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ULTRASONIC-CONTROLLED MICRO-LENS ARRAYS IN GERMANIUM FOR OPTICAL TWEEZERS TO SIEVE THE MICRO-PARTICLES

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Abstract. *The micro-lens arrays created by ultrasonic waves in the acousto-optical material (OAM) have been proposed and investigated. In previous works, the simulation results showed that the proposed micro-lens can be used for optical tweezers arrays to trap an assembly of micro-particles. In this article, the micro-particle sieving capability of optical tweezers arrays in Germanium modulated by ultrasonic waves is presented. The sieving processes are controlled by changing of initial phase or intensity and frequency of ultrasonic waves. The simulation results show that the optical tweezers arrays will act as the dynamical one, which can sieve the dielectric micro-particles in 3D space in the embedding fluid.*

Keywords: optical tweezers arrays, acousto-optical material, micro-particle, Sieving process.

I. INTRODUCTION

Up to now, there are many methods as using diffractive elements [1–3], using micro-lens arrays fabricated by proton beam writing [4], using image processing techniques [5], and intelligent control techniques [6], proposed to create the optical tweezers arrays to trap an assembly of micro-particles. The aim of all methods is to create an array of small laser spot, in which the laser intensity gradient is large [7]. The arrays of micro-lens with high numerical aperture (NA) are appreciable tool for this aim.

As shown in work of Sow and colleagues [4], the micro-lens arrays must be fabricated through process from proton writing to thermal heating, unfortunately, the dimension of micro-lens and spatial period are fixed, due to the unchanged of the input parameters. So that, it should not be resourceful if they are used for the optical tweezers arrays, which should be changed in accordance with trapped objects (micro-particles).

As well known, the acousto-optical devices proposed to use for partial reflection of light (beam splitter), and the Bragg cell have numerous applications in photonics [8]. It is fortunate, McLeod and Arnold have discussed about the tunable acoustic gradient index lens in liquid [9–11, 21]. The results presented in those works give us the idea to use two perpendicular ultrasonic waves for creating the 2D arrays of micro-lens in extra-dense flint glass (EDFG) [12] and first time show out the trapping capability of optical tweezers using created micro-lens [13,14]. Consequently, the optical tweezers arrays using micro-lens arrays created in Germanium having larger figure of merit by ultrasonic waves can be used for trapping the bigger particle as bio-molecule [15]. Up to now, there is a question how to catch the micro-particles embedded sparsely in fluid by those optical tweezers.

To answer above question, in this work, firstly, we present the micro-lens arrays optical modulated in Germanium by ultrasonic waves; secondly, the simulation of process to sieve the micro-particles and discussion about the capability to control the trapping positions in 3D space of embedding fluid.

II. THE SAMPLE OF OPTICAL TWEEZERS ARRAYS IN GERMANUIM

The optical tweezers arrays using micro-lens modulated by ultrasonic waves in Germanium is shown in Fig. 1(a). The refractive index of a square Germanium plate is modulated by two perpendicular ultrasonic waves from two LiNbO3-transducers, which is supplied by the radio frequency signal generator (Fig. 1(b)). Then the Germanium plate becomes a micro-lens arrays. The original laser beam is expanded by two lenses, so that its intensity distribution approximately is uniform in entry plane of Germanium plate. Propagating through Germanium plate (micro-lens arrays) the laser beam is separated into sub-beams, which is focused in the fluid with micro-particles. Every focused laser sub-beam become an optical tweezers.

In own work, Kotopoulis showed that the frequency and intensity of ultrasonic waves generated from LiNbO3-transducer can be controlled by changing the intensity and frequency of the applied radio signal [16]. Consequently, the dimension of micro-lens and spatial period of micro-lens arrays in proposed sample may be changed by applied radio signals. Moreover, with changing of the acoustic intensity, the gradient of refractive index, and consequently, the focal length of micro-lens and the numerical aperture of micro-lenses will be changed. So, to control the focus spot in Z-direction, the intensity of ultrasonic wave must be controlled, while to control the focus spots of micro-lenses in the plane (X,Y), the initial phase and frequency of ultrasonic waves must be controlled by the applied radio signal. The controlling process of micro-lens arrays is the sieving process of micro-particles, which will be presented in the next section.

