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DISTRIBUTION OF THE LASER INTENSITY AND THE FORCE ACTING ON DIELECTRIC NANO-PARTICLE IN THE 3D-OPTICAL TRAP USING COUNTER-PROPAGATING PULSED LASER BEAMS

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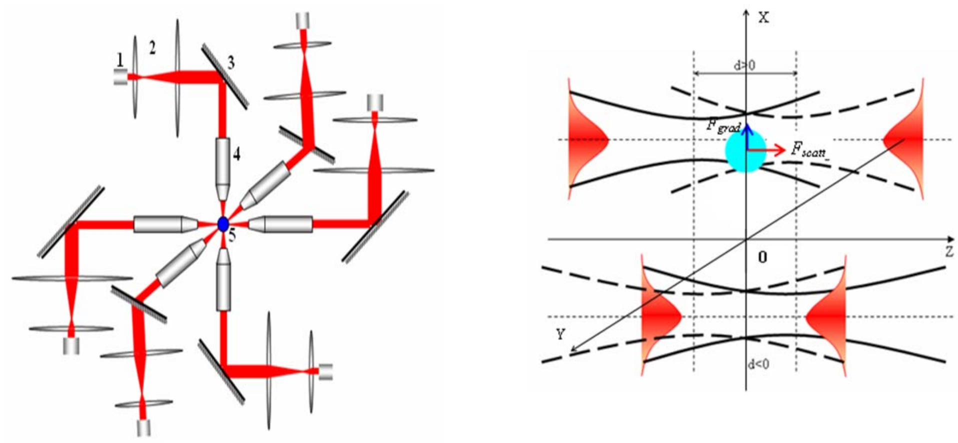
Abstract. *In this article the 3D-optical trap using counter-propagating laser beams is proposed. The expressions described the space-distribution of laser total intensity, and related optical forces acting on the dielectric nano-particle are derived. Some simulated results are presented and discussed.*

I. INTRODUCTION

Up to now, the optical trap using one Gaussian beam [1, 2] and two counter-propagating Gaussian pulsed beams [3, 4, 5] are interested in many works. Those traps will be used for manipulation particles in stable spicement, only, but not for particles in 3D-space embedded by gas or fuild. In this case it is needed to use three pairs of counter-propagating laser beams. This optical trap is called 3D-trap, which is used to design the atom cooler [6]. In this article we present the distribution of the total intensity and the optical forces acting on dielectric nanoparticle.

II. DISTRIBUTION OF TOTAL INTENSITY

A 3D-trap designed from three pairs of counter-propagating pulsed Gaussian beams (PGB) is presented in Fig.1a. For example, the pair of PGB propagating in Z-direction is illustrated in Fig.1b. We consider the optical forces are induced by two counter-propagating PGBs acting on a Rayleigh dielectric particle, i.e. the dimension of particle is more smaller than laser wavelength ($a << \lambda$). The polarization direction of the electric field is assumed to be along the x-axis.



a b

Fig. 1. (a) Sketch of 3D-Optical trap: 1- Laser source, 2- Beam expander, 3- Steering mirror, 4- Beam Focus, and 5- Dielectric nanoparticle. (b) Sketch of one pair of counter-propagating beams with optical acting on nanoparticle (example for pair in z-axis).

The expression for the electric field of the above PGB is defined by [1], for the left PGB

$$
\begin{aligned}
\vec{E}_{lz}\left(\rho_z, z, t, d\right) =& \widehat{x} E_0 \frac{ikw_0^2}{ikw_0^2 + 2\left(z + \frac{d}{2}\right)} exp\left\{-i\left[k\left(z+\frac{d}{2}\right) - \omega_0 t\right]\right\} \\
&\times exp\left\{-i\frac{2k\left(z+\frac{d}{2}\right)\rho_z}{\left(kw_0^2\right)^2 + 4\left(z+\frac{d}{2}\right)^2}\right\} \\
&\times exp\left\{-\frac{\left(kw_0^2\right)^2 \rho^2}{\left(kw_0^2\right)^2 + 4\left(z+\frac{d}{2}\right)^2}\right\} \\
&\times exp\left\{-\frac{\left[t - \frac{1}{2}\left(z+\frac{d}{2}\right)\right]^2}{\tau^2}\right\},
\end{aligned}
\qquad (1)
$$

