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TRAPPING CAPABILITY OF MICROLENS 2D ARRAY BY ACOUSTIC MODULATION

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ABSTRACT

In this article, the microlens 2D array created in acoustic-optical medium by the ultrasonic wave modulation is proposed. The expression described the refractive index induced by cross-interference of two perpendicular ultrasonic waves is approximately derived. By simulation, the 2D array of the Graded–refractive index lenses are appeared in the thin layer with certain strain-acoutstic constant and thickness. The dependence of focal length and the radius of lens, i.e. its numerical aperture (AN) on thickness and strain constant of layer, and ultrasonic wave intensity are simulated and trapping capability of optical tweezer array is discussed.

Indexing terms/Keywords

Optical tweezer, Microlens 2D Array, Acoustic modulation, Trapping capability.

Academic Discipline And Sub-Disciplines

Laser application, Optical trapping.

SUBJECT CLASSIFICATION

Optics, Photonics, Microsphere

TYPE (METHOD/APPROACH)

Theory , Simulation.

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1. INTRODUCTION

There are many works interested on optical tweezer array (OTA) to manipulate an assembly of nanoparticle in specimen [1-6]. Dufresne and colleges have created multiple optical tweezers from a single laser beam using diffrective optical elements [1] and setup the computer-generated holographic optical tweezer (HOT) arrays three years later [2]. In the next year, Curtis and colleges have simulated the dynamic of HOTs [3]. Jesacher demonstrated diffractive optical tweezers (DOT) based on Fresnel regime [4]. In this year, C. H. Sow with colleges sucessfully achieved the multiple-spot optical tweezers created with microlens arrays fabricated by proton beam writing [5]. All mentioned optical tweezer array operated basing on spatial modulation of single laser beam by optical elements. In opposite, Tanaka with colleges manipulated particles by optical tweezers combined with intelligent control techniques (using software) [6] and Pornsuwancharoen proposed novel dynamic optical tweezers array using dark soliton control within a Add/Drop multiplexer [7] basing on spatial or temporal control.

As well known, the acousto-optical modulation (Bragg diffraction) has been proposed to use for partial reflection of light (as beamsplitter), and the Bragg cell have found numerous application in photonics [8]. It is nice, McLeod and Arnold have discussed about the Tunable Acoustic Gradien index (TAG) lens in liquid [9].

In this artilce, we try to theoretically improve the appearance of microlens induced in acousto-optical medium by acoustic modulation and discuss about using capability for OTA.

2. THEORETICAL BACKGROUND

Condiser a quadrance cubic of acoustic-optical medium (AOM) with thickness d as shown in Fig.1. Two phase-matching ultrasonic waves travel in the x and y direstions in the medium with velocity V_s, frequency F_s, and wavelength $\Lambda = V_s / F_s$. The sound is a dynamic strain involving molecular vibrations that take the form of wave which travel at a velocity characteristic of the medium (the velocity of sound). The strain at position x and time t is

$$S(x,t) = S_0 cos(\Omega t - 2\pi x / \Lambda + \varphi_y) \tag{1}$$

where S_0 is the amplitude, $\Omega = 2\pi f$ is the angular frequency, φ_x is the initial phase. The acoustic intensity (W/m^2) is

$$I_S = \frac{1}{2} g V_s^3 S_0^2 \tag{2}$$

where g is the mass density of the fluid [8].

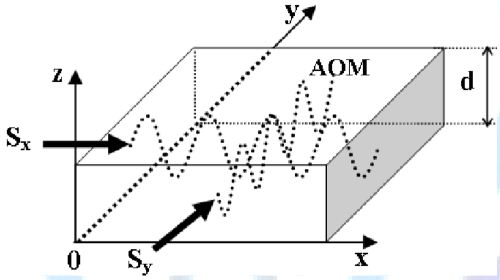


Figure 1. Two ultrasonic waves perpendicularly applying to both surfaces of AOM.

