Acousto-optical deflector for non-mechanical manipulating using optical tweezers

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Abstract. Optical tweezers are widely used in various fields of science and technology, such as biophysics, cytology and solid-state physics. Most of the existing optical tweezers use mirror or mirror-lens systems to manipulate the position of the trap. Such systems require precise alignment and do not allow the trap to be moved quickly from one arbitrary point to another due to the inertia of the mirror and lenses. We discuss acousto-optic scanning characterized by high precision and repetition rate for manipulating micro-objects using optical tweezers. Bragg diffraction of light via ultrasonic waves allows creating robust solid-state devices for precise and fast laser beam deflection. We describe a scheme of the optical tweezers with PC-driven two-dimensional scanning implemented by two sequential acousto-optical cells.

1. Introduction

Optical tweezers are a universal tool widely used in various fields of science and technology: cytology, histology, molecular biology, bioorganic chemistry, solid state physics, nanomechanics and nanotechnology [1-3].

The key element of the optical tweezers is a beam steering system necessary to control the beam direction. Mirror and mirror-lens beam steering systems are the most widely spread [4,5]. Their inertia and relatively low speed limit the range of optical tweezers applications. Liquid crystal spatial light modulators are software-controlled and enable a tunable array of traps but are able to change the position of the trap not faster than 2 ms. Therefore, assigning complicated trajectories of microobjects requires time-consuming calculations in order to generate program-synthesized holograms to be displayed on the liquid crystal modulator.
In this research, we discuss two-directional an acousto-optical (AO) scanning system for non-mechanical manipulating micro-objects using optical tweezers. In AO system, the position of the trap is determined only by the frequencies of the acoustic waves excited in the crystals. The tuning speed is limited mainly by the transit time of acoustic wave in the crystal, which is usually a few microseconds [6]. High speed and random spatial access of the trap, program control and other features of the AO deflectors provide an easy and flexible implementation of the trap positioning.

Today, AO steering is implemented in various modifications of optical tweezers [7,8]. Multiple traps are created using light deflection at a very high speed (up to 100 kHz) so that the position of each trap is refreshed at times much smaller than the diffusion time of the trapped particle to prevent it from drifting away, while the laser switches to another position. These results show the advantages and prospects of AO non-mechanical manipulating micro-objects using optical tweezers.

In this paper, we show an easy-to-install setup for manipulating micro-objects using optical tweezers with non-mechanical AO two-dimensional scanning.

2. Proposed concept
The scheme of optical tweezers for micro-objects manipulating using two-dimensional AO scanning is shown in Figure 1. Laser beam diameter is enlarged by a beam expander and then directed to two-coordinate AO deflector, which consists of two identical AO cells rotated by 90°. The first AO cell deflects the laser beam in the tangential plane, the second one - in the sagittal plane, so that the beam diameter does not change. The relay lens system is necessary for matching of the AO cells and the microobjective, which focuses the radiation onto the inspected specimen located on the stage. By moving the last lens of the relay system, it is possible to move the focus of the laser beam along the axis. Digital camera with a microscopic imaging system placed on the opposite side of the object enables real-time visualization and control of the trap position.

![Figure 1. Scheme of the optical tweezers with AO beam steering](image)

3. Acousto-optical deflector
The AO deflector is a crystal with a piezoelectric element attached to one of its edges. When the high-frequency signal is applied, an acoustic wave propagates through the crystal, which creates a dynamic diffraction grating for the incident laser beam [9]. By varying the frequency, the first diffraction maximum of the beam is deflected at controlled angles. The excitation of sound waves occurs when signals from the electronic driver are fed to the electrodes. The driver consists of a generator and a broadband amplifier. To implement the traveling sound wave mode, an acoustic absorber is attached to the opposite face of the crystal. Fast modulation leads to the fact that the optical trap is switched between different positions, i.e. creates multiple traps. AO deflector does not contain moving parts and therefore exhibits high deflection velocities and is free of the drawbacks associated with mechanical scanners. For two-directional spatial scanning, the deflector consists of two AO cells rotated by 90° and located sequentially.
For this research, we have developed a two-directional AO scanning system based on two identical cells made from TeO₂ crystals. Each of them operates in Bragg anisotropic diffraction mode. The developed deflector has a typical configuration: the light incident angle in the crystal is $\theta_0 = 5.6^\circ$ and the length of the acousto-optic interaction $L = 2$ mm. The slow shear acoustic wave in the crystal propagates in the plane (001) at an angle $\alpha = 7.5^\circ$ to the direction [110] (Figure 2). The sound wave vector $q$ is directed at an angle $\gamma = 91.5^\circ$ to the axis [110] and is tangent to the surface of the refractive indices of diffracted light. The vector diagram of this type of AO diffraction is shown in Figure 2.

