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INFLUENCE OF ENERGY AND DURATION OF LASER PULSES ON STABILITY OF DIELECTRIC NANOPARTICLES IN OPTICAL TRAP

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Abstract. *In this article the gradient force of optical trap using two counter-propagating pulsed Gaussian beam and the Brownian motion in optical force field are investigated. The influence of the energy and duration time of optical pulsed Gaussian beams on satability of nano-particle in trap is simulated and discussed.*

I. INTRODUCTION

In 1970, Ashkin[1] first demonstrated the optical trapping of particles using the radiation force produced by the focused continuous-wave (CW) Gaussian beam. Since that the optical trap and tweezer have been a powerful tool for manipulating dielectric particles [2, 3].

Usually, the optical traps or tweezer in many experiments are constructed by using the CW laser. It is well known, that the CW laser with the power of a few milliwatt can only produce the radiation force with an order of a few pN to manipulate the micro-sized particles. Recently, Ambardekar *et al.* [4], Deng *et al.* [5], Zhao [6] and Wang *et al.* [7] used a pulsed laser to generate the large gradient force, up to 2500 pN within a short duration, about ps. Up to now, we have paid attention on optical trap using pulsed Gaussian beam [7] and on optical trap using counter-propagating pulsed Gaussian beams [8]. In works [8-11], the discussions about stability of the optical trap and the tweezer as well as the effective controlling dielectric particles as gold nanoparticles, live membrane, have been discussed into account in Brownian force. But, the stabilizing process during the pulsing of the optical beam and the absolutely-stable conditions of dielectric particles were not clear. Therefore, above questions become an urgent one for the pulsing optical trap.

This paper is organized as follows: In Sec. II we introduce the Gradient Optical force acting on dielectric nanoparticles in the optical trap using two counter-propagating pulsed Gaussian beam (PGB) and the set of Langevin equations concerning thermal fluctuations of the probe, discribing the Brownian motion in the optical force field; Sec. III presents a simulated method; Sec. IV presents the radial variances of glass nanoparticles in waters, which are traped by picosecond PGB and the discussions about influence of energy and duration time of pulses on stability of them.

II. THEORY

A PGB is considered to trap fluctuating dielectic nanoparticles in the water plate (Fig.1). We consider the Gradient optical force is induced by two counter-propagating PGBs acting on a Rayleigh dielectric particle. The polarization direction of the electric field is assumed to be along the x axis.

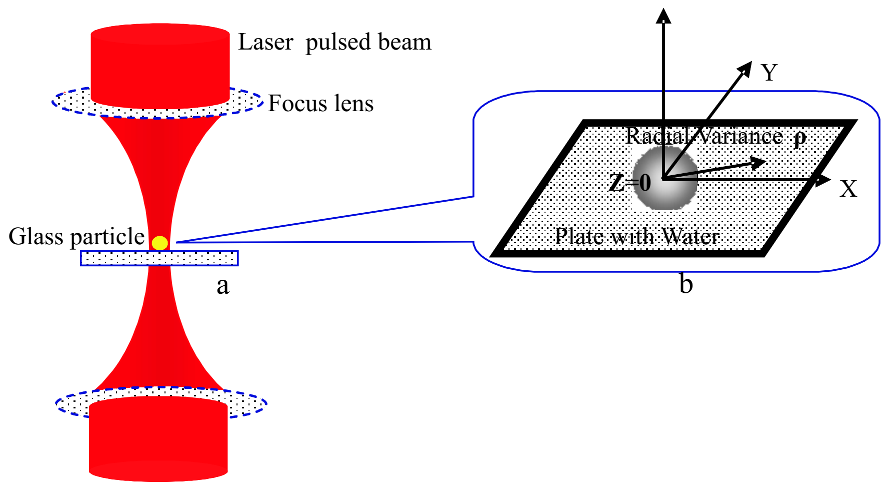

Fig. 1. Optical trap's sketch using the pulsed Gaussian beams (a) and motion with radial variance of glass particle in the water plate (b).