and for the right PGB

$$\begin{aligned}\overrightarrow{E}_{rz}\left(\rho_z,z,t,d\right)=&\widehat{x}E_0\frac{ikw_0^2}{ikw_0^2+2\left(z-\frac{d}{2}\right)}exp\left\{-i\left[k\left(z-\frac{d}{2}\right)-\omega_0 t\right]\right\}\\&\times exp\left\{-i\frac{2k\left(z-\frac{d}{2}\right)\rho_z}{\left(kw_0^2\right)^2+4\left(z-\frac{d}{2}\right)^2}\right\}\\&\times exp\left\{-\frac{\left(kw_0^2\right)^2\rho^2}{\left(kw_0^2\right)^2+4\left(z-\frac{d}{2}\right)^2}\right\}\\&\times exp\left\{-\frac{\left[t+\frac{1}{2}\left(z-\frac{d}{2}\right)\right]^2}{\tau^2}\right\},\end{aligned}\tag{2}$$

where w_0 is the spot radius of the beam waist at the plane $z=0$, ρ is the radial coordinate, $\widehat{x}$ is the unit vector of the polarization along the x direction, $k=\frac{2\pi}{\lambda}$ is the wave number, ω_0 is the carrier frequency, and τ is the pulse duration, d is the distance between two beam waists of the pair. For the fixed input energy U of a single pulsed beam, the constant E_0 is determined by $E_0^2=\frac{4\sqrt{2}U}{n_2\epsilon_0 c w_0^2(\pi)^{3/2}\tau}$. Here n_2 is the refractive index of the surrounding medium.

From the definition of the Pointing vector, we can readily obtain the intensity distribution for the left PGB as follows:

$$\begin{aligned}\overline{I}_{lz}\left(\rho_z,z,t,d\right)=&\left\langle\overrightarrow{S}\left(\rho_z,z,t,d\right)\right\rangle_t\\=&\frac{P}{1+4\left(\widetilde{z}+\widetilde{d}\right)^2}exp\left\{-\frac{2\widetilde{\rho}_z^2}{1+4\left(\widetilde{z}+\widetilde{d}\right)^2}\right\}\\&\times exp\left\{-2\left[\widetilde{t}-\frac{\left(\widetilde{z}+\widetilde{d}\right)kw_0^2}{c\tau}\right]^2\right\},\end{aligned}\tag{3}$$

and for the right PGB

$$\begin{aligned}\overline{I}_{rz}\left(\rho_z,z,t,d\right)=&\left\langle\overrightarrow{S}\left(\rho_z,z,t,d\right)\right\rangle_t\\=&\frac{P}{1+4\left(\widetilde{z}-\widetilde{d}\right)^2}exp\left\{-\frac{2\widetilde{\rho}_z^2}{1+4\left(\widetilde{z}-\widetilde{d}\right)^2}\right\}\\&\times exp\left\{-2\left[\widetilde{t}+\frac{\left(\widetilde{z}-\widetilde{d}\right)kw_0^2}{c\tau}\right]^2\right\},\end{aligned}\tag{4}$$

where $P=\frac{2\sqrt{2}U}{(\pi)^{3/2}w_0^2\tau}$, $\widetilde{z}=\frac{z}{kw_0^2}$, $\widetilde{\rho}_z=\frac{\rho_z}{w_0}=\frac{\sqrt{x^2+y^2}}{w_0}$ and $\widetilde{t}=\frac{t}{\tau}$.

From (3) and (4) the total intensity of one pair of PGB is given by

$$I_z(\rho_z, z, t, d) = \overline{I}_{lz}(\rho_z, z, t, d) + \overline{I}_{rz}(\rho_z, z, t, d). \tag{5}$$

Similarly for two pairs of PGB propagating in X-axis and Y-axis, and then the distribution of total intensity in trap is given by

$$I_{total}(x, y, z, t, d) = I_x(\rho_x, x, t, d) + I_y(\rho_y, y, t, d) + I_z(\rho_z, z, t, d). \tag{6}$$

