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The Influence of Parameters on Stable Space-time “Pillar” in Optical Tweezer using Counter-propagating Pulsed Laser Beams

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Abstract: In this article the stable process of the optical tweezer using the pulsed counter-propagating Gaussian beams is investigated using the Langevin equation with optical gradient force. The influence of parameters as the total energy, the beam waist, the radius of particle and the viscosity of fluid on the dimension of the stable space-time “pillar” is simulated and discussed.

Key words: optical tweezer, pulsed Gaussian beam, optical force, Brownian motion

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 then the optical trap and tweezers have been a powerful tool for manipulating dielectric particles [2, 3].

In works [4-7], the discussions about stability of the optical trap and the tweezers as well as the effectively controlling dielectric particles like gold nanoparticles and live membrane, have been conducted taking into account the Brownian force. However, the stabilizing process during the pulsing of the optical beam and the absolutely-stable conditions of dielectric particles were not clear. Therefore, it is desirable to advance the studies of the above questions for the pulsing optical trap.

Up to now, we have paid attention to the optical trap using counter-propagating pulsed Gaussian beams [8] and after discussing its stability in general, but not in detail.

In this paper the stable process during pulsing time of the trap and the influence of optical parameters on its stability are of interest. This paper is organized as follows: In Sec. II we introduce the Gradient Optical force acting on dielectric nano particles in the optical trap using two counter-propagating pulsed Gaussian beams (PGBs), the set of Langevin equations concerning thermal fluctuations of the probe and the simulated method. In Sec. III we present the radial variances of glass nano particles in water, which are trapped by picoseconds PGB and the discussions about influence of some parameters on dimension of the stable space-time “pillar”.

II. THEORY

Two PGBs with total energy U, and duration time τ, are considered to tweezer fluctuating dielectric nano-particles 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, which has radius a, and refractive index n_1. The polarization direction of the elec-

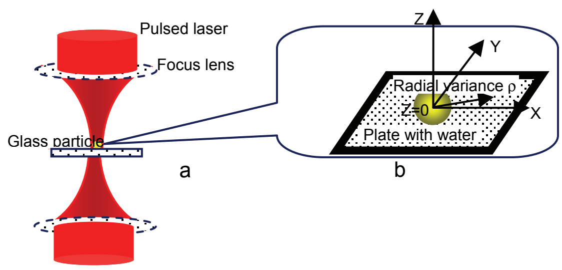

Fig. 1. (a) The schematic of optical tweezer. (b) The motion with radial variance of glass particle in the water plate

