Optics Communications 421 (2018) 94–98

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

# Nonlinear optical tweezers for longitudinal control of dielectric particles

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ARTICLE INFO

*Keywords:*
Laser
Optical devices
Nonlinear optical tweezers
Organic dye
Thin layer

ABSTRACT

A model of the optical tweezers using thin layer of organic dye as the addition nonlinear lens in configuration is proposed. The expressions of the focal length of nonlinear lens, intensity distribution of reshaped Gaussian beam, and total longitudinal optical force acting on dielectric particles are theoretically derived using paraxial approximation. The influence of the average power of incoming Gaussian laser beam, thickness of thin layer, and nonlinear coefficient of refractive index on properties of nonlinear optical tweezers are numerically observed. The results also are discussed to find out the conditions that the dielectric particle could be stable trapped and finely controlled by tuning of average power of incoming laser beam.

## 1. Introduction

Two main parts of the optical tweezers are the laser beam and microscope objective, which create a laser Gaussian beam with high gradient of intensity around the focus. Irradiating by the Gaussian beam, the dielectric particles should be pulled into center of beam waist, i.e. into the focus, generally. So that the optical tweezers are used to trap and hold the dielectric particles, and to control them in space of embedding fluid [1]. Up to now, for the diversified applications [2,3] there is a lot of methods used to control trapped dielectric particles as: laser beam scan using rotation system of mirrors [4,5], laser focus control using intelligent electro-mechanical or opto-mechnical system with help of the computer, etc. [6–10]. To control trapped dielectric particles in 2D or 3D space, all mentioned methods need two facts, at least [11]. Lately, to avoid the complexity of opto-mechanical system, a method to control dielectric particles in nonlinear embedding fluid by tuning of laser power is proposed [12]. However, this proposal for optical tweezers meets a difficulty that the embedding fluid could not change suitable to other dielectric particles due to ratio of their refractive indexes. Referring to idea of this method, the acousto-optical tweezers is proposed and investigated to control dielectric particles in 2D or 3D space of embedding fluid [13,14]. The operation principle of acousto-optical tweezers is based on the nonlinear response of refractive index of acousto-optical material to intensity of the acoustic wave. Although, our proposals could be really used to design optical tweezers, but it needs a high intensity of acoustic wave, which is the difficult problem in experiment.

As known, the classical Kerr materials as gas, liquid, etc., has very low nonlinear coefficient of refractive index, which is about of $n_2 = 3 \times 10^{-18}$ cm$^2$/W [15], consequence, the nonlinear effect is weak and then it needs a high laser intensity for practicability. But, recently there is a lot of Kerr materials, especially, organic dyes with high nonlinear coefficient of refractive index, even tens powers than of classical ones. For example, Acid Blue has $n_2 \sim 1 \times 10^{-6}$ cm$^2$/W [16], Mercurochrome has $n_2 \sim 1 \times 10^{-7}$ cm$^2$/W at laser wavelength of 532 nm [17], Acid Green has $n_2 \sim 1 \times 10^{-7}$ cm$^2$/W at laser wavelength of 635 nm [18]. All used organic dyes are not in solvent, only, but can be chemically accumulated in the glass plate with thickness below millimeter, which has been used to observe the nonlinear refraction [19]. The presence of organic dyes with high nonlinear coefficient of refractive index gives us an opportunity to design the nonlinear optical tweezers to trap and control dielectric particles in space by tuning of laser power replacing mentioned complex methods.

In this paper, the nonlinear optical tweezers using thin layer of organic dye as the addition nonlinear lens in configuration to control dielectric particles is proposed. The theoretical expressions described focal length, intensity of reshaped Gaussian beam, and longitudinal optical force acting on dielectric particles are derived. The influence of average power of incoming laser beam on the focal length, intensity of reshaped beam and optical force is numerically observed and the conditions to keep stable and fine control trapped particles are discussed.

## 2. The model for theoretical study

The model of nonlinear optical tweezers is proposed as shown in Fig. 1. Different to conventional single tweezers, in proposed model

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https://doi.org/10.1016/j.optcom.2018.03.068
Received 26 February 2018; Received in revised form 16 March 2018; Accepted 26 March 2018

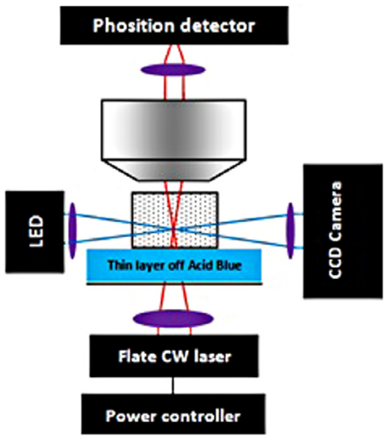


**Fig. 1.** Configuration of proposed nonlinear optical tweezers.

the pre-focusing lens has low NA, the system consisting from LED and CCD camera is set-up so that the motion of trapped particles along laser axis can be tracked, and finally, the thin layer of organic dye is placed between the pre-focusing lens and chamber of embedding fluid and dielectric particles. The laser power controller is added. The flat CW laser beam is weakly focused by the pre-focusing lens, and then powerfully by nonlinear lens appeared in thin layer of organic dye, which is irradiated by laser Gaussian beam. The power controller is used to tune the average power of laser beam to change the focal length of nonlinear lens. Initially, the dielectric particles are trapped at determined position in fluid, and then it will be hold stable in this position. By tuning of laser power, the dielectric particles are manipulated to suitable position due to the change of focal length of nonlinear lens. To affirm the operation principle of this model, its properties will be numerically observed and discussed in the next sections.

