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NONLINEAR DOUBLE-ARM OPTICAL TWEEZERS FOR CONTROLLING 3D MICROSPHERES

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Abstract. *In this paper, a new nonlinear double-arm optical tweezer combining Mach-Zenhder interferometer, objective lens and organic dye layer is proposed. Based on the ray-optical and wave optical approximations, the expression describing the separation of two trap centers and laser intensity distribution is derived. The obtained results show that the separation between two trap centers, the laser intensity distribution, trap region's area and optical trap efficiency can be controlled by tuning laser power. The proposed model is seen to be a double-arm optical tweezer for controlling 3D microsphere by optical method.*

Keywords: nonlinear optics, optical tweezers, biophysics.

Classification numbers: 42.65.-k; 87.80.Cc.

I. INTRODUCTION

There are many optical tweezers with different configurations used to manipulate microsphere and stretch DNA molecules in biophysics [1–8]. The dual-beams optical tweezers (DBOT) are used to manipulate microsphere in 2D space by mechanical method [1–3], computer-controlled method [4]. By the support of the polystyrene anchor, the single beam optical tweezers (SBOT) have been used to stretch DNA molecule by mechanical, electrical, acoustic [5–10] and optical [11, 12] methods. Recently, the DBOT as well as the double-arm optical tweezers (DAOT) [13] are successfully designed for precisely handling the micro-objects. In the newest work, Xiao and co-workers have shown that the focal spot depends on the index immersion oil [14]. Moreover, the nonlinear Kerr effect also affect affects the focusing characteristics of objective lens, especially for the intense incident Gaussian beams [15]. Similarly, in a previous work [12], organic dye

layer (ODL) has been proposed to be as an immersion oil and nonlinear medium to control focal length of nonlinear microscope objective with high spatial resolution. Advantages of nonlinear optical tweezers are shown by H. Q. Quy [16] leading us to propose the nonlinear double-arm optical tweezers (NDAOT) by combination of the Mach-Zenhder interferometer (MZI), objective lens (OL) and ODL, which will be used to manipulate microspheres and stretch DNA molecules in 3D space by optical methods.

In this paper, the principle configuration of NDAOT is proposed. The separation expression between two trap centers and beam waist of reshaped laser beam is derived. Finally, the dependence of separation between two trap centers and intensity in trap region is numerically observed. The optical trap efficiency and useful capability for manipulating microspheres and stretching DNA molecule are also discussed.

II. PROPOSED MODEL

A model of the proposed NDAOT is shown in Fig. 1. It consists of the Mach-Zenhder Interferometer System (MZIS) [1], objective lens (OL) and organic dye layer (ODL) [11, 12, 17]. After propagating through MZIS, the input laser beam is splitted into two parallel beams with waist's radius of W_0, their distance is 2R. Normally, both beams propagate through OL and are focused in the focal plane (FP) of OL. ODL operates as nonlinear lens due to nonlinear Kerr effect, two beams are focused in the tuned focal plane (TFP) before FP. Thus, there are two different spots appearing on TFP with a certain separation. This separation and radius of focal spot on TFP depend on the input laser intensity. Hence, we have a double-arm optical tweezer, the separation among its trap centers can be controlled by input laser intensity (or input average laser power).

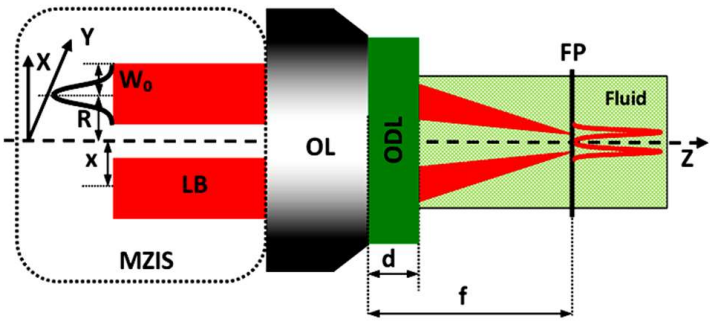

Fig. 1. Sketch of the nonlinear dual-beam tweezers. MZIS - Mach-Zenhder Interferometer system; LB - laser beam; OL – objective lens; ODL - organic dye layer; Fluid embedding trapped microspheres, FP - focal plane.