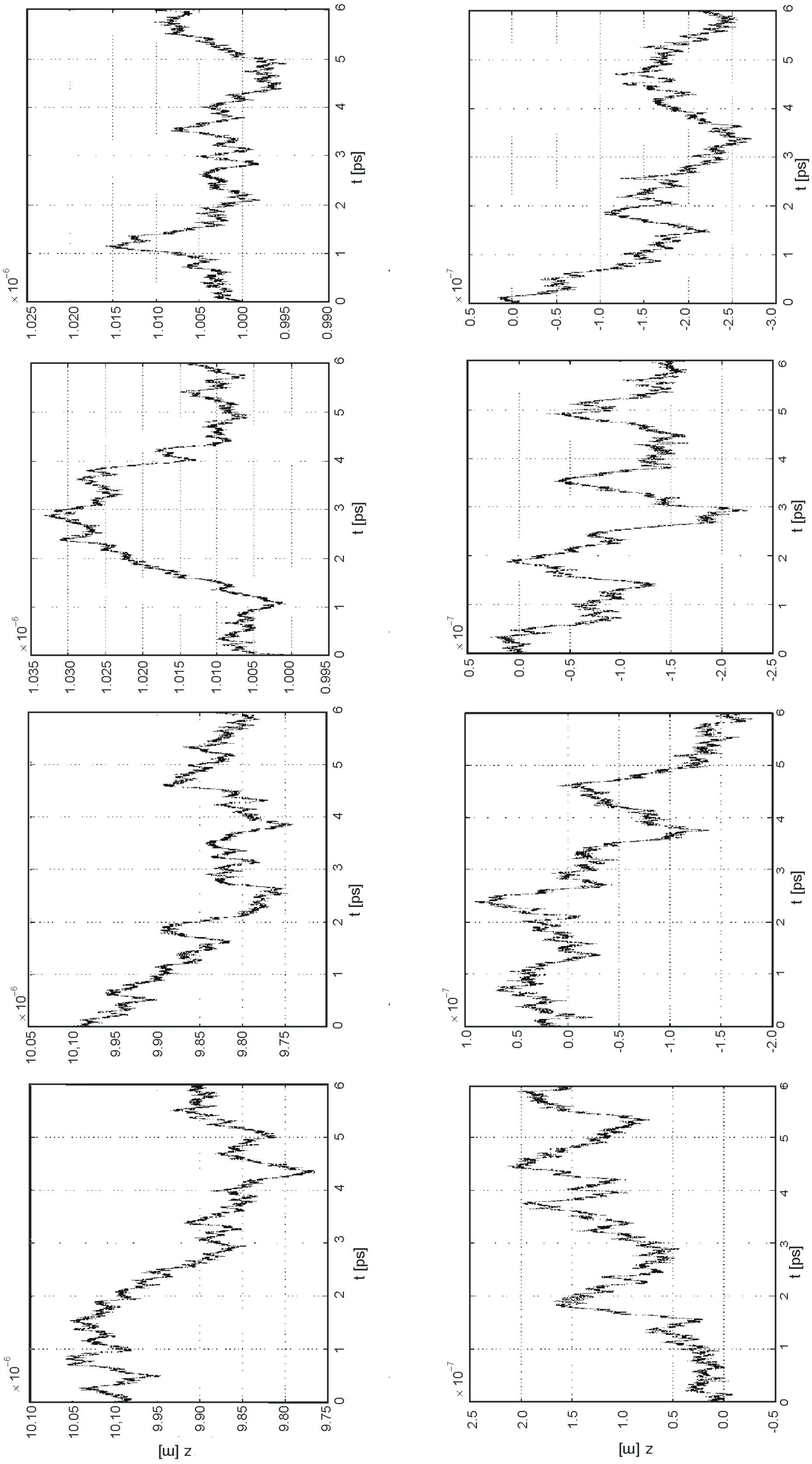

Fig. 2. The random Brownian motions of glass particle in water

tric field is assumed to be along the x axis. 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. We also assume that the refractive index of the glass particle is n_1 and $n_1 >> n_2$. Here n_2 is the refractive index of the surrounding medium (water).

The gradient optical force acting on a dielectric particle of two counter-propagating PGBs is given by [4, 8]

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

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, $\hat{\rho}$ is the unit radial vector, $\tilde{\rho} = \rho / W_0$, $\tilde{z} = z / kW_0^2$, W_0 is the waist radius of two beams at the plane $z = 0$, $m = n_1 / n_2$.

The intensity distribution for the above PGBs is as follows [4]:

$$I_{\mathrm{above}}(\rho,z,t) = = \frac{P}{1+4\tilde{z}^2}\exp\left[-\frac{2\tilde{\rho}^2}{1+4\tilde{z}^2}\right]\exp\left[-2\left(\tilde{t}-\frac{\tilde{z}kW_0^2}{c\tau}\right)^2\right], \tag{2a}$$

$$I_{\mathrm{above}}(\rho,z,t) = = \frac{P}{1+4\tilde{z}^2}\exp\left[-\frac{2\tilde{\rho}^2}{1+4\tilde{z}^2}\right]\exp\left[-2\left(\tilde{t}+\frac{\tilde{z}kW_0^2}{c\tau}\right)^2\right] \tag{2b}$$

where $P = 2\sqrt{2}U / \left[(\pi)^{3/2}W_0^2\tau\right]$, and $\tilde{t} = t/\tau$, $k = 2\pi/\lambda$ is the wave number.