The expression for the electric field of the above PGB is defined by [6]

$$\begin{aligned}\vec{E}_{above}(\rho,z,t) =& \hat{x}E_0\frac{ikW_0^2}{ikW_0^2+2z}\exp\left[-i\left(k\left(z\right)-\omega_0 t\right)\right]\\ &\times\exp\left[-i\frac{2kz\rho^2}{\left(kW_0^2\right)+2z^2}\right]\cdot\exp\left[-\frac{\left(kW_0^2\right)^2\rho^2}{\left(kW_0^2\right)^2+4z^2}\right]\\ &\times\exp\left[-\left(t-zc\right)^2/\tau^2\right],\end{aligned} \tag{1}$$

and for the below PGB

$$\begin{aligned}\vec{E}_{below}(\rho,z,t) =& \hat{x}E_0\frac{ikW_0^2}{ikW_0^2+2z}\exp\left[-i\left(k\left(z\right)-\omega_0 t\right)\right]\\ &\times\exp\left[-i\frac{2kz\rho^2}{\left(kW_0^2\right)+2z^2}\right]\cdot\exp\left[-\frac{\left(kW_0^2\right)^2\rho^2}{\left(kW_0^2\right)^2+4z^2}\right]\\ &\times\exp\left[-\left(t+zc\right)^2/\tau^2\right],\end{aligned} \tag{2}$$

where W_0 is the spot radius of the beam waist at the plane $z = 0$, ρ is the radial coordinate, $\hat{x}$ is the unit vector of the polarization along the x direction, $k = 2\pi/\lambda$ is the wave number, ω_0 is the carrier frequency, and τ is the pulse duration. For the fixed input energy U of a single pulsed beam, the constant E_0 is determined by $E_0^2 = 4\sqrt{2}U/\left[n_2\varepsilon_0 c W_0^2 (\pi)^{3/2}\tau\right]$. Here n_2 is the refractive index of the surrounding medium. From the definition of the Poynting vector, we can readily obtain the intensity distribution for the above PGB as follows:

$$\begin{aligned} I_{above}(\rho,z,t) &= \left\langle \vec{S}_{above}(\rho,z,t)\right\rangle \\ &= \frac{P}{1+4\tilde{z}^2}\exp\left[-\frac{2\tilde{\rho}^2}{1+4\tilde{z}^2}\right]\times\exp\left[-2\left(\tilde{t}-\frac{\tilde{z}kW_0^2}{c\tau}\right)^2\right] \end{aligned} \tag{3}$$

$$\begin{aligned} I_{below}(\rho,z,t) &= \left\langle \vec{S}_{below}(\rho,z,t)\right\rangle \\ &= \frac{P}{1+4\tilde{z}^2}\exp\left[-\frac{2\tilde{\rho}^2}{1+4\tilde{z}^2}\right]\times\exp\left[-2\left(\tilde{t}+\frac{\tilde{z}kW_0^2}{c\tau}\right)^2\right] \end{aligned} \tag{4}$$

where $P = 2\sqrt{2}U/\left[(\pi)^{3/2}W_0^2\tau\right]$, $\tilde{z} = z/kW_0^2$, $\tilde{\rho} = \rho/W_0$ and $\tilde{t} = t/\tau$.

For simplicity, we assume that the radius (a) of the particle is much smaller than the wavelength of the laser (i.e., $a << \lambda$), in this case we can treat the dielectric particle as a point dipole. Assume that the refractive index of the particle is n_1 and $n_1 > n_2$.

By argument similar to that shown in the work of Zhao [6] for one PGB and of Isomura for counter-PGB, the gradient optical force acting on dielectric particle of two counter-propagating PGBs is given by

$$\vec{F}_{grad,\rho}(\rho,z,t) = -\frac{\hat{\rho}2\beta\left[I_{above}(\rho,z,t)+I_{below}(\rho,z,t)\right]\tilde{\rho}}{\left[cn_2\varepsilon_0 W_0\left(1+4(\tilde{z})^2\right)\right]} \tag{5}$$

where $\beta = 4\pi n_2^2\varepsilon_0 a^3\left[\left(m^2-1\right)/\left(m^2+2\right)\right]$ is the polarizability, and $m = n_1/n_2$ [6, 7].

