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Micro-Mirror Array Control of Optical Tweezer Trapping Beams

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Abstract - The lack of tools to manipulate nanoscale objects is a major obstacle to fabricating and testing nanodevices. Optical tweezers are a promising tool for nanomanufacturing, but the efficiency of optical tweezer manufacturing depends on the number of trapping beams available. Micro optics technology offers the opportunity to significantly increase the number of trapping beams without a significant increase of the cost or size of the optics. Here we report on the sensors, optical circuit and the experimental work to control an array of laser beams generated by a single laser diode, for optical-tweezer-based nanomanufacturing. Our array of laser beams is generated by an array of servo controlled scanning dual-axis micro-mirrors. Capacitor electrodes underneath the micro-mirror plates provide electrostatic actuation, which allows control of the micro-mirror position. With proper reflecting surfaces it is possible to control the impact angle of the individual laser beams onto the micro-nano-particles, thus generating an optical beam gripper effect.

I. Introduction

Optical tweezers [1] is a powerful tool for the three dimensional manipulation (translation and rotation) of micro and nano-particles, living cells and micro-organisms, without contacting them. The manipulation is possible because of the generation of forces and moments to the particles through the transfer of photon momentum. However, trapping is generally limited to transparent and reflective particles larger than 50 nm to 100 nm. Trapping may be extended to a broader range of materials and particle shapes by using multiple beams. This would also allow the manipulation of complex structures constructed by bringing together properly coated micro and nano-particles, cells and DNA molecules. Properly shaped multiple laser beams can be used to perform ablation, extraction, vaporization and cuts on optical tweezer immobilized micro-nano-particles, living cells and microorganisms. Proper opto-mechanical and controller interfaces will make possible the addition of chips with arrays of micro-mirrors, that could allow fast and economical assembly of nano-technology products.

Arrays of micro-mirrors can be used in a variety of applications, like optical switches for telecommunications, single and dual axis bar-code scanning, miniature raster scanning displays, head mounted displays, etc. Our array of laser beams is generated by an array of servo controlled scanning dual-axis micro-mirrors. Capacitor electrodes underneath the micro-mirror plates provide electrostatic actuation, which allows control of the micro-mirror position. Good position control is necessary for the control of the reflected laser beam yaw and tilt angles.

Optical design 3D solid modeling software was used to track the light paths of the laser diode beam through the optics. The beams were captured by a CCD array for testing and display purposes. For dynamic testing a dual-axis lateral effect photodetector and a quadrant diode photodetector are used.

II. Micro-mirror array

For more than a decade the research laboratories of many semiconductor manufacturers and telecommunications equipment manufacturers have been working hard on the development of micro-mirror arrays (MMA). The first applications were in digital projection equipment, which has now expanded into digital cinema projectors, with sometimes more than two million micro-mirrors per chip switching at frequencies of up to 5 kHz [2,3]. Later these MMAs were used on telescopes to enhance fuzzy images and studies are underway to use them for the next generation space telescope and multi space object spectrometer [4]. Recently MMAs are finding applications in the large telecommunications market as optical multiplexers and cross-connect switches. State of the art devices have 512 switches, while it is expected that this number could rise to 10,000 in a few years [5]. Most of MMAs are fabricated from silicon and they fall into the general category of Micro-Electro-Mechanical-Systems (MEMS). The size of the MMA mirrors is usually smaller than a mm across, requires a very small amount of power to move and can move fast, typically in milliseconds.

The first generation of MMAs was binary, which means that the micro-mirrors could only assume two positions. In the last few years a new generation of MMAs is being introduced, which are equipped with servo control. These are sometimes referred to as Scanning MMAs (SMMA), because the micro-mirror tilt angle is a function of the input command signal.

We have started experimenting with a Scanning Two Axis Tilt Mirror MEMS Optical[1] SMMA [6]. The SMMAs are available in arrays of 4 by 1 and 8 by 1 micro-mirrors. We are currently using a 4 by 1 SMMA. The size of the micro-mirrors is 520 μm across and they have an octagonal shape. Fig. 1 shows a microscope view picture of two of those micro-mirrors.