Assuming a low Reynold's number regime [9], 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:

$$\gamma\dot{\vec{\rho}}(t) + \vec{F}_{\mathrm{grad},\rho}\vec{\rho}(t) = \sqrt{2D}\gamma\vec{h}(t) \tag{3}$$

where $\vec{\rho}(t) = \left[x(t), y(t)\right]$ 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 forces, $D = k_BT/\gamma$ is the diffusion coefficient, T is the absolute temperature, and k_B is the Boltzmann constant.

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/bead-spring model is employed to represent the glass particle, and the following equation of motion is computed for each particle:

$$\vec{\rho}(t+\delta t) - \vec{\rho}(t) = = -\frac{\vec{F}_{\mathrm{grad},\rho}\left(\vec{\rho}(t)\right)}{\gamma}\times\vec{\rho}(t)\times\delta t + \sqrt{2D}\times\delta t\times\vec{h}(t) \tag{4}$$

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. $\vec{F}_{\mathrm{grad},\rho}\left(\vec{\rho}(t)\right)$ in Eq. (4) describes the gradient optical force acting on the particle located at position ρ at time t. For example, at beginning time $t = 0$, the glass particle is assumed to locate at the position $\left|\rho(t=0)\right| = W_0$, where W_0 is the beam waist, then we understand that the gradient optical force $\vec{F}_{\mathrm{grad},\rho}(W_0, z, 0)$ acts on the particle which will be located at position $W + \Delta\rho$ after a time increment δt.

III. SIMULATED RESULTS AND DISCUSSION

We are interest only in 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 $t = -3\tau$ (or $t = 0$) to ending moment $t = 3\tau$ (or $t = 6\tau$) of the optical pulse. In the following numerical simulation we choose parameters as follows: $\lambda = 1.064\,\mu\mathrm{m}$, $m = n_1/n_2 = 1.592/1.332$ (the small glass particle and water, for instance) [8], $\eta_{\mathrm{water}} = 0.77$ (mPa.s), k_B = 1.38 × 10^{-23}J/K. $W_0 = 10\,\mu\mathrm{m}$, $a = 10$ nm, $\tau = 1$ ps, and the input power is changed by U = (0.1-0.55) µJ [10], T = 25°C. The gradient optical force $F_{\mathrm{grad},\rho}$ is calculated by expression (1) in the ranges: $t = (-3\text{-}3)\tau$, and $r = (-2\text{-}2)W_0$ at $z = 0\,\mu\mathrm{m}$ (consider the beam waist of a pulsed Gaussian beam located in the traping plane $z = 0$).

Firstly, the Brownian motions of the glass particle in water at a different beginning location (from the center of trap) are presented in Fig. 1. We can see that the motion of the glass particle is random and controlled by a random vector.

Secondly, under the action of gradient force, the particle moves from the outside (region I) to the trapping center (region III) if the beginning location of particle is outside (Fig. 3a). If the beginning location is inside, the particle begins to move outside, and then to the trapping center (Fig. 3b).

Its appearance of motion depends on the pulsing time, *i.e.* on peak intensity of pulse. In region I and IV, when the peak intensity is small, the motion of a glass particle is random. It means that the Brownian force is dominant over

