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MICROLENS FOCAL LENGTH CONTROLING FOR OPTICAL TWEEZER ARRAYS BY ACOUSTO-OPTIC MODULATION IN GERMANIUM

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ABSTRACT

The microlens arrays created by ultrasonic waves in acousto-optical material Germanium (Ge) is theoretically proposed. The simulated results show the proposed microlens arrays can be used for optical tweezers arrays to trap an assembly micro-beads. Moreover, with the control by changing of the ultrasonic intensity and frequency, the optical tweezers arrays will act as the dynamical one, which can sieve the beads in (X,Y) plane in the embedding fluid. The focal length of microlens in Germanium controling by frequency and intensity of ultrasonic wave is discussed.

Indexing terms/Keywords

Optical tweezer arrays, Acousto-optic modulation, Germanium, Operation conditions.

Academic Discipline And Sub-Disciplines

Laser application, Optical trapping;

SUBJECT CLASSIFICATION

Optics, Photonics, Microsphere

TYPE (METHOD/APPROACH)

Theory, Simulation.

1. INTRODUCTION

Up to now, there are many methods as using diffractive elements [1, 2, 3], using microlens arrays fabricated by proton beam writing [4], using image processing techniques [5], and intelligent control techniques [6], proposed to create the optical tweezer arrays to trap an assembly of micro-particles. The aim of all methods to create an arrays of small laser spots, in which the intensity gradient is powerful [7]. The arrays of microlens with high numerical aperture (NA) are appreciable tool for this aim.

As shown in work of Sow and colleagues [4], the microlens arrays must be fabricated through process from proton writing to thermal heating, unfortunately, the dimension of microlens and spatial period are fixed, related to the input fabrication parameters. So that, it should not be resourceful if they are used for the optical tweezer arrays, which should be changed in accordance with trapped objects.

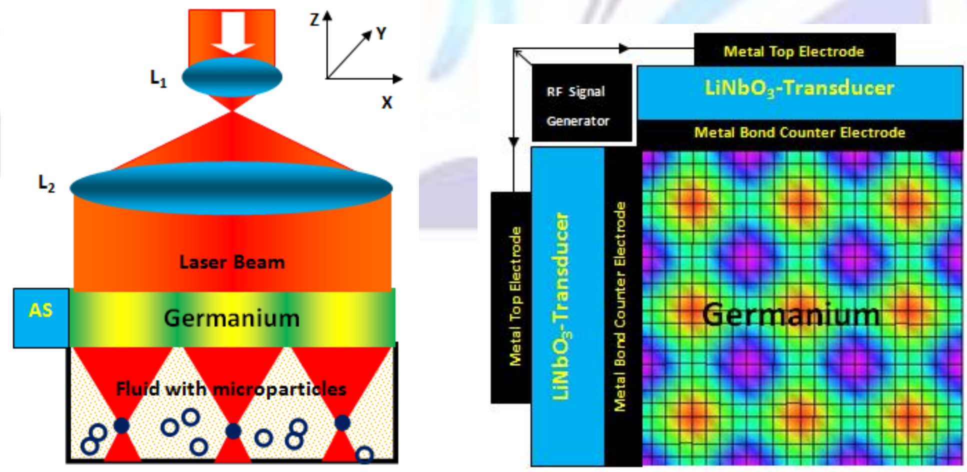
As well known, the acousto-optical devices have been proposed to use for partial reflection of light (beamspliter), and the Bragg cell have numerous application in photonics [8]. It is gread, McLeod and Arnold have discussed about the tunable acoustic gradient index lens in liquid [9-11]. Moreover, in 2014, the acousto-optical deflectors for optical tweezer arrays is anounced in European Network of Excellence for Biophotonics [20]. The results presented in those works give us the ideal to use two perpendicular ultrasonic waves for creating the 2D arrays of microlens in extra-dense flint glass (EDFG) [12] and first time show out the nanopartilce trapping capability of tweezers using created microlens [13,14]. However, there are questions if microlens created by ultrasonis waves modulation in EDFG, which has small figure of merit can be used for bigger particle as bio-molecule and how to catch the big particles embedded sparsely in fluid.

In this work, firstly, we present the optical tweezer arrays created in Germanium by ultrasonic waves; secondly, the microlens length controling by frequency and intensity of ultrasonic wave for that the trapping positions fixed in 3D space is discussed.

2. THE SAMPLE OF OPTICAL TWEEZER ARRAYS

The optical tweezer arrays using microlens modulated by ultrasonic waves in Germanium is shown in Fig. 1a. The refractive index of a Square Germanium plate is modulated by two perpendicular ultrasonic waves from two $LiNbO_3$-transducers, which is supplied by the radio frequency signal generator (Fig. 1b). Then the Germanium plate become a microlens 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 (microlens arrays) the laser beam is separated into sub-beams, which is focused in the fluid with microparticles. The foci of all laser sub-beams become the optical tweezer arrays.

