Optical Extraction of Unwanted Biological Cells at Gas-Liquid Interface Using Linearly Polarized Light Wave

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***Abstract*—The beam of light carries momentum that can be used to pull or push a particle in a medium. By letting the light scattered from one dielectric medium into another with higher refractive-index, the linear momentum of photons, according to Minkowski theory, can be amplified appropriately. As a result, surface-bound objects can be pulled back to the light source within a specific range of the incident-angle. This paper demonstrates how the optical force can be used to filter foreign particles like bacteria or virus from a biological system which is based on the different optical nature of that foreign particles from the neighboring host ones. The proposed optical-filter works at gas-liquid interface and uses the incident-angle as the filtering parameter.**

Keywords—Optical Pulling Force, Lorentz Force Density, Maxwell Stress Tensor, Optical Momentum, Inter-facial Dragging, Abraham- Minkowski, Dyadic Product, Divergence Theorem.

I. Introduction

The interaction of light with matter [1]–[4] on a nanoscale opens up new opportunities which may have far reaching implications in telecommunications [5], computation, biophotonics, sensing technologies [6], near-field microscopy [7] and spectroscopy, sub-wavelength imaging etc. In response to the electric field of the incident, an electric dipole moment is developed in the interior of a small-particle and this induced dipole is then drawn by field intensity gradients [8]. This gradient-force at the same time competes with radiation pressure due to momentum transferred from the photons in the beam for scattering phenomenon [9]–[11]. Moreover, both the spin and angular momentum [12]–[14] of the dipole changes with time if torque [15], [16] is present due to the effect of curl force component [17]. Hence, light can be used to manipulate small micron and nano-sized particles located in soft matter, allowing physics and biology related experiments with a view to obtaining required information about the particles or the surrounding environment. For instance, in order to manipulate DNA recombination indirectly or for measuring the forces involved in RNA transcription, optical trapping [18], [19] has been applied to biological specimens, such as cells, bacteria and viruses by carefully handling optical intensities that can exceed their damage-threshold. The particle itself has a strong influence on the local electric field and thereby has an active role in the trapping mechanism [20] which is in fact the so-called self-induced back-action (SIBA) and can be enhanced by the use of an optical resonance [21], [22].

Recently, the so-called optical 'tractor beams' [23]–[25] has been a focus of attention, because of their exciting capability of exerting a 'negative' (acting against the flow of light) force that pulls the scatterer in a direction opposite to the propagation of light and eventually transporting the object over a long distance without confining it at the focal point. A good candidate for a tractor beam can be a nonparaxial gradientless beam (e.g. Bessel beam) [26]–[28] because it can transfer more photons to the forward direction of the particle than the backward. According to Newton's third law, when the light strongly scatters upon the backward/forward hemisphere, the photons transfer more forward/backward momentum (respectively) to the particle resulting in a pulling/pushing force (respectively). Thus the formation of an asymmetric scattering pattern and associated momentum transfer results in the dragging (pulling/pushing) force [29]. Therefore, the fundamental requirement for a negative (pulling) force to arise naturally is that, after interaction with an object, the momentum of light should intensify along the direction of the incident beam.

Once the particle is at the gas-liquid interface, sophisticated control of structured light is no longer required. In recent research [30] it is demonstrated both theoretically and experimentally that it is possible to pull a particle through the gas-liquid interface along the direction of light source. Light wave irrespective of beam shape, polarization, relative phase, coherence, etc., can be transformed into be a tractor-beam through the amplification of photon-momentum in forward direction simply by using the bi-background medium configuration. When the momentum of the light is increased, the scattering force experienced by the object would be negative according to the conservation of momentum. With such a negative driving force, the scatterer may move along the gas-liquid interface by overcoming the viscous force of liquid at an observable velocity.

The central motivation in this paper is to show a practical implication of optical force which results from the interaction of light with matters. The ability to manipulate the particle along the gas-liquid interface has significant applications in biological systems. In this paper, detailed simulation is carried out to show how the interfacial dragging force can be used to manipulate a certain biological cell and separate it from the other particles surrounding it having different shapes and optical properties.