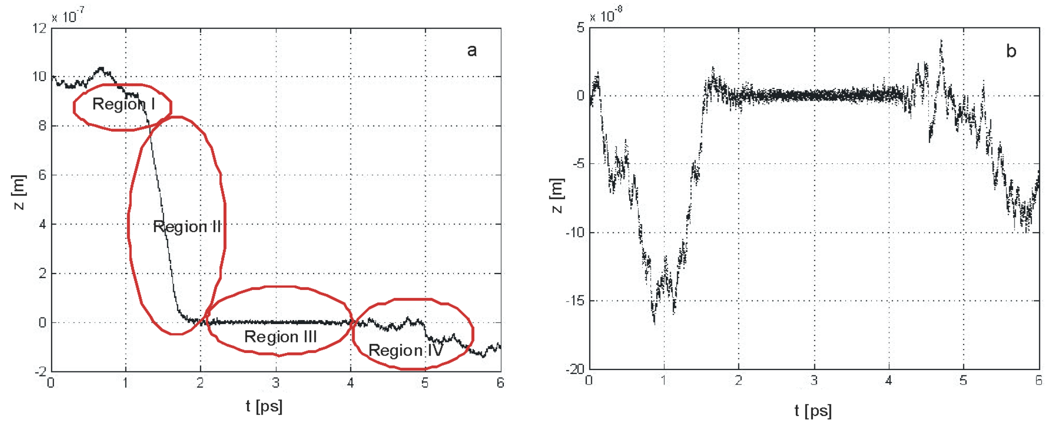

Fig. 3. The motion of a glass particle under the action of gradient force during pulse time with different beginning location: a) outside stable region, b) inside stable region

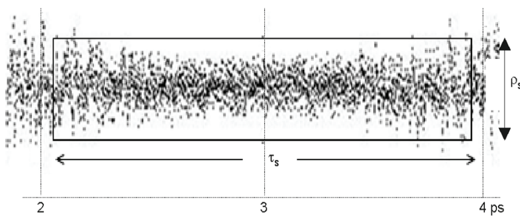

Fig. 4. "Stable" space-time pillar of the optical tweezer. The radius is about 0.05×10^{-6} m. The length is 2 ps

the gradient force and it affected the motion of the glass particle. In region II, when the intensity suddenly increases, the gradient force is high and dominant over the Brownian one. The glass particle is speedily pushed to the trapping centre for the gradient force. In the center (region III), the particle smoothly displaces inside the called "stable" space-time pillar as shown in Fig. 4.

The stabilily of the particle depends on the dimension of this stable pillar, *i.e.*, the stability is higher when the radius of pillar (ρ_s) is shorter and the length (τ_s) is longer. The radius and length of pillar depend on the optical parameters of tweezer as the total energy, beam waist, and duration time of the pulse. The influence of the above parameters on stability is calculated and illustrated in Fig. 5. From four curves in Fig. 5, we can see that the stability of the tweezer is higher when total energy is higher and the radius of beam waist is shorter.

