} = 2\pi R^3 \varepsilon_1 K^{(1)} \vec{\nabla} E^2 \tag{4}$$

where R is the radius of the object, $K^{(1)}$ is the *Clausius-Mossoti* factor. Substituting Eq. (3) into Eq. (4), the dielectrophoresis force induced by the scattering field becomes,

$$\vec{F} = 2\pi R^3 \varepsilon_1 K^{(1)} \left(\frac{k^2 P}{4\pi\varepsilon_1}\right)^2 \left(-\hat{r}\frac{2}{r^3}\sin^2\theta + \hat{\theta}\frac{2}{r^3}\sin\theta\cos\theta\right) \equiv F_r\hat{r} + F_\theta\hat{\theta} \tag{5}$$

This light-induced dielectrophoretic force consists of two components: Radial force F_r and angular force F_θ. Fig. 3 (a) and Fig. 3(b) show the direction and amplitude cross-section of the two force components, respectively. The combination effect of radial force and angular force will pull the object toward the angular force valley at $\theta = 90^\circ$. If the object is elliptical in shape, its long axis will be aligned to the $\theta = 90^\circ$ equator, orthogonal to the polarization direction of the incident light. Since the polarization direction of the incident light can be tuned very precisely, fine orientation control can be achieved.

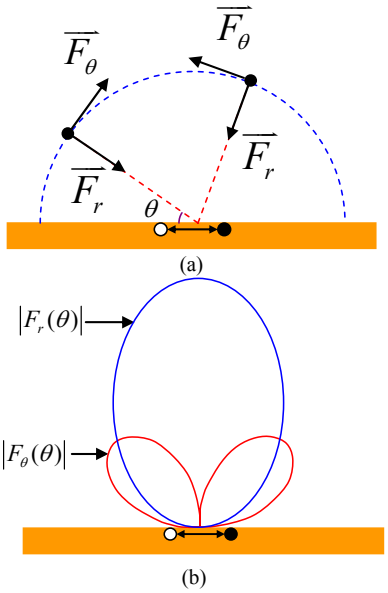


Fig.3 (a) Direction of the radial force and angular force; (b) Amplitude cross section of the radial force and angular force. The distance between a point on the curve and the origin represents the force amplitude at that position.

IV. Modeling for Biological Cells

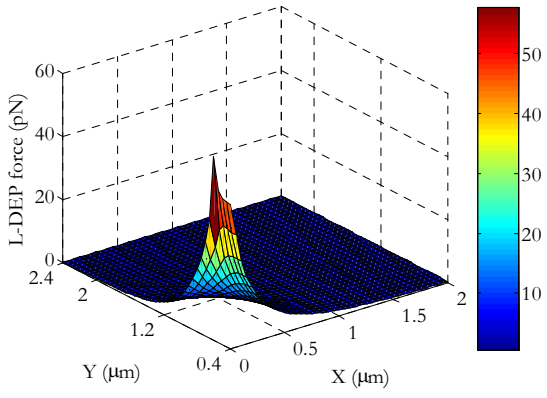
Most of the biological cells are non-spherical. We use *L. monocytogenes* as an example to simulate the 3-dimentional dielectrophoretic force and associated torque. *L. monocytogenes* is an intracellular bacterial pathogen that rapidly invades host cells by hijacking the host cells' actin polymerization machinery for motility [7]. It is elliptical in shape. The physical parameters of the cell are shown in Table I. A shell model is used to represent the equivalent dielectric constant of the whole cell [8],

$$\varepsilon_p^* = \frac{2\varepsilon_m^* + \varepsilon_i^* - 2(\varepsilon_m^* - \varepsilon_i^*)(\frac{2R}{2R+d})^3}{2\varepsilon_m^* + \varepsilon_i^* + (\varepsilon_m^* - \varepsilon_i^*)(\frac{2R}{2R+d})^3}\varepsilon_m^* \approx 6\varepsilon_0 \qquad (8)$$

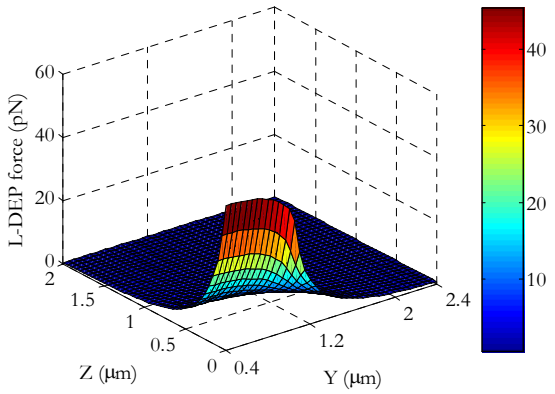
By approximating the cell as an array of spherical elements, the 3-dimentional dielectrophoretic force and associated torque can be calculated using Eq. (5). Figure 4 shows the simulation results for the distribution of the induced dielectrophoretic force. The Au nanostructure array is on the *XZ* plane, and the incident light from *Y*-direction is polarized along *X*-direction. The simulation results show that force ~ 1 *pN* can be achieved at a radial distance of 3 μm, with the light intensity as low as 100 μW/ 100 μm^2. Such intensity is significantly lower than what is required for optical tweezers to achieve the same force amplitude [3]. Furthermore, the 3-dimentional trapping trajectory of the cell is simulated by solving the differential equations according to Newton's Law, which is shown in Fig. 5.