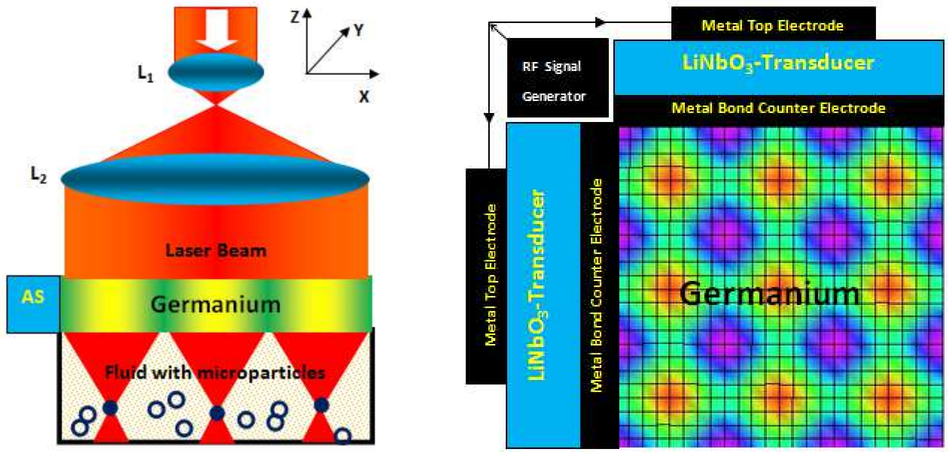
III. 2D SIEVING PROCESS

Considering two identical acoustic plane wave propagate in the X- and Y-directions of Germanium plate (see Fig. 1), then the strain at positions x and y and time t are given as follows [8, 17]:

$$S_x(x,t) = S_0 \cos\left(\Omega t - 2\pi x/\Lambda + \phi_x\right), \tag{1}$$

$$S_y(y,t) = S_0 \cos\left(\Omega t - 2\pi y/\Lambda + \phi_y\right), \tag{2}$$

where, S_0 is the amplitude; $\Omega = 2\pi F_s$ is the angular frequency; $\Lambda = V_s/F_s$ is wavelength; ϕ_x, ϕ_y are the initial phase in x- and y-direction, respectively; F_s is frequency; and V_s is the velocity. Due to



(a) (b)

Fig. 1. (a) Schematic diagram of optical tweezers arrays, and (b) Germanium crystal modulated by two ultrasonic waves from LiNbO3-transducer

the interference of two waves, from Eq. (1) and Eq. (2), the strain at position (x,y) and time t is given follows:

$$S_{(x,y)}(x,y,t) = S_0\left[\cos\left(\Omega t - 2\pi x/\Lambda + \phi_x\right) + \cos\left(\Omega t - 2\pi y/\Lambda + \phi_y\right)\right]. \tag{3}$$

The strain $S_{(x,y)}(x,y,t)$creates a proportional perturbation of the refractive index in Ge, analogous to the Kerr effect [8]:

$$\Delta n(x,y,t) = -\frac{1}{2}\gamma n^3 S_{(x,y)}(x,y,t), \tag{4}$$

where γ is a phenomenological coefficient known as the photo-elastic constant, n is the refractive index of Germanium in the absence of sound. Because the acoustic frequency is typical much smaller than the optical frequency, an adiabatic approximation for studying light-sound interaction may be adopted. Considering that two waves are phase matching, i.e. $\phi_x = \phi_y = \phi$. Using Eq. (3) and Eq. (4), the spatial-varying inhomogeneous refractive index is [15]:

$$\begin{aligned} n(x,y) =& n - \Delta n_0\left[\cos\left(2\pi x/\Lambda + \phi\right) + \cos\left(2\pi y/\Lambda + \phi\right)\right] \\ \approx& n - 2\Delta n_0 \cos\left(\pi\frac{x+y}{\Lambda} + \phi\right)\cos\left(\pi\frac{x-y}{\Lambda}\right) \end{aligned}, \tag{5}$$

where $\Delta n_0 = \sqrt{MI_s/2}$ is the amplitude of refractive-index wave, i.e. a material parameter representing the effectiveness of sound in altering the refractive index, $M = \gamma^2 n^6/\rho V_s^3$ is a figure of merit for the strength of the acousto-optic effect in the material, ρ is the mass density of the medium, and I_s is the intensity of sound. The acousto-optic material with refractive index distributing as shown in Eq. (5) became a micro-lens arrays.