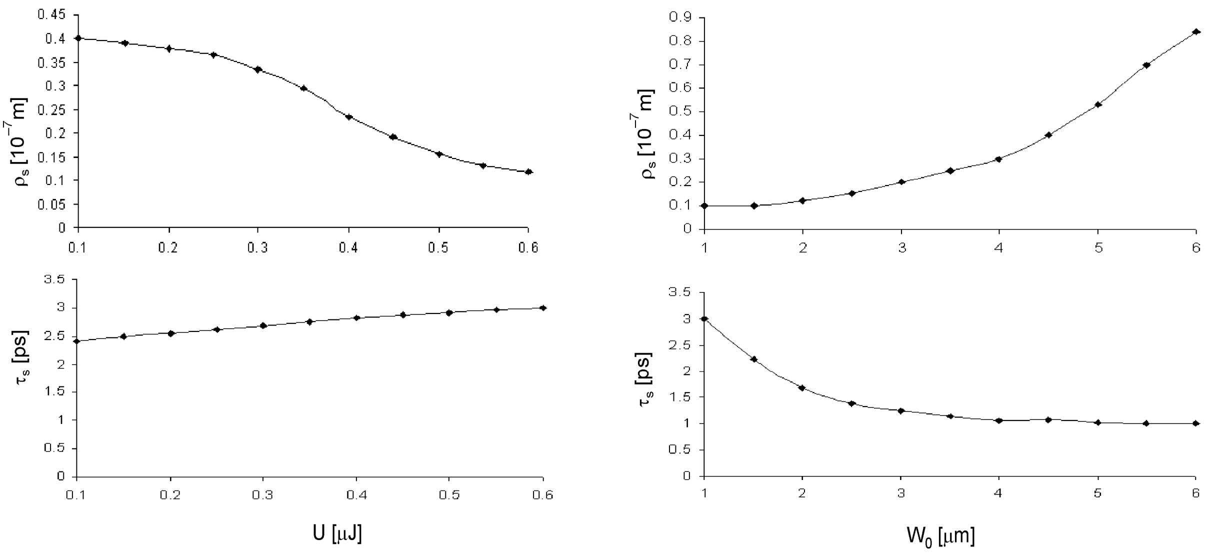

Fig. 5. Left: ρ_s and τ_s *vs* U; right: ρ_s and τ_s *vs* W_0

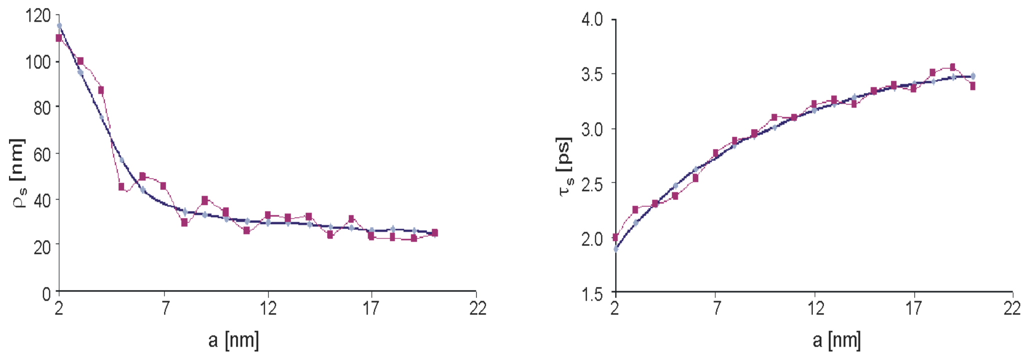

Fig. 6. Left: ρ_s *vs a*; right: τ_s *vs a* with: $\tau = 1\,\text{ps}$, $\lambda = 1.064\,\mu\text{m}$, $U = 0.1\,\mu\text{J}$, $\eta_{\text{water}} = 1.00\,\text{mPa.s}$, $T = 20°\text{C}$

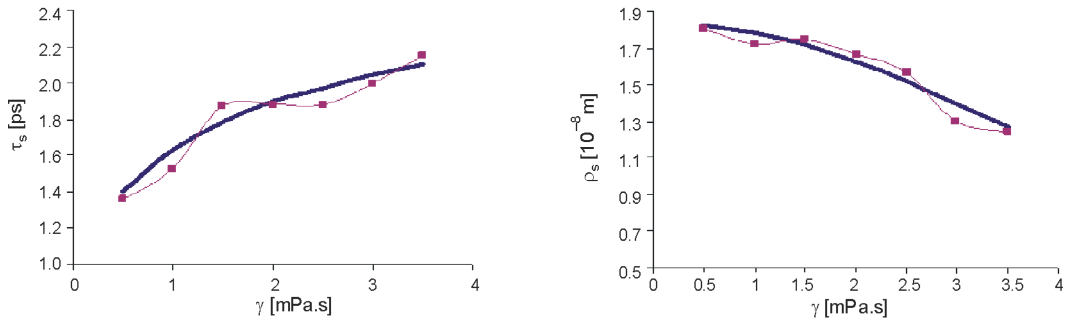

Fig. 7. Left: τ_s *vs* γ; right: ρ_s *vs* γ with: $\tau = 1\,\text{ps}$, $\lambda = 1.064\,\mu\text{m}$, $U = 0.1\,\mu\text{J}$, $a = 10\,\text{nm}$, $T = 20°\text{C}$