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 $n_1 >> n_2$. By argument similar to that shown in work of Zhao [1] for one PGB, the optical force acting on dielectric particle of two counter-propagating PGBs are given by for the pair propagating in Z-axis

$$\begin{cases} \vec{F}_{scat} = \widehat{z}\dfrac{n_2}{c}\sigma I(x, y, z, t), \\ \vec{F}_{grad,z} = \widehat{z}\dfrac{2\pi a^3}{c}\left(\dfrac{m^2-1}{m^2+2}\right)^2 \dfrac{\partial I(x, y, z, t)}{\partial z}, \\ \vec{F^z}_{grad,x(y)} = \widehat{x}(\widehat{y})\dfrac{2\pi a^3}{c}\left(\dfrac{m^2-1}{m^2+2}\right)^2 \dfrac{\partial I(x, y, z, t)}{\partial x(y)}, \end{cases} \tag{7}$$

where $\beta = \frac{4\pi n_2^2\epsilon_0 a^3}{c}\left(\frac{m^2-1}{m^2+2}\right)$ is the scattering cross section, $\sigma = \frac{128\pi^5 a^6}{3\lambda^4}\left(\frac{m^2-1}{m^2+2}\right)^2$ is the poarizability, and $m = \frac{n_1}{n_2}$.

All optical forces in (7) are similar to those of two other pairs propagating in X-axis and Y-axis. So, on particle act three total forces, which belong to three axises X, Y, Z. It means that

$$\begin{cases} \vec{F}_X = \vec{F}_{scat,x} + \vec{F}_{grad,x} + \vec{F^y}_{grad,x} + \vec{F^z}_{grad,x} \\ \vec{F}_Y = \vec{F}_{scat,y} + \vec{F}_{grad,y} + \vec{F^x}_{grad,y} + \vec{F^z}_{grad,y} \\ \vec{F}_Z = \vec{F}_{scat,z} + \vec{F}_{grad,z} + \vec{F^y}_{grad,z} + \vec{F^x}_{grad,z} \end{cases} \tag{8}$$

Using (3), (4), (5), (7), (8), the force in X-axis is given by

$$\begin{aligned} \vec{F}_X = & \ \widehat{x}\left(\begin{array}{c} \frac{n_2}{c}\sigma I_{lx}(\rho_x, x, t, d) + \frac{2\alpha I_{rx}(\rho_x,x,t,d)}{cn_2^2\epsilon_0 k w_0^2} \\ \times\left[\frac{2(\widetilde{x}-\widetilde{d})\left(1+4(\widetilde{x}-\widetilde{d})^2-2\widetilde{\rho}_x^2\right)}{\left(1+4(\widetilde{x}-\widetilde{d})^2\right)^2} + \frac{k^2 w_0^4(\widetilde{x}-\widetilde{d})}{c^2\tau^2} - \frac{k w_0^2\widetilde{t}}{c\tau}\right] \end{array}\right) \\ & - \widehat{x}\left(\begin{array}{c} \frac{n_2}{c}\sigma I_{rx}(\rho_x, x, t, d) + \frac{2\alpha I_{lx}(\rho_x,x,t,d)}{cn_2^2\epsilon_0 k w_0^2} \\ \times\left[\frac{2(\widetilde{x}+\widetilde{d})\left(1+4(\widetilde{x}+\widetilde{d})^2-2\widetilde{\rho}_x^2\right)}{\left(1+4(\widetilde{x}+\widetilde{d})^2\right)^2} + \frac{k^2 w_0^4(\widetilde{x}+\widetilde{d})}{c^2\tau^2} - \frac{k w_0^2\widetilde{t}}{c\tau}\right] + \frac{2\alpha k\widetilde{x}}{cn_2^2\epsilon_0} \\ \times\left[\frac{I_{ly}(\rho_y,y,t,d)}{1+4(\widetilde{y}+\widetilde{d})^2} + \frac{I_{ry}(\rho_y,y,t,d)}{1+4(\widetilde{y}-\widetilde{d})^2} + \frac{I_{lz}(\rho_z,z,t,d)}{1+4(\widetilde{z}+\widetilde{d})^2} + \frac{I_{rz}(\rho_z,z,t,d)}{1+4(\widetilde{z}-\widetilde{d})^2}\right], \end{array}\right) \end{aligned} \tag{9}$$

where $\rho_x = \sqrt{y^2 + z^2}$.