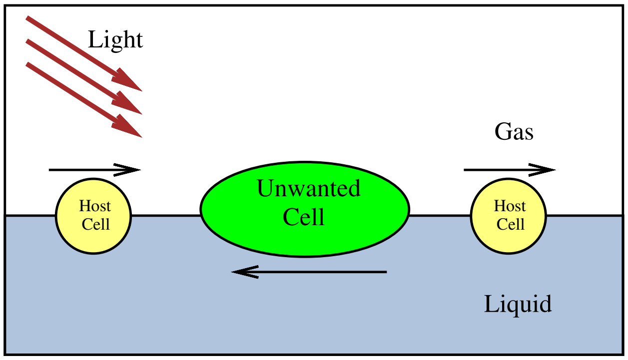

Fig. 1. Projection of plane wave on a biological system consisting of unwanted cell surrounded by host cells. Black arrows denote the direction of optical force acting on cells.

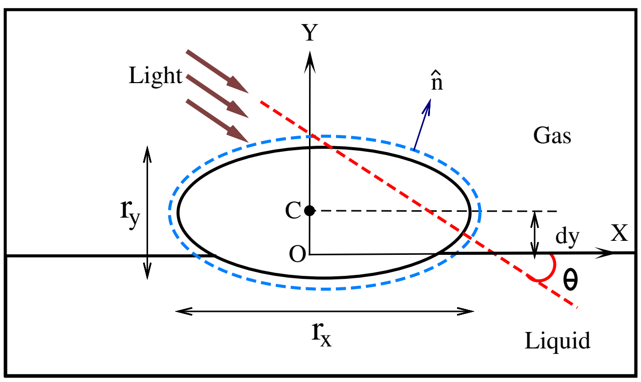

Fig. 2. Cross sectional view of a particle at the gas-liquid interface. Where θ is angle of incidence of the light beam, r_x and r_y denote dimensions along principle and secondary axes respectively, dy is distance between the gravitational center and gas-liquid interface and $\hat{n}$ represents the unit normal vector of the outer surface shown by dotted blue colored line.

II. Physical System

In this paper the authors propose that it is possible to separate foreign particles like bacteria in a biological system consisting of blood cells with the use of inter-facial dragging force which has recently been demonstrated theoretically and experimentally in [30].

In Fig.1 the green colored elliptical object indicates the unwanted foreign particle which is neighbored by some other sphere shaped blood cells and all of them are floating between a gas-liquid interface. The target is to separate the green particle from the pink ones using the unique momentum action of light for different shaped particles.

This simple system is used to demonstrate the optical force at gas-liquid interface. A particle centered at, above or below the gas-liquid interface can be denoted with the vertical distance dy being zero, positive or negative on how much the object is submerged. The size of the particle is defined by its principal and secondary axes dimensions r_x and r_y respectively. For $r_x = r_y$, particle is spherical, otherwise particle is elliptical. Angle of incidence (θ) and wavelength (λ) of the light beam are varied from 0^0 to 90^0 and $600nm$ to $1200nm$ respectively.

In the 2D geometry dealt with here, an incident wave has been employed whose magnetic field is linearly polarized along z-direction given by $H_z = H_{z0}e^{-j(\mathbf{k}.\mathbf{r}-\varpi t)}$, where H_{z0} is the amplitude of the magnetic field, $\mathbf{k}$ is the wave vector of incident wave and $\mathbf{r}$ denotes the radial vector.

III. Methods of Calculating Optical Force on a Dielectric Particle

The momentum conservation theorem, [31] derived from the Lorentz force-law along with the Maxwell equations, relates the total force on a material object in terms of the momentum of the incident and scattered fields at all times. When time-harmonic fields are considered, the time-averaged force on a material body can be calculated from a single divergence integral. This can be shown by derivation of the momentum conservation theorem with the assumption that all fields have $\mathbf{e^{-j\omega t}}$ time dependence. The Lorentz force provides the fundamental relationship between electromagnetic fields and the mechanical force on charges and currents [31]. The time averaged Lorentz force, $\mathbf{f}$ is given in terms of the electric field strength $\mathbf{E}$ and magnetic flux density $\mathbf{B}$ by

$$\mathbf{f} = \frac{1}{2}\,\mathrm{Re}\left\{\rho\mathbf{E}^* + \mathbf{J}\times\mathbf{B}^*\right\} \tag{1}$$

where ρ and $\mathbf{J}$ represent charge density and current density, respectively, $\mathrm{Re}\{\}$ represents real part of an expression and $(^*)$ represents complex conjugate of a quantity.