Similar to the ultrasonic wave in the x-direction, the one in the y-direction makes the strain at position y and time t, which is given

$$S(y,t) = S_0 cos(\Omega t - 2\pi y / \Lambda + \varphi_y) \tag{3}$$

Because that two waves interfere one with other, so from Eq. (1) and Eq. (3) the strain at position (x,y) and time t is

$$S(x,y,t) = S_0 \left[cos(\Omega t - 2\pi x / \Lambda + \varphi_x) + cos(\Omega t - 2\pi y / \Lambda + \varphi_y) \right] \tag{4}$$

Consider two waves are phase matching, i.e. $\varphi_x = \varphi_y = 0$ and because the acoustic frequency F_s is typical much smaller than the optical frequency, an adiabatic approach for studying light-sound interaction may be adopted, then Eq. (4) can be reduced to

$$S(x,y) = S_0 \left[cos(2\pi x / \Lambda) + cos(2\pi y / \Lambda) \right] \tag{5}$$

The strain $S(x,y)$ creates a propotional perturbation of the refractive index in medium, analogous to the Kerr effect

$$\Delta n(x,y) = -\frac{1}{2} \gamma n^3 S(x,y) \tag{6}$$

where γ is a phenomenological coefficient known as the photoelastic constant (strain-acoutstic constant), n is the refractive index of AOM in the absence of sound. As consequence, the medium has the refractive index as a static (frozen) sinusoidal function

$$n(x,y) = n - \Delta n_0 \left[cos\left(2\pi x/\Lambda\right) + cos\left(2\pi y/\Lambda\right) \right] \tag{7}$$

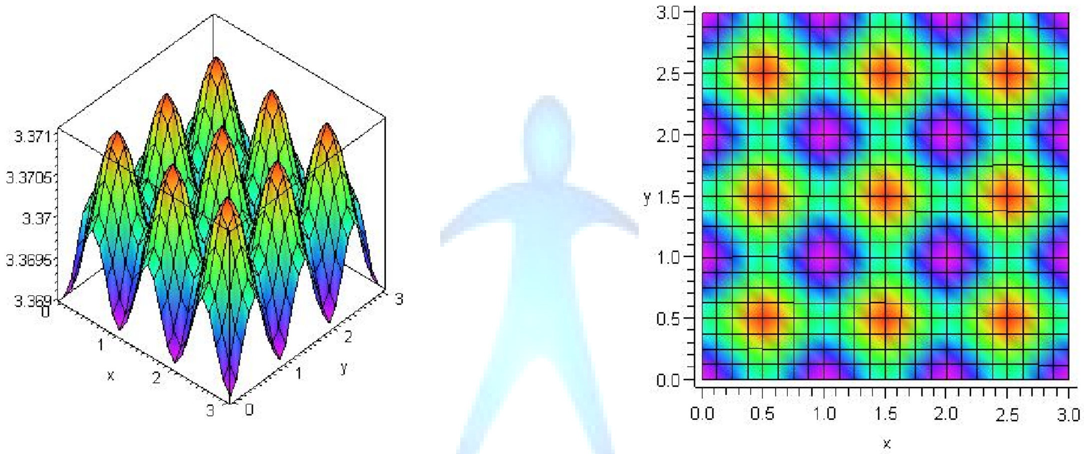
with amplitude

$$\Delta n_0 = \frac{1}{2}\gamma\ n^3 S_0 = \sqrt{\frac{1}{2} M I_s} \tag{8}$$

where

$$M = \frac{\gamma^2 n^6}{g V_s^3} \tag{9}$$

is a figure of merit for the strength of the acoustic-optic effect in the material.



a **b**

Figure 2. RID in plane (x,y) (a) and Acoustic lens array in medium (b).