TABLE I
PHYSICAL PARAMETERS FOR *L. MONOCYTOGENES*

Symbol	Parameter	Value
L	long axis radius	0.2 μm
l	short axis radius	0.65 μm
R	equivalent radius	0.47μm
d	membrane thickness	10 nm
ε_m	membrane permittivity	6 ε_0
σ_m	membrane conductivity	10-7 S/m
ε_i	cytoplasm permittivity	50 ε_0
σ_i	cytoplasm conductivity	0.5 S/m



(a)



(b)

Fig.4 Distribution of the induced dielectrophoretic force.

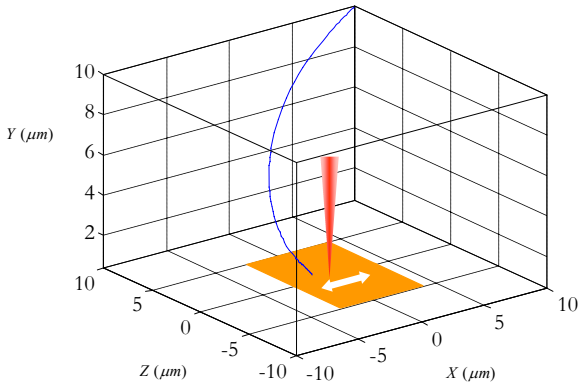


Fig.5 3-dimensional trapping trajectory of the biological cell.

The relationship between the dielectrophoretic torque and long axis orientation of the cell relative to the direction orthogonal to light polarization is shown in Fig. 6. Positive torque induces counter-clockwise rotation, which happens when the long axis of cell is oriented clockwise relative to the orthogonal direction to polarization (negative angle). The simulation shows the magnitude of the torque and confirms that the long axis of the cell will be aligned to the direction orthogonal to the polarization of the incident light. This conclusion is consistent with the force analysis in Section III, which explains the mechanism for orientation control.

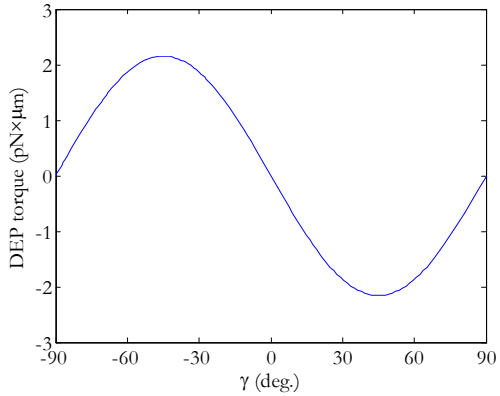


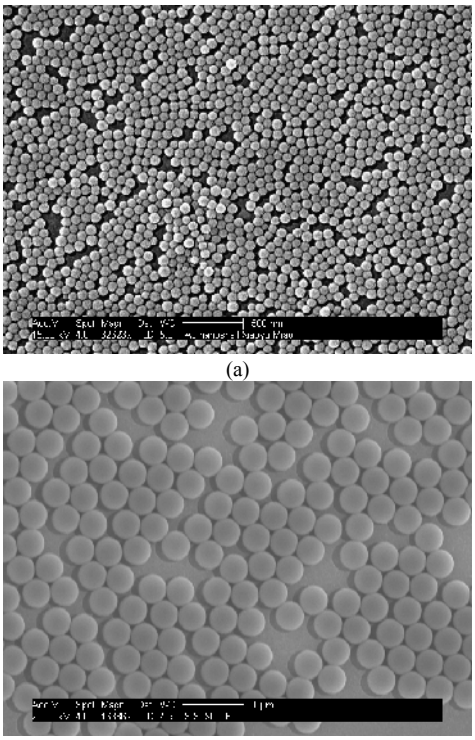
Fig. 6 Simulated DEP torque versus the long axis orientation of the cell.