$$\nabla.\mathbf{D} = \rho \tag{2}$$

$$\nabla\times\mathbf{H} = \mathbf{J} - j\omega\mathbf{D} \tag{3}$$

$$\nabla.\mathbf{B} = 0 \tag{4}$$

$$\nabla\times\mathbf{E} = j\omega\mathbf{B} \tag{5}$$

The above four equations represents Maxwell's equations in phasor form. Carrying out some mathematical analysis (1) becomes a symmetrical one [32].

$$\begin{aligned}\mathbf{f} = &\frac{1}{2}\,\mathrm{Re}\left\{(\nabla\cdot\mathbf{D})\,\mathbf{E}^* + (\nabla\times\mathbf{E}^*)\times\mathbf{D}\right\}\\ &+\frac{1}{2}\,\mathrm{Re}\left\{(\nabla\cdot\mathbf{B}^*)\,\mathbf{H} + (\nabla\times\mathbf{H})\times\mathbf{B}^*\right\}\end{aligned} \tag{6}$$

The momentum conservation theorem for time harmonic fields is reduced to

$$\mathbf{f} = -\frac{1}{2}\,\mathrm{Re}\left\{\nabla\cdot\overleftrightarrow{\mathbf{T}}(\mathbf{r})\right\} \tag{7}$$

Maxwell stress tensor is given as

$$\overleftrightarrow{\mathbf{T}}(\mathbf{r}) = \frac{1}{2}\left(\mathbf{D}.\mathbf{E}^* + \mathbf{B}^*.\mathbf{H}\right)\overleftrightarrow{\mathbf{I}} - \mathbf{D}\mathbf{E}^* - \mathbf{B}^*\mathbf{H} \tag{8}$$

$\mathbf{DE}^*$ and $\mathbf{B}^*\mathbf{H}$ are dyadic products and $\overleftrightarrow{\mathbf{I}}$ is the 3×3 identity matrix. By integration over a volume enclosed by a surface S (Fig. 2) and by applying the divergence theorem, the total force $\mathbf{F}$ on the material enclosed by S is given by

$$\mathbf{F} = -\frac{1}{2}\,\mathrm{Re}\left\{\oint_S dS\left(\hat{n}\cdot\overleftrightarrow{\mathbf{T}}(\mathbf{r})\right)\right\} \tag{9}$$

where $\hat{n}$ is the outward normal to the surface S. When applying (9) to calculate the force on a material object, the stress tensor in (8) is integrated over a surface chosen to completely enclose the object.

IV. Simulation Results

The optical force along X-axis of gas liquid interface is shown in Fig. 3. The simulation is carried over for two different shaped particles. The black one with cross-marker and the red one with circle are for spherical and elliptical shaped particles respectively. For explanation purpose Fig. 3 is partitioned into A and B regions. In region A for elliptical particle the obtained optical force is pulling in nature (direction of the force is along negative X-axis) whereas it is positive (pushing) for the spherical particle. On the other hand, in region B (incident angle greater than 15^0) negative (pulling) force occurs for both shaped particles.

The more eccentric the particle is, the wider the incident angle range becomes for which the negative dragging force is increased. For the spherical particle the negative force occurs for the angle above 20 degree whereas for ellipsoid particles the angle-range may either increase or decrease depending upon the flatness of it, the flatter the particle the wider the angle range.

On the vertical direction, surface energy-well is deep enough to overcome the thermal Brownian motion, and also the gravitational energy. The experienced optical force in vertical direction (along Y-axis) is positive for all incident angles which confirms the scatterer to be floating on the water-air interface stably, and moving along the tangential direction simultaneously. The corresponding simulation results of this fact are shown in Fig.4.