The refractive index distribution is simulated for Gallium arsenide (GaAs) $M = 104\times 10^{-15} m^2/W$, $n = 3.37$ (at optical wave length 1.15µm) [10]. An ultrasonic wave of intensity $I_s = 100W/cm^2$ creates a refractive index wave of amplitude $\Delta n_0 \approx 5\times 10^{-4}$. The refractive index distribution (RID) in plane (x,y) is simulated with ultrasonic wave of velocity $V_s = 5340 m/s$, $F_s = 350\times 10^6 Hz$ and shown in Fig.2a (unit of x and y is $\Lambda \simeq 15.26\mu m$). Can see that in GaAs crystal appears 2D array of circles in the area with dimension $\Lambda/2\times\Lambda/2$, whose RIDs are same (Fig.2b). In certain circles (Fig.3a), the refractive index reaches one maximum of $n = 3.371$ at center and minimum values $n = 3.37$ at edges (Fig.3b). This means the mentioned circle of medium becomes the thin Graded refractive index (GRIN) cylinder. Thus, the GRIN cylinder of medium becames a called acoustic lens.

The diameter of acoustic lens is about $D \approx \Lambda/2 = 15.26\mu m$, so it can be called microlens, and acoustic-optical medium became the microlens 2D array. To find the focal length of each GRIN microlens, we must introduce Eq.7 to the expresion of refractive index relating to GRIN medium. We consider a GRIN microlens at point of (x,y) and two waves are phase matching, i.e. $x = y$, using trigonometry relation, Eq.(7) is rewritten as

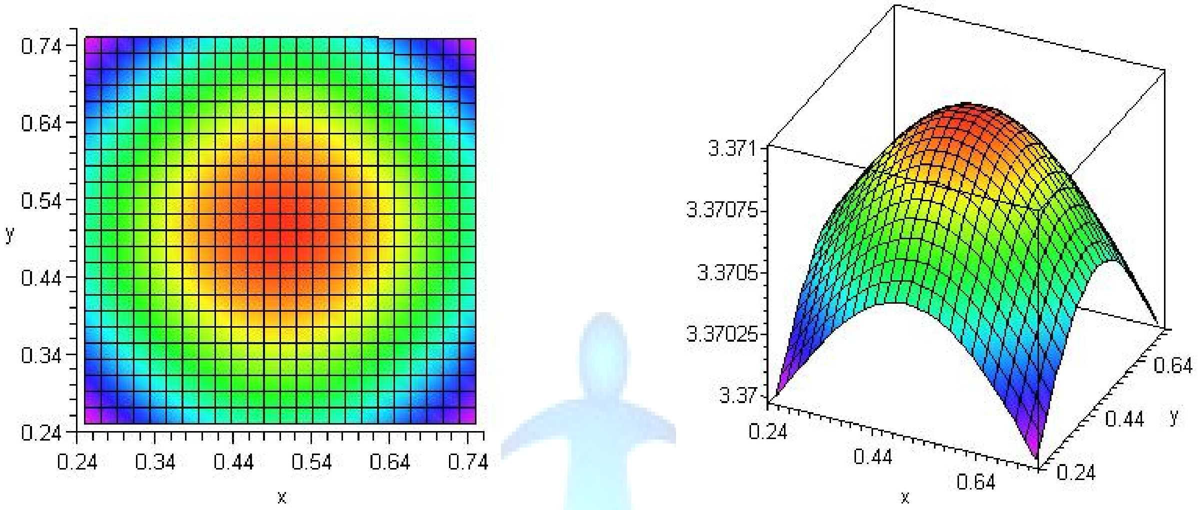
$$\begin{aligned} n(x,y) &= n - \Delta n_0 \left[cos\left(2\pi\frac{x}{\Lambda}\right) + cos\left(2\pi\frac{y}{\Lambda}\right)\right] = n - 2\Delta n_0 cos\left(\pi\frac{x+y}{\Lambda}\right) cos\left(\pi\frac{x-y}{\Lambda}\right) \\ &= n - 2\Delta n_0 cos\left(2\pi\frac{x}{\Lambda}\right) = n - 2\Delta n_0 + 4\Delta n_0 sin^2\left(\pi\frac{x}{\Lambda}\right) \end{aligned} \tag{9}$$