After propagating through MZI, the distribution of two laser beams on the principle plane of objective lens is described as following [18]:

$$I_1(x,y) = I_0(R,0)\exp\left(-\sqrt{2}\frac{(x-R)^2+y^2}{W_0^2}\right) \quad (1)$$

$$I_2(x,y) = I_0(-R,0)\exp\left(-\sqrt{2}\frac{(x+R)^2+(y)^2}{W_0^2}\right) \tag{2}$$

where R is the distance between axes of laser beam and objective lens, W_0 is the radius of laser beam waist, x is radial distance in the X–direction from axis of objective lens, y is the radial distance in Y–direction, $I_0(R,0)$, $I_0(-R,0)$ are the peak intensities in the axis of beams. The relation of axes of beams I_1 and I_2 to axis of objective lens make R and x plus and minus signs respectively.

Using the laser Gaussian beam given in (1) or (2), the ODL becomes a nonlinear lens with focal length given as follows [11, 12]:

$$f_{nl} = \frac{W_0^2}{dn_2 I_0(R)} \tag{3}$$

where d is the thickness of ODL, n_2 is the nonlinear index coefficient of ODL. Using ray - optical approximation as shown in Fig. 2, we derive the expression of the separation among two spots on TFP.

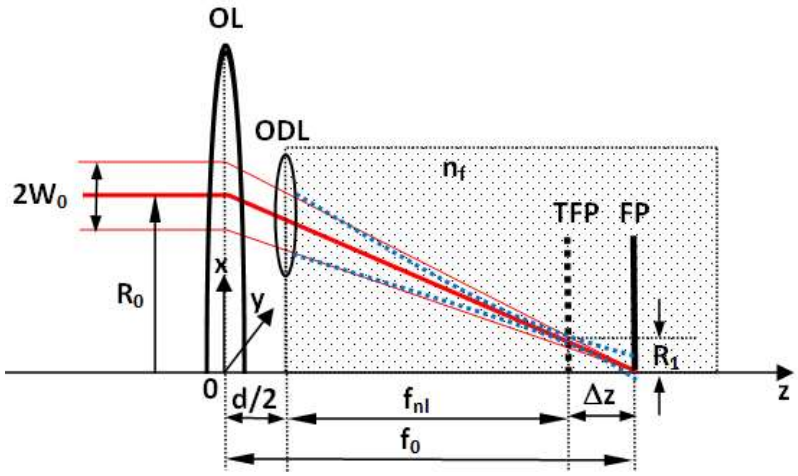

Fig. 2. Optical path of laser beam through NDAOT.

In Fig. 2, we see that, before reaching the tuned focal plane (TFP), the laser beam with position and direction $(x = R, \alpha = 0)$ propagating through an optical system consists of OL with focal length f0, ODL with thickness $d/2$, nonlinear lens with focal length fnl, and fluid with thickness fnl. Therefore, its new position and direction (x_1, α_1) on TFP satisfy the transfer matrix equation:

$$\begin{pmatrix} x_1 \\ \alpha_1 \end{pmatrix} = \begin{pmatrix} 1 & n_f f_{nl} \\ 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 \\ -1/f_{nl} & 1 \end{pmatrix}\begin{pmatrix} 1 & n_0 d/2 \\ 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 \\ -1/f & 1 \end{pmatrix}\begin{pmatrix} R \\ 0 \end{pmatrix} \tag{4}$$

From Eq. (3) we have:

$$\begin{cases} x_1 \equiv R_1 = R(f_0 - n_0 d/2 - n_f f_{nl})/f_0 \\ \alpha_1 = -R/f_0 \end{cases} \tag{5}$$

where f_0 is the focal length of *OL*, n_0 is the linear index of ODL, and n_f is the index of fluid, which is used to embed dielectric microsphere. Hence, the position of laser beam on TFP depends on the focal length of nonlinear lens. It means that the separation among two focal spots can be controlled by tuning the input laser intensity. If $n_0 = n_f = 1$, $d + f_{nl} \equiv f_0$, and then $R_1 = 0$, two beams will focus into one spot at focus point of OL.