Fig.5 and Fig.6 demonstrate the effect of optical wavelength on the spherical and elliptical shaped particle respectively. The shape of the graph is almost identical which confirms the little dependence of optical force on the optical wavelength. So the particle can be optically manipulated in a similar manner for a wide wavelength region.

It is clear from the above section that elliptical shaped particle can be pulled whereas spherical particle can be pushed by the light for wide range of optical wavelength for the incident angle below 15 degree. In a biological system where the foreign particle of elliptical shape with the neighboring ones of spherical shape, the foreign one acts fully opposite and it is possible to extract the unwanted foreign particle from that system softly by using the mechanical action of light. It is not necessary for the particle to be elliptical or spherical, rather particles can be of any other shapes and in that case the angle-region must be chosen in such a way that the direction of the optical force for the foreign particles is opposite to that for the host particles.

Efficient filtering of foreign particles from a desired system requires the following facts to be considered.

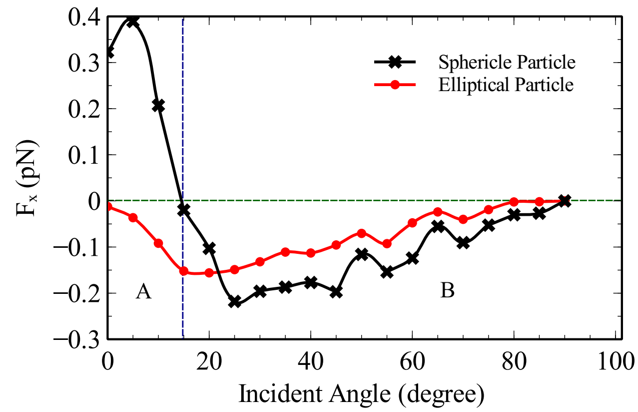

Fig. 3. Optical force in X-direction exerted on the particle for different incident angle of light illumination. The black line with cross marker and red line with circle represents represents the spherical ($r_x/r_y = 1$) particle the elliptical particle ($r_x/r_y = 3/2$) respectively with the same major axis $r_x = 1\mu m$. The wavelength of light used here is 1024 nm.

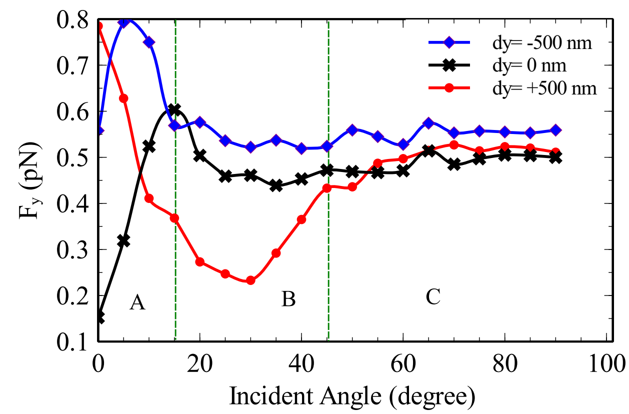

Fig. 4. Optical force in Y-direction exerted on a spherical ($r_x/r_y = 1$) particle for different incident angle of light illumination. The blue line with diamond, black line with cross and red line with circle represents the cases while $dy = -500nm$, $dy = 0nm$, $dy = 500nm$ that means the particle center is below, at and above the gas-liquid interface respectively. The wavelength of light is 1024 nm.

i. The incident angle of light is to be selected in such a way that the pulling force on the unwanted foreign particles can relatively be much stronger than the pushing force on the desired biological host particles.

ii. The intensity of the light must not exceed the damage-threshold of the biological particles and at the same time should be strong enough to overcome the viscous drag of the liquid.

iii. If the unwanted particles are fully immersed into the liquid-medium, then at first the unwanted particles are to be conveyed from liquid to gas-liquid interface for which structured light is needed and this part is out of scope of this paper. Once the unwanted particles are at the gas-liquid interface, we can use simple plane-wave to drag particles without the aid of structured lights ensuring that the vertical component of the optical force is strong enough to uphold the particles at the interface.