The micro-mirrors are actuated by electrostatic actuators, which are located behind the reflecting front face of the mirrors. Fig. 2 shows a microscope picture of these actuators. They consist of four capacitor pads separated by two orthogonal channels parallel to the two axes of rotation of the corresponding micro-mirror. The mirror is grounded and the four pads are placed under a bias voltage to mechanically preload the mirror. By modulating the voltage of the four pads about the bias level it is possible to generate controlled rotations of the micro-mirrors. The range of rotation is +/- 3^o, which corresponds to a +/- 6^o of laser beam rotation. The manufacturer measured resonant frequencies are approximately 1,400 Hz for one axis and 1,000 Hz for the other.

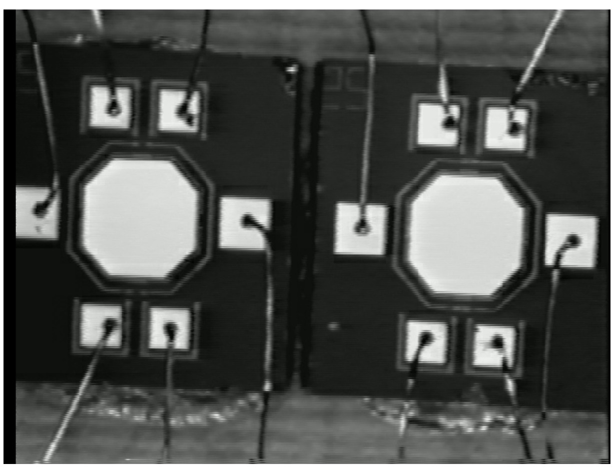

Figure 1. Two of the array micro-mirrors

[1] Certain commercial products are identified in this paper to specify experimental procedures adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the products identified are necessarily the best available for the purpose.

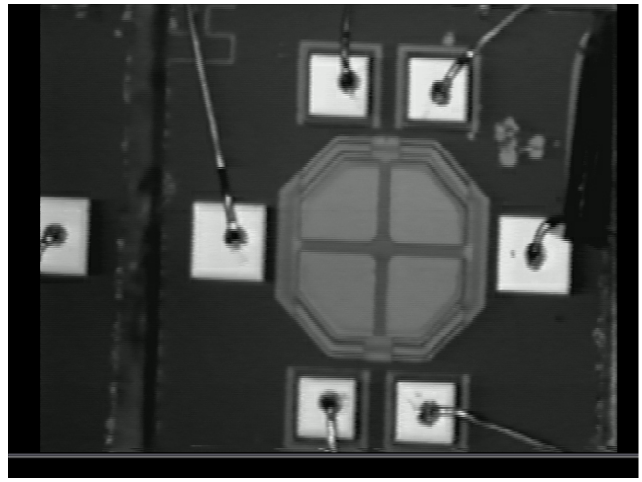

Figure 2. Micro-mirror electrostatic actuation pads

III. Optical nano-gripper

We are developing a technique for the use of micro-mirror arrays, for optical manipulation of nano-particles, which resembles the action of an optical nano-gripper. The laser beam that illuminates the array is split into a number of micro-beams, equal to the number of the micro-mirrors. These micro-beams are then aimed to the proper target and reflecting surfaces. By reflecting or refracting the micro-beams on the substrate and other select surfaces it is possible to bend the micro-beams in various controlled directions. The micro-beams impact the target nano-particle from various controlled directions generating a vector force and moment that result in a desired movement. While using multiple mirrors reduces the numerical aperture of each beam, thus limiting the gradient force [1] that can be used for optical trapping, it allows more flexibility in applying radiation pressure forces, and may allow the manipulation of a wider variety of particles.

Fig. 3 shows a schematic diagram of the paths of four micro-beams, from the mirror array that creates and controls them, as they pass through the microscope optics in order to be focused on a test slide by the microscope objective. In this particular example two of the micro-beams are aimed by the micro-mirror controller to the reflecting substrate at the proper angles in order, after they are reflected, to hit the lower surface of the targeted nano-particle, thus surrounding the target with gripping forces.

One of the objectives of our work is to study the design of standard opto-mechanical interfaces for the micro-mirror arrays. These interfaces will make possible a modular design with many micro-beams that can manipulate a large number of nano-particles at high speed. Such a system will require sophisticated control of the position and orientation of the target particles, all the micro-beams in the microscope workspace and the reflecting and refracting objects that can be used to redirect these beams. Another objective of our work is to experiment with various interfaces and control algorithms that will accomplish such a complex task. Performance measures and calibration techniques will have to be developed in order to identify the best possible choices of hardware and software.