From Fig. 2, the shift of TFP is given as:

$$\Delta z = f_0 - d/2 - f_{nl} \tag{6}$$

In order to control the separation by tuning the laser intensity, the initial laser intensity must be chosen so that $R_1 = 0$. From (3) and (5) we have:

$$I_{0,ini} = \frac{W_0^2 n_f}{dn_2(f_0 - n_0 d/2)} \tag{7}$$

Assuming the focal length of OL is long enough so that it does not influence on the laser intensity distribution. The laser Gaussian beam will be reshaped by nonlinear lens as follows [11, 18]:

$$I(\rho, z) = \frac{I_0}{1 + \left(\frac{z\pi(dn_2 I_0)^2}{\lambda W_0^2}\right)^2} exp\left(-\sqrt{2}\frac{\rho^2}{\left(\frac{\lambda W_0}{\pi dn_2 I_0}\right)^2\left[1 + \left(\frac{z\pi(dn_2 I_0)^2}{\lambda W_0^2}\right)^2\right]}\right) \tag{8}$$

where z is the distance from beam waist and

$$W_1 = \frac{\lambda W_0}{\pi dn_2 I_0} \tag{9}$$

is the waist radius of focused beam on TFP.

Using (1), (2) and (8), the distribution of laser intensity in TFP is given as:

$$I(x, y, z) = \frac{I_0}{1 + \left(\frac{z\pi(dn_2 I_0)^2}{\lambda W_0^2}\right)^2} exp\left(-\sqrt{2}\frac{(x \pm R_1)^2 + y^2}{\left(\frac{\lambda W_0}{\pi dn_2 I_0}\right)^2\left[1 + \left(\frac{z\pi(dn_2 I_0)^2}{\lambda W_0^2}\right)^2\right]}\right) \tag{10}$$

where the sign of R1 is suitable to sign of x coordinate. Using (3), (5) and (10), we have explicit expression of the laser intensity distribution on TFP. Simulation calculation is shown in the next part.

III. RESULTS AND DISCUSSION

We consider a laser beam with the wavelength of $\lambda = 1.06\ \mu$m. Propagating through MZIS, the input beam is split into two beams of waist's radius of 0.05 cm, the separation of 0.2 cm (R = 0.1 cm) [1]. The ODL uses Orange G solution with $n_0 = 1.465$, $n_2 = 1 \times 10^{-5}$ cm^2/W, $d = 0.05$ cm [19, 20]. The water index of 1.334 [21] is used as the fluid. The OL's focal length of $f_0 = 2$ mm [22] is used.

Using Eq. (7) for the initial laser intensity to be fixed $I_{0,ini} = 4.08310^4$ W/cm^2, and associated with Eqs. (3), (6) and (9) we have $f_{nl}(I_{0,ini}) = 124.75\ \mu$m and $\Delta z(I_{0,ini}) = 52.5\ \mu$m, $W_1(I_{0,ini}) = 0.83\ \mu$m. Tuning laser intensity by an amount ΔI (or ΔP) around $I_{0,ini}(P_{ini})$, the dependence of f_{nl} and W_1 on input laser power is observed and illustrated in Figs. 3 and 4, respectively.

As results, W1 and fnl decrease with the deceasing of P. If the laser power is tuned by an amount of $\Delta P = 0.01$ mW, f_{nl} will be shifted by a distance 0.75 μm (Fig. 3) and W_1 will be changed by 20 nm (Fig. 4).