For simplicity and from the RID in Fig.3, we consider approximately that Eq.9 describes the RID in interval from $x = -\Lambda$ to $x = 0$ in x-direction as shown in Fig.4a. Eq.9 can be rewritten as function of new argument, x' relating to x by

$$x = \frac{\pi x'}{\Lambda} - \frac{\pi}{2} \tag{10}$$

$$n(x') = n - 2\Delta n_0 + 4\Delta n_0 sin^2\left(\pi\frac{x'}{\Lambda} - \frac{\pi}{2}\right) \tag{11}$$

where $-\Lambda/2 < x' < \Lambda/2$, and then RID is shown in Fig.4b. This RID is a symmetric function centered about $x' = 0$.



a **b**

Figure 3. Circle in area with dimension $\Lambda/2 \times \Lambda/2$ (a), its RID (b).

After comparison Fig.3 with Fig.4b, the diameter of GRIN microlens is $D = \Lambda/2$, and its RID is concerned to x' co-ordinates, which satisfies

$$|x'| \leq \Lambda/4 \ll \Lambda/2\,. \tag{12}$$

Moreover,

$$sin^2(\frac{\pi x'}{\Lambda} - \frac{\pi}{2}) = \begin{cases} 1 \; if \;\; x' = 0 \\ 0 \;\; if \;\; x' = \pm\Lambda/2 \end{cases}. \tag{13}$$

Using Eq.12 and Eq.13, we can take approximation:

$$sin^2(\frac{\pi x'}{\Lambda} - \frac{\pi}{2}) \approx 1 - \frac{8x'^2}{\Lambda^2} \tag{14}$$

for $-\Lambda/4 < x' < \Lambda/4$.

Substituting Eq.14 to Eq.11 we have

$$n(x') = n + 2\Delta n_0 - 32\Delta n_0 \frac{x'^2}{\Lambda^2} \tag{15}$$

where $-\Lambda/4 < x' < \Lambda/4$, and then RID by Eq.15 is shown in Fig.4c.

From Fig.4d, we can see that approximation RID by Eq.15 is well fitting to that by Eq.11 in interval $-\Lambda/4 < x' < \Lambda/4$. When x' replaced by y', the modified Eq.15 describes the RID in y-direction, and finally, that means RID is centrical symmetry about the point $(x', y') = (0,0)$. Consequently, we can replace x' by radial co-ordinate, $-\Lambda/4 \leq \rho = \sqrt{x^2 + y^2} \leq \Lambda/4$, and then Eq.15 is rewritten as:

$$n(\rho) = N_0(1 - \frac{1}{2}\alpha^2\rho^2) \tag{16}$$

where

$$N_0 = n + 2\Delta n_0,\; \alpha^2 = \frac{64\Delta n_0}{N_0\Lambda^2} \tag{17}$$

for RID in GRIN cylinder. Using Eq.16, we have the focal length of GRIN microlens as following [8]