## 3. Focal length of thin layer of Acid Blue

Irradiating by the laser beam with intensity, $I$ the refractive index of the nonlinear Kerr medium depends on intensity and is given by [20]:

$$n_K = n_0 + n_2 I\,, \tag{1}$$

where $n_0$ is the linear index, $n_2$ is the nonlinear coefficient of refractive index. If the irradiating laser beam is a Gaussian one with intensity distribution given as $I = I_0 exp\left(-\rho^2/W_0^2\right)$, then Eq. (1) will be modified as:

$$n_K(\rho) = n_0 + n_2 I_0 exp\left(-\frac{\rho^2}{W_0^2}\right), \tag{2}$$

where, $W_0$ is the beam waist of laser beam, $I_0$ is the peak intensity in its axis and $\rho$ is the radial distance of laser beam. From Eq. (2) we can see that the nonlinear medium with thickness $d$ will be a GRIN medium. Using paraxial approximation as follows:

$$I(\rho) = I_0 exp\left(-\frac{\rho^2}{W_0^2}\right) \approx I_0\left(1-\frac{\rho^2}{W_0^2}\right), \tag{3}$$

we have

$$\begin{aligned} n_K(\rho) &= n_0 + n_2 I_0\left(1-\frac{\rho^2}{W_0^2}\right) \\ &= \left(n_0+n_2 I_0\right)\left(1-\frac{n_2 I_0}{W_0^2\left(n_0+n_2 I_0\right)}\rho^2\right) = N_0(-\alpha^2\rho^2). \end{aligned} \tag{4}$$

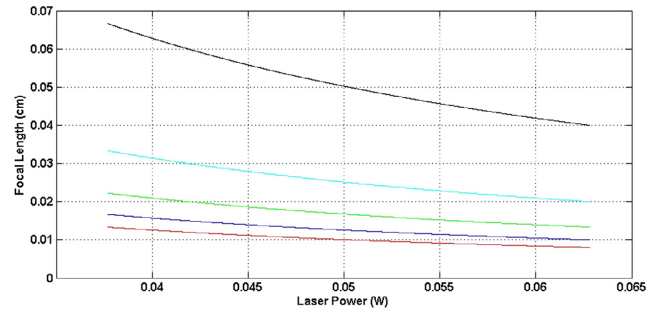


**Fig. 2.** Focal length of thin layer with different thickness v.s. average power of incoming Gaussian laser beam, and $W_0 = 0.002$ cm, $n_2 = 10^{-6}$ cm$^2$/W.

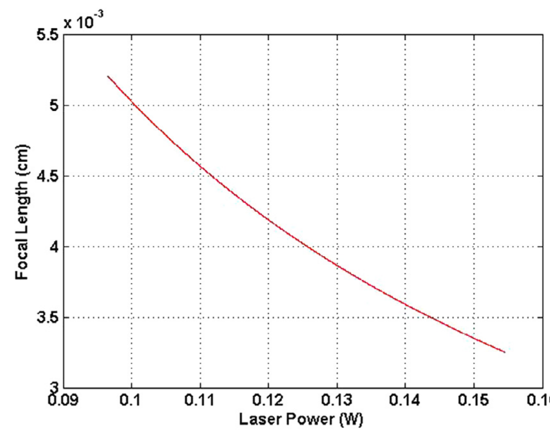


**Fig. 3.** Focal length of thin layer with thickness of $d = 0.05$ cm irradiated by Gaussian laser beam with average laser power tuned in interval of (90 ÷ 160) mW, and $W_0 = 0.002$ cm, $n_2 = 10^{-6}$ cm$^2$/W.

As shown in [20], the thin GRIN plate will be the nonlinear lens with focal length given as follows:

$$\begin{aligned} f_{nl} &= \frac{1}{N_0 \alpha sin(\alpha d)} \\ &= \frac{1}{\left(n_0+n_2 I_0\right)\sqrt{\frac{n_2 I_0}{W_0^2(n_0+n_2 I_0)}}\, sin\left(d\sqrt{\frac{n_2 I_0}{W_0^2(n_0+n_2 I_0)}}\right)}. \end{aligned} \tag{5}$$

With condition $\alpha d \ll 1$, the focal length in Eq. (5) can be reduced to:

$$f_{nl} = \frac{W_0^2}{d n_2 I_0}. \tag{6}$$

As shown in Eqs. (5) and (6), the dimensionless fact $n_2 I_0$ can be seen as specific parameter for different organic dye, which has different nonlinear coefficient of refractive index, $n_2$. So, next we observe the influence of average laser power, $P = \pi I_0 W_0^2/2$ and thickness, $d$ on the focal length of Acid Blue thin layer irradiated by Gaussian beam, as an example. From Fig. 2, it is clear that the focal length decreases if thickness of layer and average power of laser beam increase. The important point here is that we can choice a suitable average power of laser beam so that the nonlinear lens has high NA. For example, when the average power is tuned to 125 mW (see Fig. 3), the focal length of nonlinear lens reads 0.004 cm, and then its $NA \approx 2W_0/f_{nl} = 2 \times 0.002/0.004 = 1$, which is high enough for optical tweezers to trap dielectric particles [1]. The nonlinear lens is created by the Gaussian beam propagating through Acid Blue thin layer, in turn, the appearance of this lens causes the laser Gaussian beam reshaped.