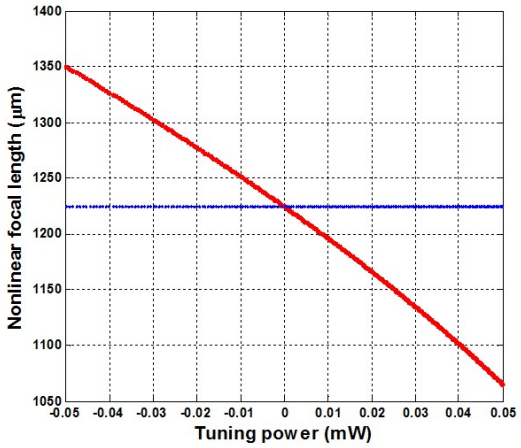

Fig. 3. f_{nl} vs. ΔP.

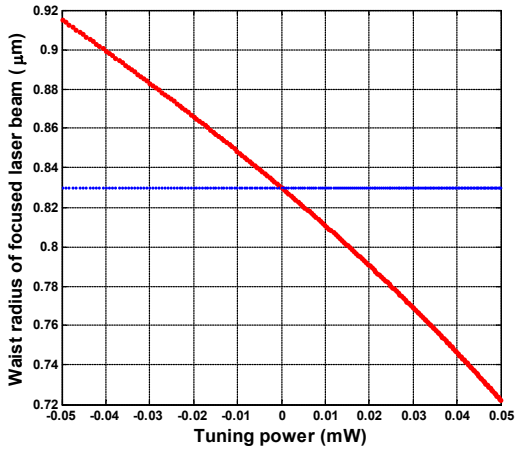

Fig. 4. W_1 vs. ΔP.

The dependence of the separation between focal spots, 2.R1 and shift of TFP from initial position, $\Delta z(I_0) - \Delta z(I_{0,ini})$ on tuning power ΔP of input laser are illustrated in Fig. 5 and Fig. 6, respectively. We see that 2R1 as well as $\Delta z(I_0) - \Delta z(I_{0,ini})$ decrease if the laser power increases to P0,ini = 0.522mW and proportional to laser power bigger than $P_{0,ini}$.

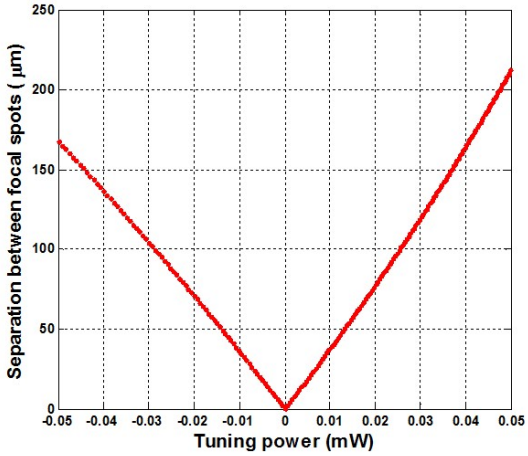

Fig. 5. Separation ($2R_1$) vs P.

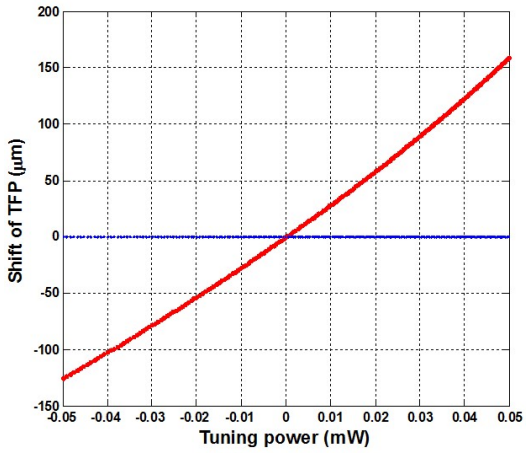

Fig. 6. Shift of TFP $(\Delta z(I_0) - \Delta z(_{I0,ini}))$ vs P.