Now, we focus on the stability of the glass particle of a different radius in different fluid. Consider the glass particle with refractive index, $n_1 = 1.592$, radius, a = (2-20) nm; the viscosity of fluids is changed from $\eta_{\text{al.meth}} = 0.59\,[\text{mPa.s}]$ (of alcohol methyl), $\eta_{\text{al.ethyl}} = 1.1\,[\text{mPa.s}]$ (of alcohol ethyl), $\eta_{\text{al.isoprophyl}} = 2.4\,[\text{mPa.s}]$ (of alcohol isoprophyl), $\eta_{\text{syrup}} = 3.0\,[\text{mPa.s}]$ (of syrup) to $\eta = 4.5\,[\text{mPa.s}]$ correlating to them refractive index at temperature of 20°C determined by [11]

$$\frac{n^2-1}{n^2+2}\left(1/\overline{\rho}\right) = a_0 + a_1\overline{\rho} + a_2\overline{T} + a_3\overline{\lambda}^2\overline{T} + \frac{a_4}{\overline{\lambda}^2} + \frac{a_5}{\overline{\lambda}^2 - \overline{\lambda_{UV}}^2} + \frac{a_6}{\overline{\lambda}^2 - \overline{\lambda_{IR}}^2} + a_7\overline{\rho} \tag{5}$$

where $\overline{T} = \frac{T}{T^*}$, $\overline{\rho} = \frac{\rho}{\rho^*}$, $\overline{\lambda} = \frac{\lambda}{\lambda^*}$, $a_0 = 0.24425773$, , $a_1 = 0.00974634476$, , $a_2 = -0.00373234996$, $a_3 = 0.000268678472$, $a_4 = 0.0015892057$, $a_5 = 0.00245934259$, $a_6 = 0.90070492$, $a_7 = -0.0166626219$, $\overline{\lambda_{UV}} = 0.229202$, $T^* = 273.15\,\text{K}$, $\rho^* = 1000\,\text{kg m}^{-3}$, $\lambda^* = 589\,\text{nm}$, $\overline{\lambda_{\text{IR}}} = 5.432937$.

Considering the temperature of the fluid is fixed at 20°C and mass density is chosen to be $\rho = 1000\,\text{kg}\,\text{m}^{-3}$ and wave length of laser $\lambda = 1.064\,\mu\text{m}$, using (5) we have $n_2 = 1.289$.

From curves in Fig. 6 which describes the dependence of the stable radius and stable time of particle in trap, we can see that with fixed optical parameters the stability of the particle in trap is higher when the radius of particle is shorter. In detail, when trapped particle has radius of $(14\text{-}20)\,\text{nm}$, the stable radius $\rho_s \approx 25\,\text{nm}$ and stable time $\tau_s \approx 3.3\,\text{ps}$. It means that the particle oscillates around its centre, and the designed optical trap is useful with the particle of $(14\text{-}20)$ nm radius.

However, the above-mentioned stable conditions changes in different fluid. From Fig. 7 we can see the dependence of a stable radius and stable time on the viscosity of fluid. The same particle which is mixed in fluid with high viscosity will be more stable than that which is mixed in fluid with low viscosity. It is obvious that in the fluid with high viscosity the flexibility of particle is lower, and then the Brownian force is lower.

In general, to have the stability of a dielectric particle in a given optical trap, it is convenient to choose a suitable particle, and to mix it in suitable fluid.

IV. CONCLUSION

From the results presented above we can draw the following conclusions: Firstly, the Brownian force influences the stabilizing process of glass particles in water by the optical tweezer using the pulsed Gaussian optical beam; Secondly, the stability of glass particle in trap depends on the pulse energy, the radius of beam waist, the radius of particle and the viscosity of fluid; Thirdly, it is possible to choose a collection of parameters so that the radius of stable region could be reduced to the dimension of the particle, *i.e.* the particle is absolutely stable, and the stable time could be increased.

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