As an example, we use the Germanium crystal, which is one of the effective acousto-optic crystals with figure of merit is about 10^3 times larger than one of the extra-dense flint glass [17,18]. The main parameters of Germanium are given as: optical transmission of$(2.0 \div 20.0)\mu$m, mass density of $g = 5.33\,g/cm^3$, acoustic velocity in Germanium of $V_s = 5.5$ km/s [17], refraction index of $n = 4.0$, and figure of merit of $M = 1.68 \times 10^{-11}$ m^2/W. Consider the refractive index of crystal Germanium is modulated by two ultrasonic waves from LiNbO3 transducer with intensity of about $I_s = 3 \times 10^4$ W/m^2 [16] and the frequency of $F_s = (25 \div 500)$ MHz, consequently, wavelength of $\Lambda = (550 \div 11)\,\mu m$. This ultrasonic wave creates a refractive-index wave of amplitude about $2\Delta n_0 \approx 1.0 \times 10^{-3}$. Assuming the initial phase of two waves is same of $\varphi = 0$, the refractive index distribution in area $3\Lambda \times 3\Lambda$ of crystal Germanium is simulated and illustrated in Fig. 2.

The period appearance of graded-index area of $\Lambda \times \Lambda$ (see Fig. 3a) leads the acousto-modulated crystal Germanium to become 2D micro-lens arrays. With the initial phase of $(\varphi = 0)$, in the area of $3\Lambda \times 3\Lambda$ there are 9 micro-lenses, whose centers,(x_i, y_i), are equidistant from each adjacent one in both directions X and Y with a distance of Λ (Fig.2). From Fig.3a, the center of the first micro-lens can be described by following relation:

$$(x_1 = 0.5\Lambda, y_1 = 0.5\Lambda) \;\; if\, \phi = 0 \tag{6}$$

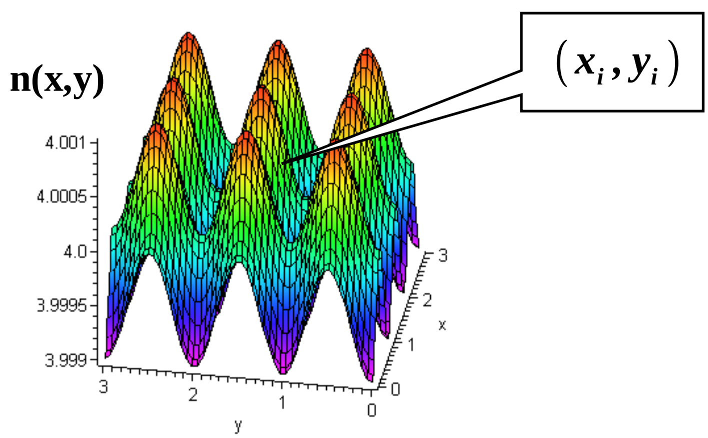


Fig. 2. Distribution of refraction index in area $3\Lambda \times 3\Lambda$of crystal Germanium and the position of the center of micro-lens(x_i, y_i)

Assuming the initial phase of two waves will be changed, for example $\varphi = \pi/4$ and $\varphi = \pi/2$. The center of the first micro-lens has changed as shown in Figs. 3b and 3c. The positions of center of i^{th} micro-lens can be described by following relations:

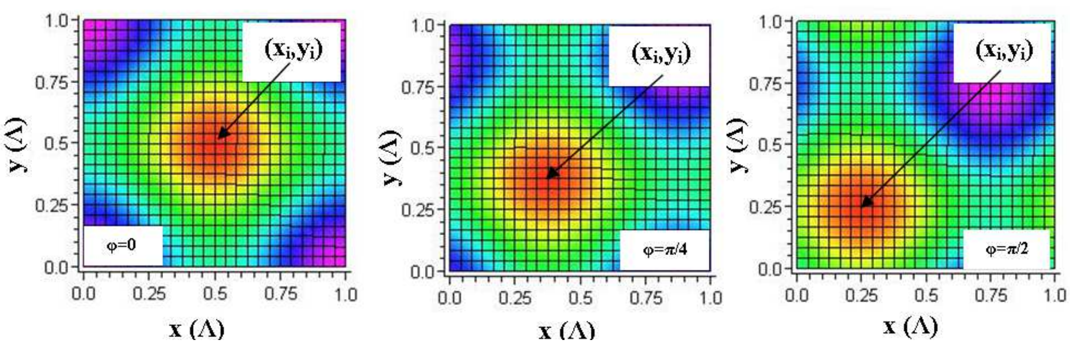
$$\begin{cases} (x_1 = 0.375 \times \Lambda, y_1 = 0.375 \times \Lambda) & if\ \phi = \pi/4 \\ (x_1 = 0.250 \times \Lambda, y_1 = 0.250 \times \Lambda) & if\ \phi = \pi/2 \end{cases} \tag{7}$$