The obtained results in Figs. 5 and 6 show that the focal spots will move in radial direction as well as in axial direction by tuning laser power. As the operation principle of optical tweezers,

the trapped microsphere in center of focal spots can be controlled in 3D space by tuning laser power (see Fig. 7). The control distance is in micrometer scale, which is in good agreement with that we have obtained in previous works [7, 11, 12].

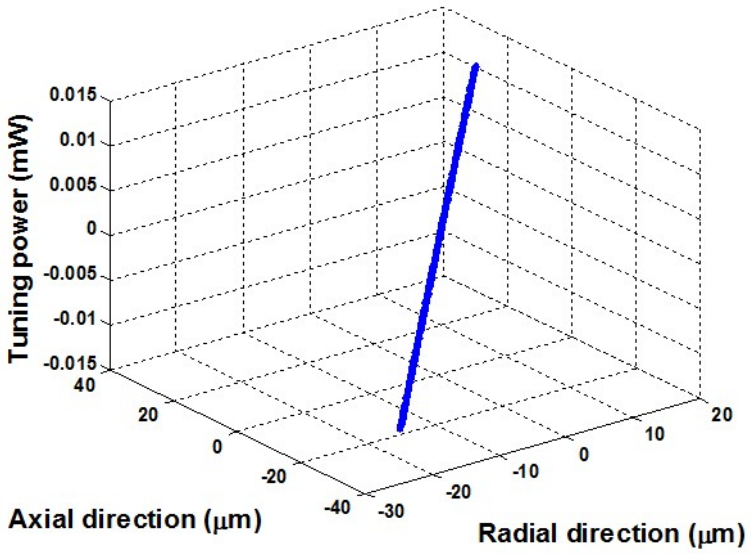

Fig. 7. Trajectory of trapped microsphere in controlling process by power tune.

Using (5) and (10), the intensity distribution in TFP and its cross - section are numerically observed with different peak intensities in Fig. 8. The obtained results in Fig. 8 are predicted by M. P. MacDonald [1], C. J. Firby [4].

It is clear that the separation between two focal spots (i.e., between two trap centers) as well as focal shift are in micrometer scale with chosen collection of parameters. They can be controlled by tuning laser power. Comparing the changed distance of the focused beam waist (Fig. 4), the separation between two trap centers (Fig. 5) and TFP shift (Fig. 6) we see that the change of beam waist is negligible in controlling process. However, as shown in a previous work [23], since the increase of laser power makes the focused beam waist decrease. Consequently, the trap optical efficiency increases significantly. Thus, all of phenomena in our proposed model of NDAOT is in good agreement to that obtained in previous works [8–10, 12, 16, 23].

However, there is an advantage that the change of the separation between two trap centers and shift of TFP appear at the same time. They change in the large distance, from 0 to about 100 μm by tuning laser power from 0 to 0.1mW. This advantage is good for using NDAOT to manipulate microsphere in 3D space [22, 24, 25] with the high accuracy of about 1 μm/10 μW. Specially, for stretching DNA molecule with different contour lengths [26] without choosing the suitable configuration [27].