The intensity and frequency of the radio signal are changing to control the frequency and intensity of ultrasonic waves. Consequently, the dimension of microlens and spatial period of microlens arrays will be changed. Moreover, with changing of the acoustic intensity, the gradient of refractive index, and consequently, the focal length of microlens and the numerical aperture of microlenses will be changed. So to control the intensity gradient of the laser in focus spot and the its position in Z-direction, the intensity of ultrasonic wave must be controled, while to control the focus spots of microlenses in the plane (X,Y), the initial phase and frequency of ultrasonic waves must be controled by the controling electric signal. The controling principle will be presented in the next section.



a) b)

Fig.1. Schematic diagram of optical tweezer arrays (a) and Germanium crystal modulated by two ultrasonic waves (b).

3. THEORICAL BACKGROUNDS

3.1 Distribution of refractive index

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

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

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

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

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

The strain $S_{(x,y)}(x,y,t)$ creates a propotional 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 phenomennological coefficient known as the photoelastic constant, n is the refractive index of Ge in the absence of sound. Because the acoustic frequency is typical much smaller than the optical frequency, an adiabatic appoach for studying light-sound interaction may be adopted. Considering that two waves are phase matching, i.e. $\varphi_x = \varphi_y = \varphi$. Using Eq. (3) and Eq. (5), the spatial-varying inhomogeneous refractive index is [15]:

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

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 microlens arrays.

3.2 Focal length of microlens

Now, we pay attention on the circle of acousto-optic material centered at point (x_i, y_i) and limited in the circle of radius Λ. Considering the refractive index distribution reaches the maximum value at point (x_1, y_i), and the initial phase to be zero $\varphi = 0$, i.e. $x_i = y_i$. With considerations and using trigonemetry relations, from Eq.(5) the refractrive index distribution in the area of $(x \ll \Lambda, y \ll \Lambda)$ of the acousto-optic circle can be approximately rewritten as follows:

$$\begin{aligned} n(x,y) &= n - 2\Delta n_0 cos\left(\pi\frac{x+y}{\Lambda} + \varphi\right) cos\left(\pi\frac{x-y}{\Lambda}\right) \\ &\approx n - 2\Delta n_0 cos\left(\pi\frac{x+y}{\Lambda}\right) = n - 2\Delta n_0\left[2cos^2\left(\pi\frac{x+y}{\Lambda}\right) - 1\right] \\ &= n - 4\Delta n_0\left[cos^2\left(\pi\frac{\rho}{\Lambda}\right) - \frac{1}{2}\right] \end{aligned} \tag{6}$$

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:

$$n(\rho) \cong n + 4\Delta n_0\left(\frac{1}{2} - \ln 2\frac{\pi^2\rho^2}{(\Lambda/2)^2}\right), \tag{7}$$

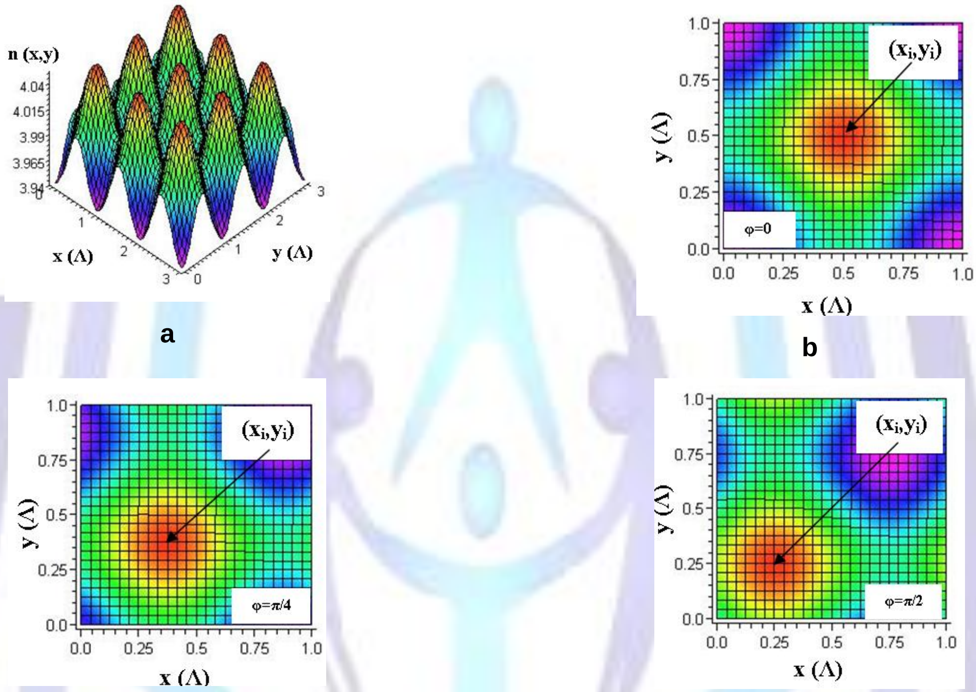
which describes the refractive index distribution of the GRIN microlens [8]. From Eq.(7), the focal length of microlens is given by:

$$f_s = \frac{\Lambda^2}{4\ln 2\Delta n_0 d} \; or \; f_s = \frac{\left(V_s / F_s\right)^2}{4\ln 2\sqrt{MI_s}\, d}, \qquad (8)$$

where d is the thickness of acousto-optic material.