Similarly, replacing $\widehat{x}$ by $\widehat{y}$ or $\widehat{z}$, and $\rho_x = \sqrt{y^2+z^2}$ by $\rho_y = \sqrt{x^2+z^2}$ or $\rho_z = \sqrt{x^2+y^2}$ we have total optical forces in y-axis or z-axis.

III. SIMULATED RESULTS AND DISCUSSION

In Fig.2 the distribution of total intensity in phase plane (x,y) (it is similar in other phase planes) is simulated for the collection of parameters given as: $w_0 = 1.0 \times 10^{-6}m$ dimension of particle $a = 10 \times 10^{-9}m$, refractive index of particle $n_1 = 1.59$, refractive of surrounding medium $n_2 = 1.33$, energy of every beam $U = 0.1 \times 10^{-6}J$, laser wavelength $\lambda = 0.8 \times 10^{-6}m$, distance between two beam waist of every pair $d = 20 \times 10^{-6}m$, duration od pulse $\tau = 1 \times 10^{-12}s$, radius of beam waist changes from $w_0 = 1.0 \times 10^{-6}m$ (a), through $w_0 = 1.5 \times 10^{-6}m$ (b) to $w_0 = 2.0 \times 10^{-6}m$ (c).

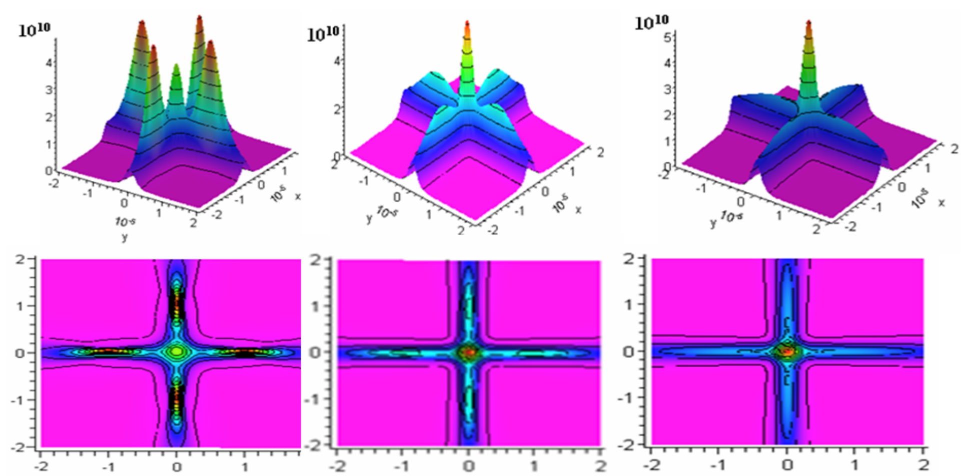


Fig. 2. Distribution of total intensity (W/m^2) in phase plane (X,Y) with different beam waist's radius. (a) $w_0 = 1.0 \times 10^{-6}m$. (b) $w_0 = 1.5 \times 10^{-6}m$. (c) $w_0 = 2.0 \times 10^{-6}m$.

The intensity of laser pulsed beam is chosen at time, when it reaches a peak, it means at $t = 0$. The simulations show that the total intensity focuses on five space regions: four of them is around waist's position, and the firth one around the cross position. The total intensity redistributes with increasing of beam waist, its magnitude increases at cross position, from $3.0 \times 10^{10} W/m^2$ through $4.5 \times 10^{10} W/m^2$ to $5.0 \times 10^{10} W/m^2$, and decreases at waist positions.

In Fig.3 the distribution of total optical force in X-axis $(\overrightarrow{F}_x)$ is simulated for above collection of parameters. The simulations show that the total optical force acting on the dielectric particle are divided into two parts whose directions are opposite to each other and magnitudes are distributed as Gaussian functions of radial distance. With increasing of beam waist the peak of force decreases from $5.0 \times 10^{-6}N$ through $1.5 \times 10^{-6}N$ to $6.0 \times 10^{-7}N$, meanwhile the stable region (a microsphere with radius from coordination origin to position where optical force is maximum) increases.