From the refractive index distribution in Fig. 2 and Eqs. (6) and (7), the position of the center of i^{th} micro-lens can be described by following relations:

$$\begin{cases} x_i(y_i) = [0.5 + (i-1)]\,\frac{V_s}{F_s} & if\ \phi = 0 \\ x_i(y_i) = [0.5 - 5(\phi/\pi) + (i-1)]\,\frac{V_s}{F_s} & if\ \phi \neq 0 \end{cases} \tag{8}$$

As shown in Fig. 1, the center of micro-lens is the center of the independent optical tweezers. So the center of the independent optical tweezers can be sieved by changing of the initial phase and frequency.

Assuming that, initially, with chosen initial phase and frequency of ultrasonic waves, the micro-particles are trapped in the centers of all independent tweezers. If the frequency or initial phase of ultrasonic waves are changing, the positions of micro-particles will be periodically changed in both directions X and Y (the distance between two micro-particles is not changed). Instead, with given initial phase and frequency the micro-particles are not trapped in centers of all independent tweezers, it is need to change initial phase or frequency to catch micro-particles. This process will be called 2D sieving process. There are advantages in comparison to the micro-lens arrays fabricated by proton beam writing [4], that the acousto-modulated micro-lens arrays have the controllable spatial period,Λ, by acoustic frequency and the controllable position of micro-lenses by the acoustic frequency or initial phase.



(a) (b) (c)

Fig. 3. Sieving process of the first micro-lens by changing initial phases of acoustic waves: (a) $\varphi = 0$, (b) $\varphi = \pi/4$, (c) $\varphi = \pi/2$

IV. SIEVING IN Z-DIRECTION

Now, we pay attention on one independent optical tweezers, whose center is located at point (x_i, y_i), it means the refractive index distribution reaches the maximum value at point (x_i, y_i), and the initial phase to be zero $\varphi = 0$, i.e. $x_i = y_i$. By using trigonometry relations, from Eq.(5) the refractive index distribution in the area of $(x < \Lambda, y < \Lambda)$ of the micro-lens can be approximately rewritten as follows:

$$n(x,y) \approxeq -n4\Delta n_0 \left[\cos^2\left(\pi\frac{\rho}{\Lambda}\right) - \frac{1}{2}\right] \tag{9}$$

where $\rho = \sqrt{x^2+y^2}$ is defined as the radial radius. From Eq.8, the refractive index distribution in the circle of radius $\Lambda/2$ can be rewritten as follows [13, 14]:

$$n(\rho) \cong n + 4\Delta n_0 \left(\frac{1}{2} - \ln 2\frac{\pi^2\rho^2}{(\Lambda/2)^2}\right), \tag{10}$$

which describes the refractive index distribution of the GRIN micro-lens [8]. From Eq. 10, the focal length of micro-lens is given by:

$$f_s = \frac{\Lambda^2}{4\ln 2\Delta n_0 d} \; or \; f_s = \frac{(V_s/F_s)^2}{4\ln 2\sqrt{MI_s}d}, \tag{11}$$

where d is the thickness of OAM.

As the operation principle of optical tweezers, the dielectric particle is trapped in the foci of lens. So, to sieve micro-particle in the z-direction, i.e. in the laser beam axis, the focal length (or depth of foci) must be changed. As shown in Eq.11, the focal length of micro-lens depends on two changeable parameters as frequency (F) and intensity of acoustic wave, since the parameters of OAM could be chosen in practice. Considering the thickness of Germanium plate is of 1mm (d=1mm) and using given parameters above, the dependence of the focal length (or depth of foci) of micro-lens on acoustic frequency is illustrated in Fig. 4.