$$f = \frac{1}{N_0 \alpha^2 d} \tag{18}$$

where d is thickness of GRIN cylinder. Subsituting Eq.17 into Eq.18, we have

$$f = \frac{\Lambda^2}{64 \Delta n_0 d} \tag{19}$$

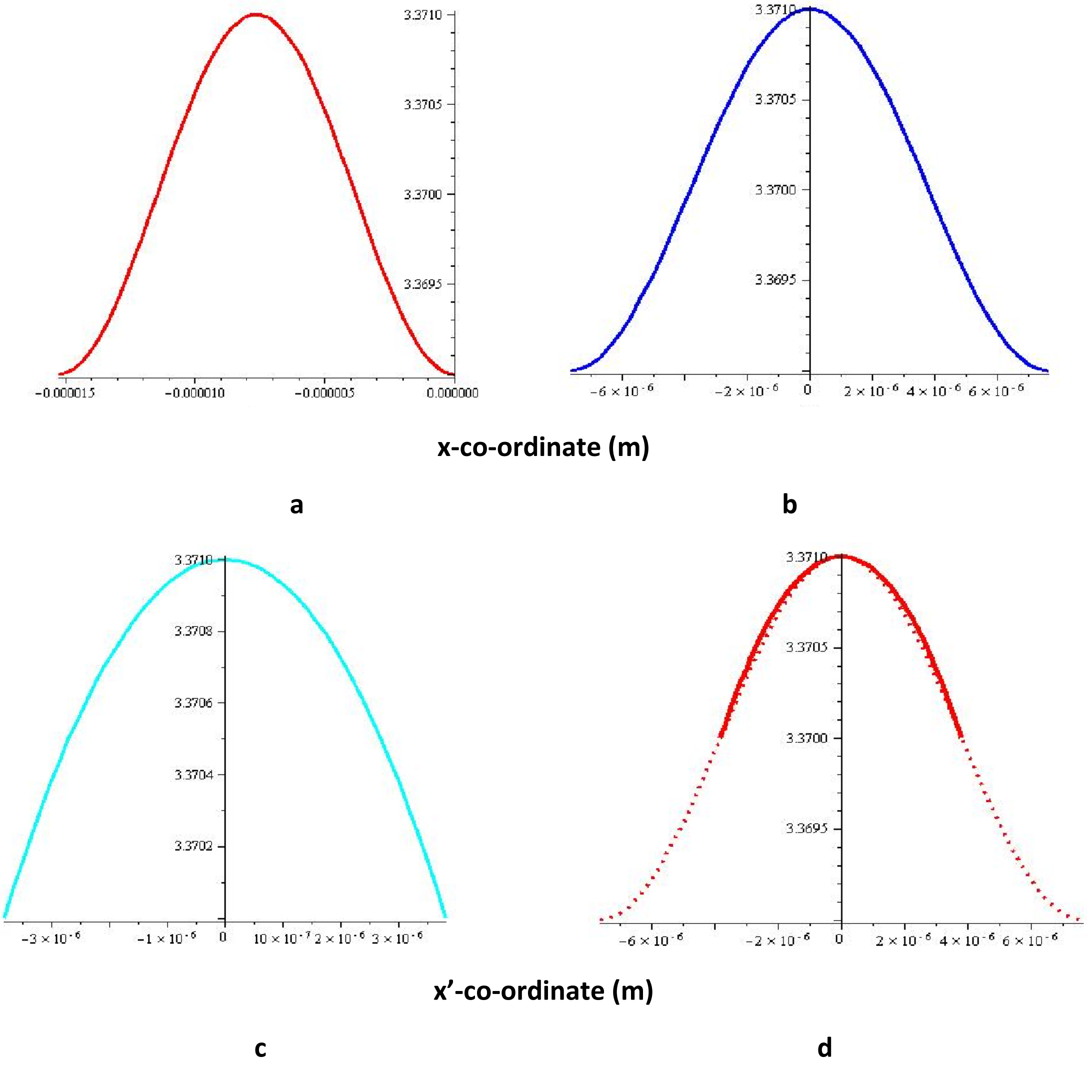


Figure 4. RID simulated using different Eqs.: 9(a), 11(b), 15(c), and fiting of Eq.11 (*dots*) and Eq.15 (*solid*) in interval $-\Lambda/4 < x' < \Lambda/4$ (d).

3. DISCUSSION ABOUT TRAPING CAPABILITY

The dependence of focal length on the thickness of GRIN microlens is simulated with given above experimental paramters, and shown in Fig.5a. We can see that, the focal length of GRIN microlens is in order of the sound wavelength (or its diameter) and decreases when thickness increares from 100µm to 1mm. Thus, its trapping capability will be hoped. To use this GRIN microlens to optical trapping, which needs high numerical aperture (NA) objective [11], firstly, we must examine its NA. As well known, NA is given by [12]:

$$NA \approx n_m \frac{D}{2f} \tag{20}$$

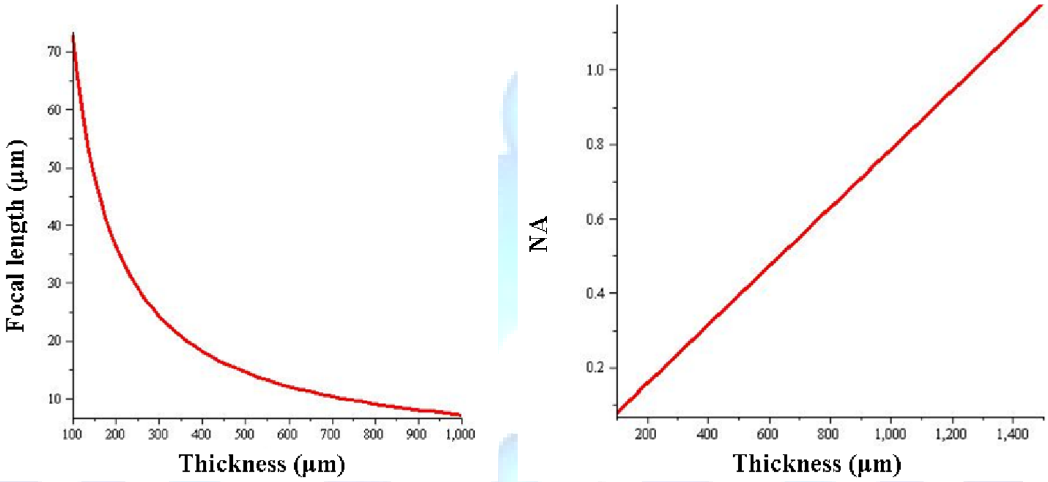
where n_m is the refractive index of medium behide GRIN microlens. As shown above, $D = \Lambda/2$, substituting Eq.19 into Eq.20 , we have

$$NA = \frac{16\Delta n_0 d n_m}{\Lambda} \tag{21}$$

Substituting Eq.8 into Eq.21, we have

$$NA = \frac{16\sqrt{MI_s}\, d n_m}{\sqrt{2}\Lambda} \tag{22}$$

describes the dependence of NA on the parameters of sound (I_s , Λ), acoustic-optical medium (M , d) and medium behind GRIN microlens (n_m). Example, for fixed parameters: $\Lambda \simeq 15.26\mu m$, $I_s = 100W / cm^2$, for ultrasonic wave, $M = 104 \times 10^{-15} m^2 / W$ for GaAs, and $n_m = 1.326$ for water as embedding fluid of traped particle [13], the dependence of NA on thickness is shown Fig.5b.



a b

Figure 5. Focal length (a) and Numerical Aperture (b) vs. thickness.

From Fig.5, when thickness of GRIN cylinder of GaAs increases from 1 mm to 1.4mm, the numerical aperture of GRIN microlens have values in the region from 0.8 to 1.4, which are as that of the high quality optical objective using for optical trap [1], [5], [14]. However, NA can be increased by choice material with higher figure of merit ($M > 104 \times 10^{-15} m^2 / W$), increasing the sound intensity ($I_s > 100W / cm^2$) or using shorter ultrasonic wavelength ($\Lambda < 15.26\mu m$). Moreover, the NA will be increased if the trapped particle is embedded in the fluid with higher refractive index ($n_m > 1.326$).

4. CONCLUSIONS

The appearance of microlens 2D array modulated by ultrasonic wave ($V_s \sim 5000m / s$, $F_s = 350 \times 10^6 Hz$) induced in acousto-optical material (GaAs) is theoretically improved. The approximation expression of refractive index distribution of microlens is derived to find the its focal length ($f \sim \mu m$). Based on simulated numerical aperture ($NA \sim 1$) with experimental parameters, the optical trapping capability of microlens is discussed. Finally, by acoustic modulation, a quadrance cubic of acousto-optical material could be microlens 2D array using to demonstrate the optical tweezer array, which will be presented in the next article.

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Author' biography with Photo

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