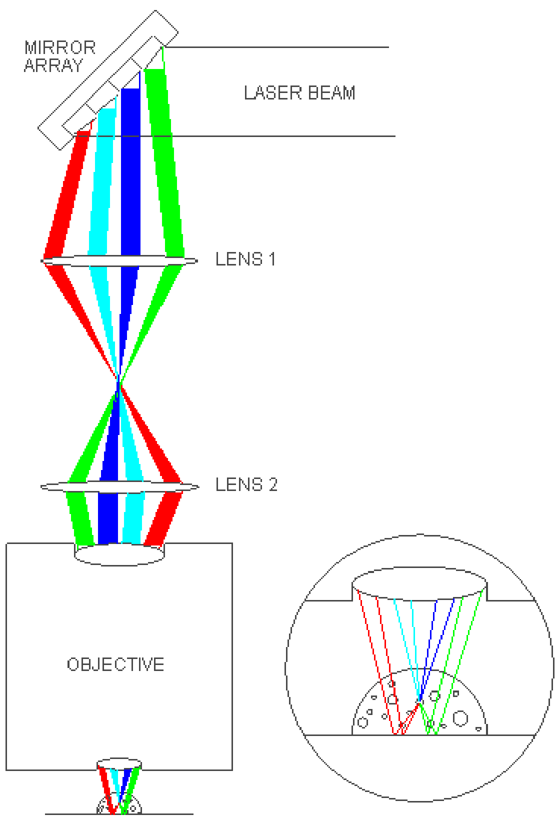

Figure 3. Paths of individual micro-beams to target nano-particle (not to scale)

Fig. 4 shows a schematic block diagram of our controller. The controller will includes a local and a remote control capability. Sophisticated mathematical models will be utilized in order to calibrate and model optical manipulation operations.

IV. Test and Calibration

A rectangular array CCD sensor camera is used for bench-top calibrations. To test the mirror array a telescope is used to expand and focus a diode laser beam so that it simultaneously illuminates all four micro mirrors before it converges to a point. As shown in Fig. 5, a CCD camera is placed either at the focal point, or directly after the mirror array to measure the beam deflection and characterize the beam quality. The image of the beam just after the mirror array is shown in Fig. 6. Scattering and diffraction from the four mirror actuators is visible, and two of the mirrors have been deflected to show the image of the scan beams. The linearity of the beam deflection is shown in Fig. 7 for scans in X and Y. Similar tests will be repeated while the micro-beams pass through the microscope objective. A dual-axis lateral effect photo-detector or a quadrant photo-detector will be used in order to monitor the position of the micro-beams.

To support the development of control algorithms we need mathematical models of the micro-mirror arrays. These models provide the direction of the micro-beams in the workspace of interest as a function of the corresponding input command signals. We are conducting static and dynamic calibration tests to determine these models.

V. Conclusions

Preliminary test results indicate that it is possible to use a single laser beam and micro-mirror arrays to create clusters of laser micro-beams with independent directional control. An optical design is described that allows the aiming of these micro-beams to target nano-particles from various controlled directions. This technique has the effect of creating optical grippers that have the potential to allow dexterous manipulation of nano-particles.

Acknowledgement

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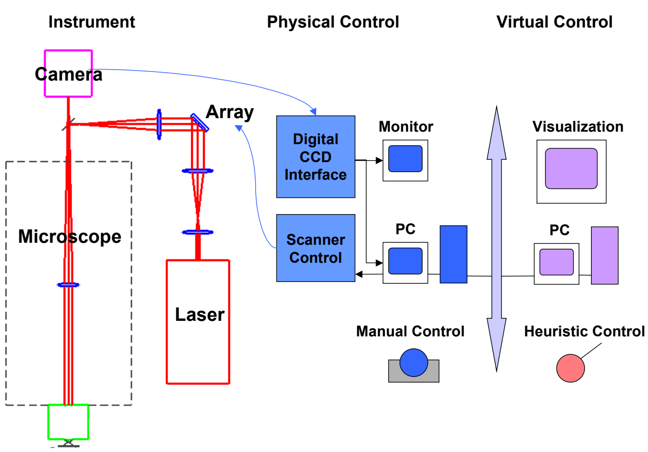