4. SIMULATION AND DISCUSSION FOR GERMANIUM

The Germanium (Ge) is one of the effective acousto-optic crystals with figure merit is about 10^3 times larger than one of the extra-dense flint glass [17,18].



a

b

c

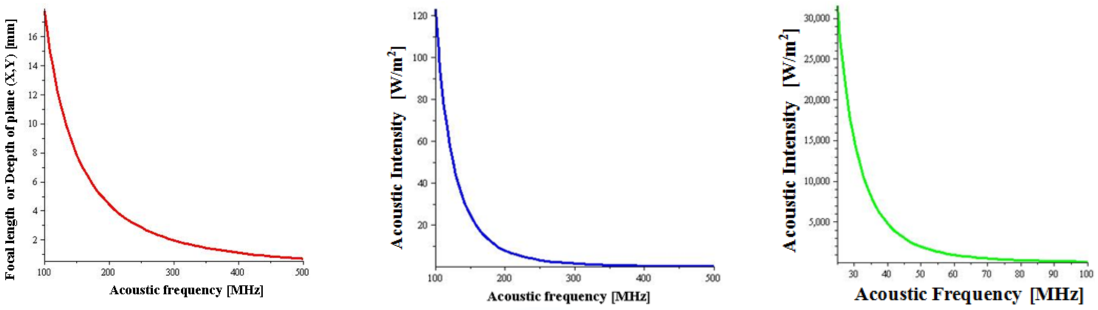
d

Fig. 2 Distribution of refraction index in Ge (a); Position of microlens in Ge (x_i,y_i) with different initial phases of acoustic waves: b-$\varphi = 0$, c-$\varphi = \pi/4$, d-$\varphi = \pi/2$.

The main parameters of Ge 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 Ge of $V_s = 5.5 km/s$ [17], Refraction index of $n = 4.0$, and Figure of merit of $M = 1.68\times10^{-11} m^2/W$. The refractive index of crystal Ge is modulated by two ultrasonic waves from $LiNbO_3$ transducer with intensity of $I_s = [1 \div 120] W/m^2$, which is more smaller than that given in work of S. Kotopaulis [19], 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 $\Delta n_0 = 2.89\times10^{-2}$. With considering the initial phase of two waves is same of $\varphi = 0$, the refractive index distribution in area $3\Lambda \times 3\Lambda$ of crystal Ge is simulated and illustrated in Fig.2a. The period appearance of graded-index areas of $\Lambda \times \Lambda$ (see Fig.2b) leads the acousto-modulated crystal Ge became 2D microlens arrays.

There are advantages in comparision to the microlens arrays fabricated by proton beam writing [4], that the acousto-modulated microlens arrays have the controlable spatial period, Λ , by acoustic frequency and the controlable position of microlenses in Ge crystal, (x_i, y_i) by the acoustic frequency or initial phase (Fig. 2b-d). If the acoustic modulated microlens arrays used to design an optical tweezers, the trapping positions, (x_i, y_i), in the plane (X,Y) at a deepth in the fluid, $z_d = f_s$ can be controled by the frequency and initial phase of acoustic waves. By this ways the microparticles randomly located in the plane (X,Y) of fluid will be sieved.

As shown in Eq.8, the focal length of microlens will be changed when the acoustic frequency changing, that means the deepth of plane (X,Y), z_d , will be changed on the Z-direction in the sieving process (see Fig.3a). To fix the plane (X,Y) at chosen deepth in fluid when changing frequency, i.e. the focal length is unchanged, it is necessary to choice the acoustic intensity suitable to the controling frequency. With parameters given as $V_s = 5.5km/s$, $M = 1.68\times10^{-11}m^2/W$ and $d = 15\mu m$, the dependence of acoustic intensity on the frequency for the focal length (or deepth of plane (X,Y)) fixed at $z_d = 16mm$ is shown in Fig.3b.



a b c

Fig.3 Focal length (a) and Acoustic intensity (b and c) vs Acoustic frequency.

Up to now, the LiNbO$_3$ - transducer generating the ultrasonic wave with intensity upto $3\times10^{-2}W/mm^2 (3\times10^4 W/m^2)$ is really designed and manufactured [19], so to fix the trapping plane (X,Y) at $z_d = 16mm$ for example, the frequency can be reduced from 100MHz downto 25MHz as shown in Fig.3c.

5. CONCLUSION

The microlens arrays in the Germanium crystal modulated by two perpendicular ultrasonic (acoustic frequency in range of MHz) waves is proposed for the optical tweezers. The simulated results show that by those microlens arrays, the trapping positions (x,y,z) in fluid embedding the microparticles can be controled the changing the acoustic frequency, consequently, the randomly locating microparticles in fluid can be siewed to tweezers centers. Moreover, the microparticles located in fixed plane (X,Y) of the fluid will be trapped if the acoustic intensity is chosen suitable to the controling frequency. With the focal of milimeters and the dimenssion of micrometers, the arrays of the microlens Ge modulated by ultrasonic waves with frequency in range (25÷100) MHz generated from LiNbO$_3$-transducer are useful for trapping the biological molecules.

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