Assuming a low Reynold number regime [12], the Brownian motion of the dielectric in the optical force field (in the optical trap) is described by a set of Langevin equations as follows:

$$\gamma\dot{\vec{\rho}}(t) + \vec{F}_{grad,\rho}\vec{\rho}(t) = \sqrt{2D}\gamma\vec{h}(t) \tag{6}$$

where $\vec{\rho}(t) = [x(t), y(t)]$ is the dielectric particle's position in the water plate, $\gamma = 6\pi a\eta$ is its friction coefficient,η is the medium viscosity, $\sqrt{2D}\gamma\vec{h}(t) = \sqrt{2D}\gamma\left[h_x(t), h_y(t)\right]$ is a vector of independent white Gaussian random processes describing the Brownian force, $D = k_B T/\gamma$ is the diffusion coefficient, T is the absolute temperature, and k_B is the Boltzmann constant.

III. SIMULATION METHOD

We compute the two-dimensional motion and the radial variance (position) of a glass particle in water using the Brownian dynamic simulation method. A particle/beadspring model is employed to represent the glass particle, and the following equation of motion is computed for each particle:

$$\vec{\rho}\,(t+\delta t)-\vec{\rho}\,(t)=-\frac{\vec{F}_{grad,\rho}\left(\vec{\rho}\,(t)\right)}{\gamma}\times\vec{\rho}\,(t)\times\delta t+\sqrt{2D}\times\delta t\times\vec{h}\,(t) \tag{7}$$

where δt is the time increment of the simulation, $\vec{h}\,(t)$ is a random vector whose components are chosen from the range [-1, 1] in each time step. $\vec{F}_{grad,\rho}\left(\vec{\rho}\,(t)\right)$in Eq.(6) describes the gradient optical force acting on particle located at position $\vec{\rho}$ at time t. For example, at beginning time t=0, the glass particle is assumed to locate at the position$|\rho\,(t=0)|=W_0$, where W_0 is the beam waist, then we understand that the gradient optical force $\vec{F}_{grad,\rho}\,(W_0,z,0)$ acts on particle, which will be located at position $W+\Delta\rho$ after a time increment δt.

We interest only on the radial variance of glass particle in the pulsing time (this parameter describes the stability of particle), so the simulation will be computed from beginning moment t=-3τ (or t=0) to ending moment t=3τ (or t=6τ) of the optical pulse. In following numerical simulation we choose parameters as follows: $\lambda=1.064\mu m$, $m=n_1/n_2=1.592/1.332$, $\eta=7.797\times10^{-1}Pa.s$ (the small glass particle and water, for instance) [6], $W_0=1\mu m$, $a=10nm$, $\tau=(0.1\div100)\,ps$, and the input power is changed by $U=(0.01\div100)\,\mu J$[7], T=25^{o}C. The gradient optical force $F_{grad,\rho}$ is calculated by expression (5) in the ranges: $t=(-3\div3)\,\tau$, and $\rho=(-2\div2)W_0$ at $z=0$ μm (consider the beam waist of pulsed Gaussian beam located in the traping plane $z=0$).

IV. RESULTS

IV.1. Distribution of optical force

The simulations show that the gradient optical forces acting on the glass particle in water are divided into two parts whose directions are opposite to each other (Fig. 2a) and magnitudes are distributed as Gaussian function of radial distance (Fig. 2b), and of pulsing time (Fig. 2c). This distribution of gradient optical force is in good agreement to that presented in the work [6], it means gradient forces are centripetal.

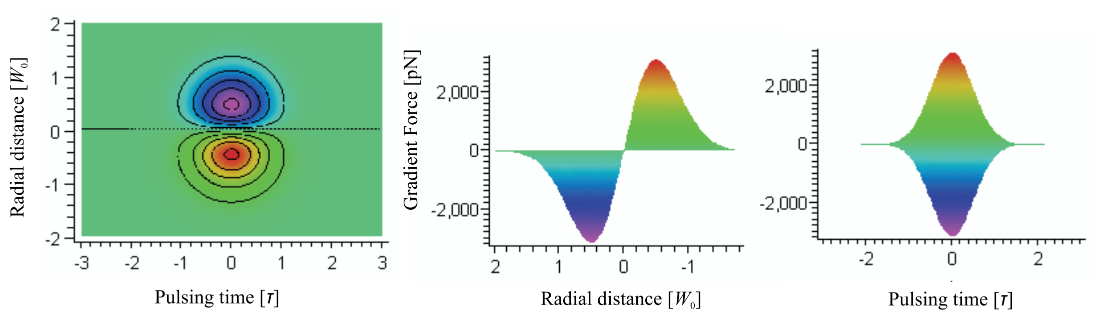

Fig. 2. Distribution of optical force in phase plane (ρ, t) (a), in direction ρ (b), and in pulsing time (c).