![Figure 2. Scheme (left) and wave diagram (right) of AO cell](image)

The maximal deflection angles $\Delta \varphi_x \times \Delta \varphi_y$ may be calculated as $\Delta \varphi_x = \left( \frac{2}{\Gamma_{RS}} \right) \arctan \left( \frac{\Delta x}{2 f_{MO}} \right)$, $\Delta \varphi_y = \left( \frac{2}{\Gamma_{RS}} \right) \arctan \left( \frac{\Delta y}{2 f_{MO}} \right)$, where $\Delta x \times \Delta y$ – dimensions of the specimen, $f_{MO}$ – focal length of the microobjective, $\Gamma_{RS}$ – magnification of relay system.

The angular resolution of AO deflector is limited by the diffraction and cannot exceed $1.22(\lambda/D)$. Number positions $N_x \times N_y$ resolved by AO deflector is determined by the ratio of the angular scanning range $\Delta \varphi_x \times \Delta \varphi_y$ and the angular resolution: $N_x = \Delta \varphi_x D_0/1.22\lambda$, $N_y = \Delta \varphi_y D_0/1.22\lambda$, where $D_0$ – laser beam diameter, $\lambda$ – laser wavelength, $D_0 = \Gamma_{BE}d$, $\Gamma_{BE}$ – magnification of a beam expander, $d$ – initial laser beam diameter. The entrance pupil diameter of AO cell $D$ should be larger, than the laser beam diameter $D \geq D_0$. The frequency range of ultrasound applied to AO cells may found as $\Delta f = V(\alpha) \Delta \varphi/\lambda$. $V$ – ultrasound velocity, which is 669 m/s at $\alpha = 7.5^\circ$.

With these formulas, we may calculate the parameters of the AO cells. For example, it is necessary to trap the particle with diameter $\delta = 1$ μm within the range $\Delta x \times \Delta y = 100$ μm $\times$ 100 μm using microobjective with $f_{MO} = 3.6$ mm and He-Ne laser ($\lambda = 632.8$ nm) with beam diameter $d = 1.2$ mm. Using the formulas given above, the main parameters of the setup may be calculated: $\Gamma_{BE} = 5$, $\Gamma_{RS} = 1$, $D_0 = 6$ mm, $\Delta \varphi_x \times \Delta \varphi_y = 1.5^\circ \times 1.5^\circ$, $N_x \times N_y = 250 \times 250$, $\Delta f = 32$ MHz.

4. Experiments

We have manufactured AO cells made of TeO₂ crystals and assembled two-directional AO deflector. Figure 3 shows the appearance of the setup used for this device calibration. To check the correctness of the theoretical considerations, we have measured the dependence of deflection angle $\Delta \varphi$ on acoustic frequency $f$. For both crystals, this dependence is the same and is shown in Figure 3. Experimentally measured values of deflection range are $\Delta \varphi_x \times \Delta \varphi_y \approx 1.8^\circ \times 1.8^\circ$. Acoustic frequency range is $f_0 \pm 0.5\Delta f = 80 \pm 15$ MHz. These values are in good correspondence with theoretical values obtained above.
5. Conclusion
In this paper, we discuss AO two-dimensional deflection system for non-mechanical manipulating micro-objects using optical tweezers. We have developed and manufactured the AO cells, which may become the basis of such scanning system. Experiments with the deflector confirm the correctness of the theoretical consideration. Proper assignment of AO deflector parameters and parameters of other components allows building a flexible system for optical trapping.

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