V. Fabrication and Experimental Results

A. Fabrication process and SEM images

The key component in the opto-plasmonic tweezers is the Au nanostructure array. We utilize a chemical assembly approach to form the Au nanostructure array by using surface-adsorbed polystyrene spheres as a template [9]. Au was first evaporated on the silicon substrate to a thickness of 20 nm using Cr as the adhesion layer. The polystyrene template was self-assembled by exposing the Au-coated substrate to a mixture of carbodiimide, polystyrene sphere suspension and deionized water. The adsorption process was allowed to last for 1 hour. Non-adsorbed spheres were washed away with a copious amount of water; subsequently the formed monolayer was allowed to dry in air. For the final step, another 20 nm of Au was evaporated on the sphere monolayer which forms the Au nanostructure array.

Scanning electron microscope (SEM) is used to characterize the samples formed with different sizes of polystyrene spheres. The images in Fig. 7 show the monodisperse layers with good coverage.



(a)

(b)

Fig.7 SEM micrograph of the Au nanostructure array (a) formed with 85 nm diameter polystyrene spheres; (b) formed with 500 nm polystyrene spheres.

B. Scattering peak of the Au nanostructure

A fiber-coupled UV/VIS spectrometer (OSM-100, Newport/Spectra Physics, CA) is used to characterize the scattering spectrum of the Au nanostructure array. A typical measured scattering spectrum is shown in Fig. 8. The main scattering peak lies at $\lambda = 656.3$ *nm* for the Au nanostructure formed with 1 μm diameter polystyrene spheres.

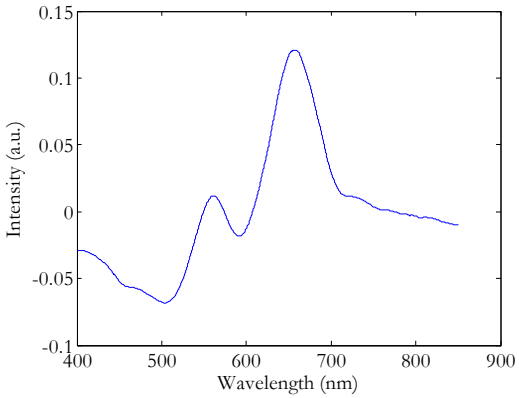


Fig.8 Scattering spectrum of the Au nanostructure array..

C. Future work

A bench-top optical system that includes a fluorescence microscope and an excitation laser is being built to demonstrate the proposed approach. The magnitude of the dielectrophoretic force and torque will be measured and analyzed.

VI. Conclusion

A new opto-plasmonic tweezers is presented as a solution for manipulation and rotation of biological cells. Theoretical analysis is performed to show the trapping and rotation effect of the approach. *L. monocytogenes* is used as an example to simulate the 3-dimentional light-induced dielectrophoretic force and associated torque for the biological cell. Fabrication of the Au nanostructure array and the preliminary experimental results are also presented.

With the opto-plasmonic tweezers, optical manipulation of single biological cells with fine orientation control and low optical intensity requirement can be achieved. Such capability can be useful for researchers in probing various force mechanism in biological cells, as well as biofilm growth and tissue engineering.

References

[1] B. Sakmann, E. Neher, "*Single-Channel Recording*", Plenum Press, New York, 1995.

[2] T. B. Jones, "*Electromechanics of Particles*," Cambridge University Press, Cambridge, UK, 1995.

[3] A. Ashkin, "Optical trapping and manipulation of neutral particles using lasers," *Proc. Natl. Acad. Sci. USA*, vol. 94, pp. 4853-4860, 1997.

[4] K. C. Neuman, E. H. Chadd, G. F. Liou, K. Bergman, and S. M. Block, "Chracterization of photodamage to Escherorichia coli in optical traps," *Biophys. J.*, vol. 77, pp. 2856-2863, 1999.

[5] E. Hutter, and J. H. Fendler, "Exploitation of localized surface plasmon resonance," *Adv. Mater.,* vol. 16, pp. 1685-1706, 2004.

[6] D. J. Griffiths, "*Introduction to electrodynamics*," Prentice Hall, New Jersey, 1999.

[7] J. A. Theriot, "The cell biology of infection by intracellular bacterial pathogens," *Annu. Rev. Cell Dev. Biol.*, vol. 11, pp. 213-239, 1995.

[8] M. Nishioka, S. Katsura, K. Hirano, and A. Mizuno, "Evaluation of cell characteristics by step-wise orientational rotation using optoelectrostatic micromanipulation," *IEEE Trans. Ind. Appl.*, vol. 33, pp. 1381-1387, 1997.

[9] M. Himmelhaus, and H. Takei, "Cap-shaped gold nanoparticles for an optical biosensor," *Sens. and Actuators B*, vol. 63, pp. 24-30, 2000.