Figure 4. Optical manipulator and controller

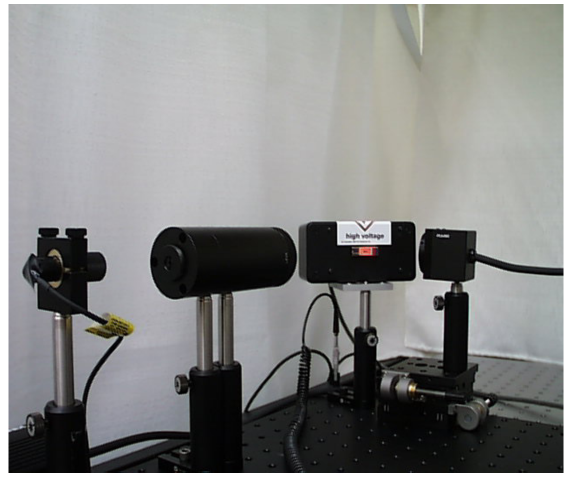

Fig. 5. Picture of experimental geometry

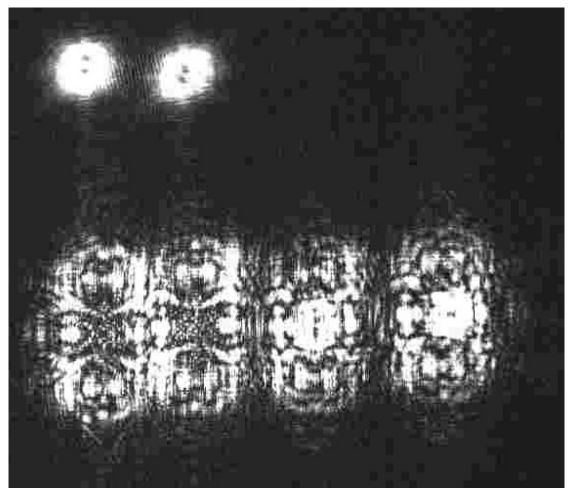

Fig. 6. Laser light scattered from array of four mirrors. Two of the beams have been deflected vertically.

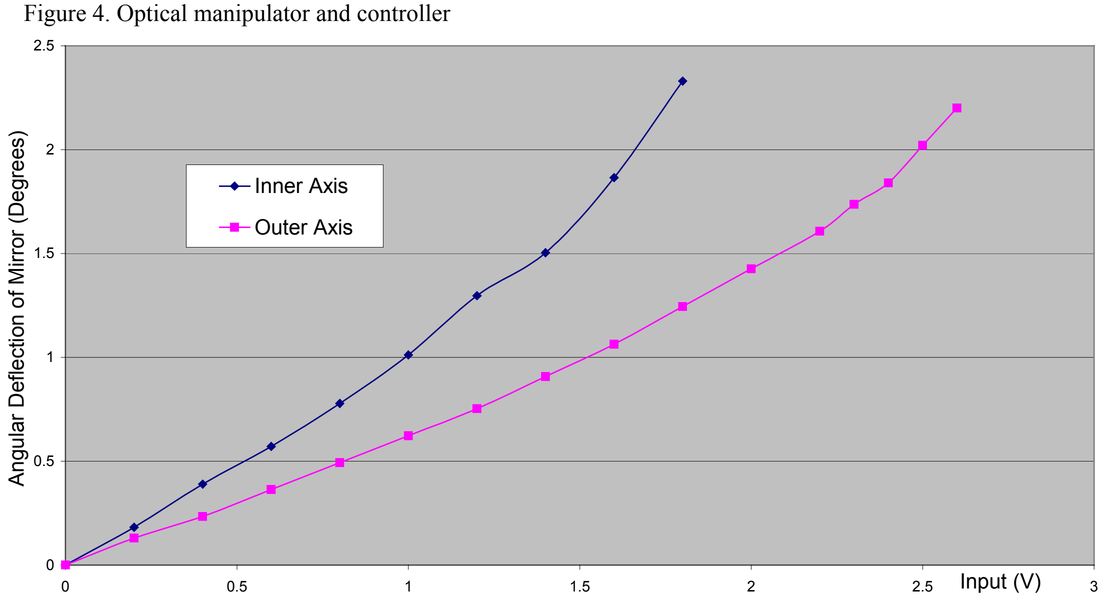

Fig. 7 Angular Deflection of Mirror vs. Input Voltage (Mirror BD05199)