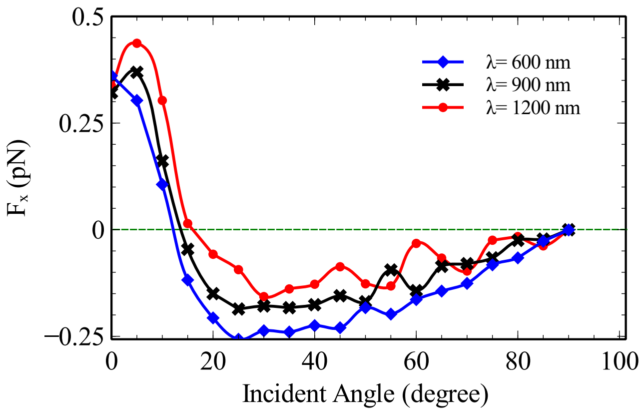

Fig. 5. Optical force in X-direction exerted on a spherical ($r_x/r_y = 1$) particle centered at the gas-liquid interface for different incident angle of light illumination. The blue line with diamond, black line with cross and red line with circle represent the cases $\lambda = 600nm$, $\lambda = 900nm$, $\lambda = 1200nm$ of incident light wavelength respectively.

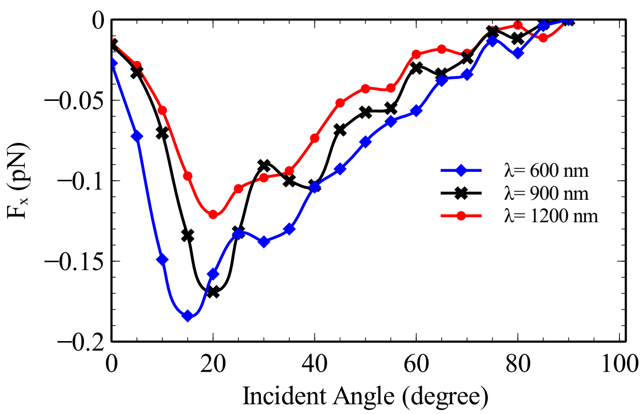

Fig. 6. Optical force in X-direction exerted on a elliptical ($r_x/r_y = 3/2$) particle centered at the gas-liquid interface for different incident angle of light illumination. The blue line with diamond, black line with cross and red line with circle represent the cases $\lambda = 600nm$, $\lambda = 900nm$, $\lambda = 1200nm$ of incident light wavelength respectively.

V. Conclusion

Optical pulling can have several important biological applications in future. In medical science, the presence of bacteria or virus in the blood-stream is known as bacteremia and viremia respectively and millions of people each year depend on the transfusion of quality blood. If there exists any way of separating virus or bacteria from a bag of contaminated blood collected from a patient, the same blood after purication can be pushed inside the same patient. Optical pulling can be such an effective way of blood purification without damaging the blood-cells and hence patients will be less dependent on quality blood from blood-donors. Another application might be the separation of red blood-cells or a specific type of white blood-cells from the blood. At present, a convenient way of obtaining white cells from whole blood is to allow EDTA-blood (blood mixed with Ethylene Diamine Tetra-acetic Acid) to settle in siliconized glasses and then pipette off the leucocyte-rich supernatant after 1.5 hour or more. Simple light waves can be an alternative and easier way of this separation using pulling phenomena of light because white cells namely Monocyte, Lymphocyte, Eosinophil, Basophil and Neutrophil have distinct sizes and shapes. In this light-related process, no chemical like EDTA is required to be mixed with blood during the separation. The same technique can be implemented to separate red blood-cells if needed. The optical traction mentioned above can only be applicable for gas-liquid interface while a particle inside the liquid cannot be separated in this way. In case of fully immersed particles inside the liquid, at first the particles are to be conveyed onto the surface of liquid which requires structured beams such as Bessel beam instead of simple plane wave. The authors are trying to nd an effective way of lifting a fully immersed particle out of the liquid. If a well-developed way can be implemented to shift a particle inside the liquid with full control, it can have far reaching application in biological research field.

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