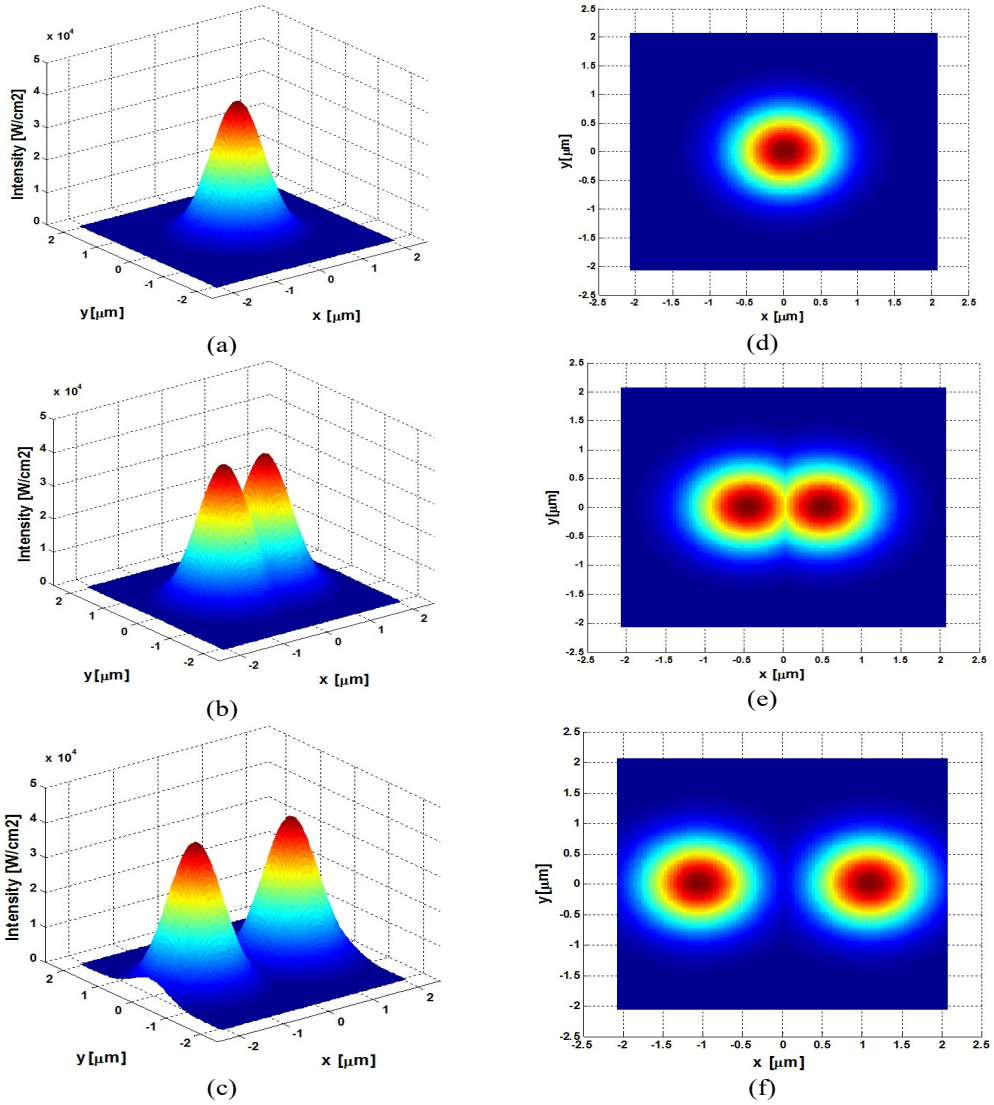

Fig. 8. Intensity distribution in TFP ((a), (b), (c)) and its cross - section ((d), (e), (f)) with different intensity peak of input laser beam: 4.08310^4 W/cm^2 ((a), (d)), 4.08510^4 W/cm^2 ((b), (e)), 4.08710^4 W/cm^2 ((c), (f)).

IV. CONCLUSION

The model of NDAOT combining the Mach - Zehnder interferometer, objective lens and organic dye layer is proposed. The expressions of the separation between two trap centers, shift of focal plane and laser intensity distribution in the TFP are derived. The dependences of the separation between two trap centers and shift of TFP, waist of focused beams, intensity distribution on tuning power of input laser are numerically observed for a configuration consisting of realized

technology parts. Obtained results show that the trapped microsphere under NDAOT can be controlled in 3D space with high accuracy and improved trap optical efficiency. The ADN molecule with any contour length can be stretched by our proposed NDAOT (all - optical method) without bio - chemical anchor support. Specially, the proposed NDAOT are possible to unzip DNA molecule [28, 29]. It can be seen as an advantage of this model in comparison to conventional double - arm optical tweezers or dual - beam optical tweezers. These are initial studies of NDAOT for the applications in biophysics. The condition of improving the accuracy, solution and trap efficiency for certain cases will be investigated in the next time.

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