IV.2. Particle's motion in trap

The motions of two glass particles, whose beginning position $|\rho\,(t=0)| = W_0\sqrt{2}$ (for example: $x(0) = W_0$, $y(0) = W_0$) and $|\rho\,(t=0)| = W_0$ (for example: $x(0) = 0$, $y(0) = -W_0$), during pulsing time are simulated and discribed in Fig.3f. We can see that, at beginning and ending time of the pulse when energy is low, the particle moves randomly (Figs. 3a, d and e). With increasing of energy beginning from second picosecond of the pulse, i.e. the gradient optical force increases, the particles are pulled into, "called" stable circle with radius W_0 of the trap (Fig. 3b). When energy is high enough the optical force predominates over Brownian force, particle is trapped in center of the trap (Fig. 3c). In this case we can affirm that particle is absolutely stable.

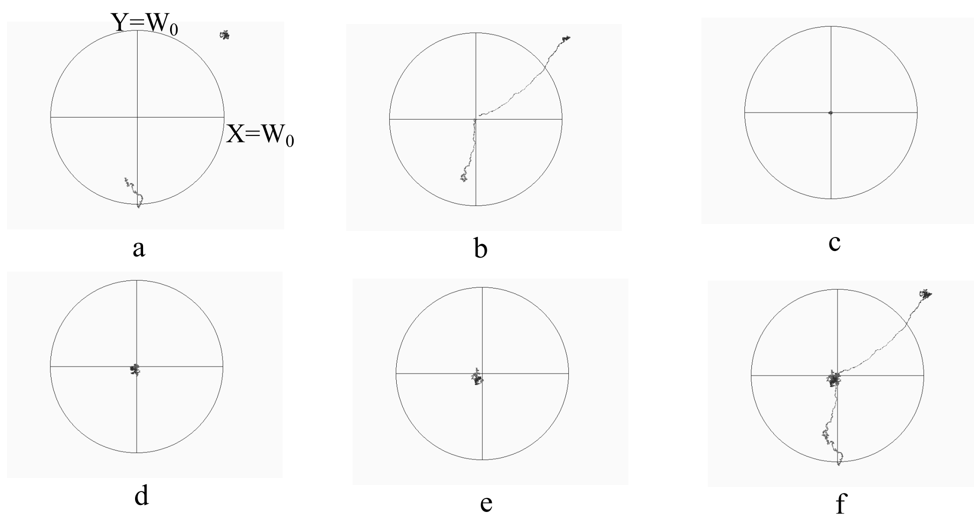

Fig. 3. Position of glass particle in trap during pulsing time of the pulse $\tau = 1$ps
a- first ps, b- second ps, c- third and fourth ps, d- firth ps, e- sixth ps, f)- all pulse

IV.3. Influence of duration time and energy of pulse

With given particle and fluid, i.e. with the given Brownian force, stability of particle in optical trap depends on optical force. It means stability of particle depends on duration time and energy of the pulse. It is proved in Fig. 4 and Fig. 5. If energy (U) is too low or duration time (τ) is too long, particle moves randomly (Fig. 4a and Fig. 5a), even the particle in center of the trap. But when duration time descreases or energy increases, the particle is forced by optical gradient force, so it is pulled into center of the trap (Fig. 4b, Fig. 4c, Fig. 5b, and Fig. 5c). With shorter duration time or higher energy, stability of the particle is more reached and stable time is longer (Fig. 4c, Fig. 4d, Fig. 5c, and Fig. 5d). Therefore, to reach stability of the particle in optical trap, we must to choose pulsed beams with energy and duration time optimal, appropriate to dielectric particle and its fluid. Moreover, to long stable time, we must to use pulsed beam so that optical force is always predominant over Brownian force. These questions will be solved when radius, refractive index of the particle and viscovity of the fluid are known.