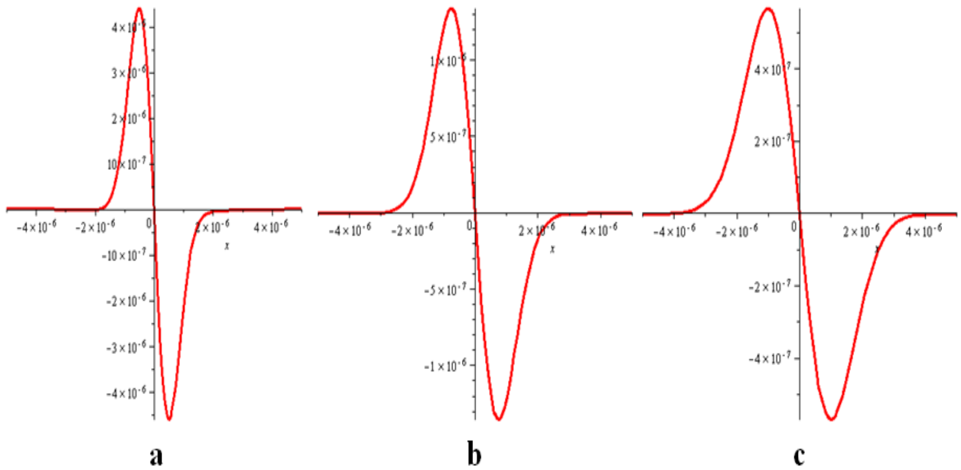


Fig. 3. Distribution of total optical force (N) in X-axis with different beam waist's radius: (a) $w_0 = 1.0 \times 10^{-6}m$; (b) $w_0 = 1.5 \times 10^{-6}m$; and (c) $w_0 = 2.0 \times 10^{-6}m$.

The distribution of the optical force is similar for other axis through the origin of trap. This means that the stable region is a sphere, in whose surface there are maximum centripetal forces. In every cross-section through the origin of trap, the distribution of the optical force creates a potential cone, in which the particle always trends to fall down to the bottom (see Fig.4).

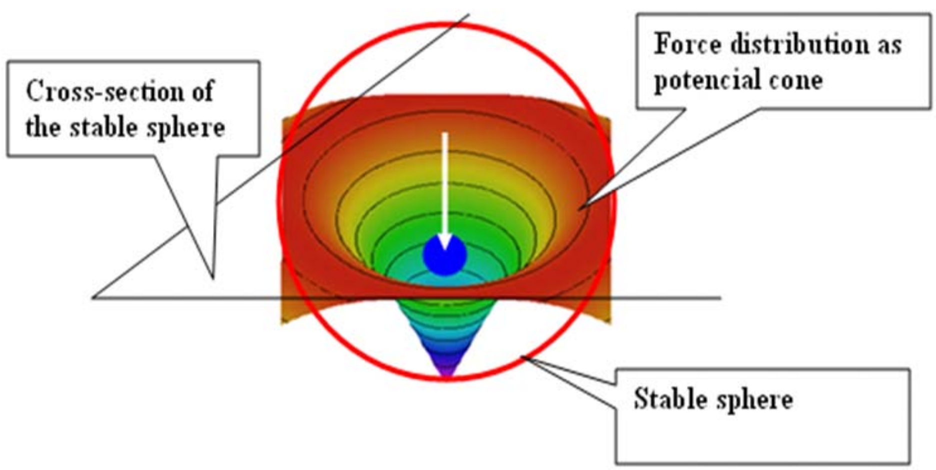


Fig. 4. State of particle in the stable sphere.

IV. CONCLUSION

In conclusion, we find that the total intensity and total optical forces in 3D-trap using counter-propagating laser Gaussian beams are symmetrically distributed and depends on beam waist, firstly. But, the magnitude of optical force and the stable region depend on many principle parameters as radius of particle, refractive index of particle and of surrounding medium, distance between beam waists,...As shown in this article the total optical force depends on the polarization vector, which plays an important role in process for atom cooling. So it is necessary to discuss in the future. Moreover, from results for 3D-trap, some questions for 2D-trap can be answered easily.

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