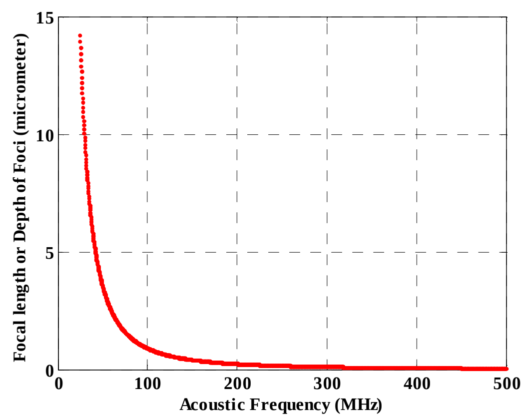
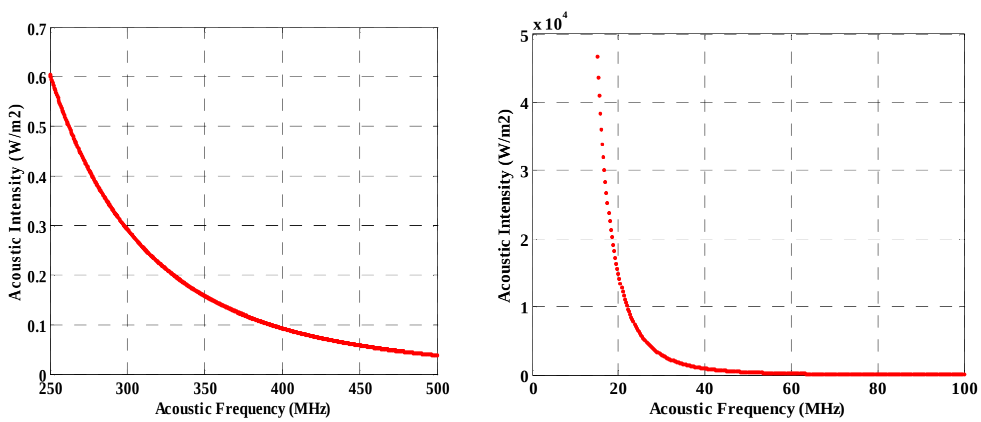


Fig. 4. Focal length (or depth of foci) vs. acoustic frequency

The focal length-acoustic frequency characteristic in Fig. 4 show that it is able to sieve the particles in Z-direction by changing frequency. But, with the increasing of the frequency, i.e. with decreasing of the wavelength ($\Lambda = V_s/F_s$), the focal length decreases. This leads to first situation that the numerical aperture of the micro-lens ($NA \approx n_f\Lambda/f_s$) will be changed, which influences on the trapping capability of optical tweezers.



(a) (b)

Fig. 5. Acoustic intensity vs. acoustic frequency for $f_s = 10\ \mu$m

It is fortunate, the limit conditions for that the numerical aperture is higher 1 $(NA > 1)$ have been found out and presented in previous works [18, 19]. The second situation that the focal length depends on the acoustic intensity too (see Eq.11), so what is the ways to sieve the particles in a fixed plane (X, Y) at a depth (z_s) in the fluid. Using Eq. 11, the relation between intensity and frequency of acoustic wave so that $z_s = f_s = 10\ \mu\text{m} = \text{const}$ is illustrated in Fig. 5.

As shown in Fig. 5, we can see that to sieve particles in plane (X, Y) at the depth of z_s=10μm inside fluid by changing acoustic frequency in the interval of $(250 \div 500)$ MHz, we can control the relating acoustic intensity not more than 0.6 W/m^2 (see Fig. 5a). Meanwhile, when using higher acoustic intensity up-to 3×10^4 W/m^2, the acoustic frequency can be reduced down-to 18 MHz (see Fig. 5b).

V. CONCLUSION

The sieving process of micro-particles in optical tweezers arrays created in Germanium plate modulated by ultrasonic waves is investigated. The simulation results show that the sieving process can be done in 3D space of embedding fluid with controlled initial phase, intensity and frequency of acoustic waves. Moreover, the micro-particles located in fixed plane (X,Y) of the fluid will be trapped if the acoustic intensity is chosen suitable to the controlling frequency. With the focal length of millimeters and the dimension of micrometers, the arrays of the micro-lens in Germanium modulated by ultrasonic waves with frequency in range (18÷100) MHz and intensity up-to 3×10^4 W/m^2, generated from $LiNbO_3$-transducer as shown in [16], are useful for designing the optical tweezers arrays to sieve the biological molecules in 3D space of embedding fluid.

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