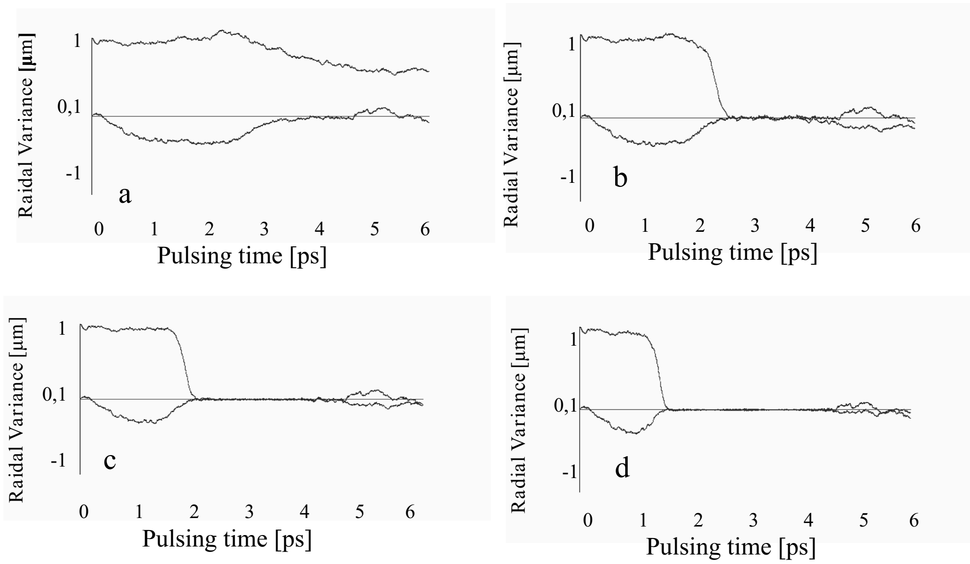

Fig. 4. Radial variance of glass particle during pulsing time a) -τ=100 ps, b) τ=10 ps, c) τ=1 ps, d) τ=0.1 ps.

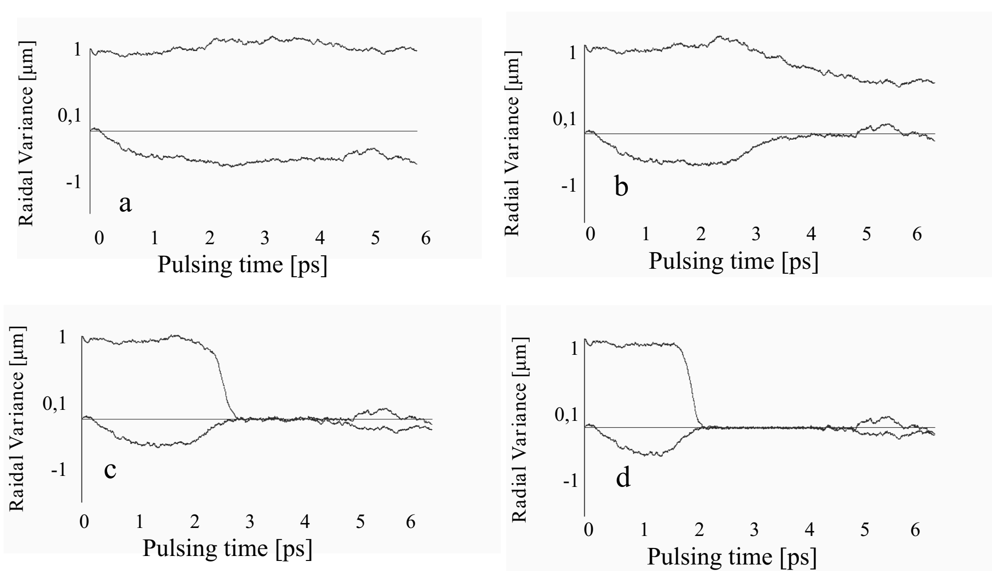

Fig. 5. Radial variance of glass particle during pulsing time a) $U = 0.01$ μJ, b) $U = 0.1$ μJ, c) $U = 1$ μJ, d) $U = 10$ μJ.

V. CONCLUSION

Using the Langevin equation describing the Brownian motion in force field for optical trap, stability of the dielectric particle in fluid is investigated and discussed. From all results and discussions, we can conlude that: first, the Brownian force influences on stabilizing process of the glass particles in water by the optical trap using the pulsed Gaussian optical beams; second, energy and duration of the pulses influence on stability of the trap; third, to have absolute stability of the trap for application, an appropriateness between parameters of the pulse, particle and fluid must be chosen.

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