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Interferometer Control of Optical Tweezers

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June 2002

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Interferometer Control of Optical Tweezers

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ABSTRACT

This paper discusses progress in using spatial light modulators and interferometry to control the beam profile of an optical tweezers. The approach being developed is to use a spatial light modulator (SLM) to control the phase profile of the tweezers beam and to use a combination of the SLM and interferometry to control the intensity profile. The objective is to perform fine and calculable control of the moments and forces on a tip or tool to be used to manipulate and interrogate nanostructures. The performance of the SLM in generating multiple and independently controllable tweezers beams is also reported. Concurrent supporting research projects are mentioned and include tweezers beam scattering and neural-net processing of the interference patterns for control of the tweezers beams.

1. INTRODUCTION

NASA has a Nanotechnology Project to support its Aerospace Propulsion and Power Base Research and Technology Program.[1] The objectives are to demonstrate novel multidisciplinary nanotechnologies to create new materials and devices on the atomic and sub-atomic level that revolutionize the operation and performance of propulsion and power systems for aerospace applications. To this end, there is emphasis on materials research such as the synthesis of SiC nanotubes, but there is also an opportunity to adapt optical technology for a supporting role. Perhaps photonic technology can assume a dominant role in the distant future for controlling the assembly, the measurement and the remote transmission of the assembly information of nanostructures.

The high-resolution direct interrogation of nanostructures with propagating light waves is untenable, but systems that combine material probes with optical measurements for direct interrogation are well known. Perhaps the atomic force microscope is the best- known example.[2] Here a tip is mounted to a cantilever and kept in contact with the material to be probed. The deflection of the cantilever is measured optically with a laser beam. Atomic-size deflections are detected in this manner. Another concept is to hold the tool or tip, together with the nanostructures, in one or more converging, diverging light beams called optical tweezers. In the simplest case, an optical tweezers consists of a laser beam focused by an oil-immersion microscope objective (Fig. 1). Small particles are pulled into the focus of the beam. There have been many calculations of the details of this phenomenon, but a very simple concept is to imagine a particle on the diverging side of the beam refracting light rays more parallel to the optical axis. The increase in axial momentum of the light is balanced by an equal change in momentum of the particle in the opposite direction toward the focus. The momentum given to the particle from the refraction of the beam holds the particle at the focus of the beam.

The concept being developed assumes one or more tweezers beams. A tweezers beam is imagined to hold a large particle called the tool or tip in analogy with the atomic force microscope and to hold the nanostructures. The tweezers beams are to be shaped in three ways: by manipulation of the phase distribution using a spatial light modulator (SLM), by manipulation of the intensity distribution using interferometry, and by scattering from the tool or tip. The tool can affect the nanostructure chemically, by contact, by evanescent-wave interaction, or by shaping the scattered tweezers beam.

The eventual success of this approach depends on several researchers and the effectiveness of a number of technologies to be developed for a number of years. The operation of the tweezers requires controlling the phase and intensity distributions of the beams. The potential of using interferometry to control the intensity distribution of a tweezers beam and to vary the forces on a particle trapped by the beam was demonstrated by adding an interferometer loop to the tweezers hardware shown in Fig. 1.[3] The fringe pattern could be moved, if one of the interferometer mirrors was piezoelectrically vibrated. A trapped particle was observed to move back and forth with the fringe motion. A more

sophisticated phase modulator is required for useful control of the forces and moments on the tool. There is also a need to calculate and predict the forces and moments on the tool as well as the fields felt by the nanostructures. Finally there is a need for efficient comparison of the input and output beam patterns so that the tweezers can be used for its intended application: a materials processor and process controller.

A SLM has been acquired that can be used to establish the phase independently at 480 by 480 pixels[4] for interferometric control of the optical tweezers. The performance of this modulator is encouragingly good and will be discussed in this paper for phase modulation and multiple beam generation. The scattering of tweezers beams has been evaluated for more than a decade,[5] and work on the calculation of near-field scattering from spherical and non-spherical tools is currently being supported for Gaussian beams as well as Gaussian beams modified by phase modulation and interferometric intensity modulation. This work is admittedly critical for selecting the correct beam conditioning, but is in progress by other researchers, and will not be discussed in any detail. Finally artificial neural networks have been used successfully for pattern-based process control[6,7] and fringe-pattern interpretation[8,9] for more than a decade. The possibility of using neural nets to interpret the post-scattering interference patterns and change the input interference patterns will be discussed briefly.

Fig. 1: Optical tweezers setup showing an interferometer loop, microscope and particles to be manipulated.

The setups for testing the SLM and the measured performance are discussed in the next three subsections.

2. SLM FOR OPTICAL TWEEZERS

2.1 Properties of SLM

The phase modulator is the critical component for performing interferometric control of optical tweezers. The SLM for phase modulation[4,10] is still being evaluated at the time of the writing of this paper. But the initial results are very encouraging and are discussed in some detail below.

The ideal phase modulator would be programmable independently over a large number of pixels; would be linear in the inputs; would have a phase-modulation range of at least 0 to 2π; would be free of artifacts and pixelation effects; would have no residual intensity modulation; and would have a fast response. The modulator acquired for interferometric control of the optical tweezers does not achieve these properties flawlessly, but approximates several of them well. The modulator acts like an adaptable mirror able to change the phase of a reflected beam independently at 480 by 480 pixels. The mirror has 90 percent reflectivity and a size of 20 by 20 mm. This mirror arrangement is easily inserted into the interferometers intended for the optical tweezers. The change in phase at each resolution element of the mirror is approximately proportional to the pixel intensity imaged from a Liquid Crystal Display (LCD) that is an integral part of an SLM, Lens, LCD combination. It is sufficient to note that the complete modulator produces a phase variation in the

reflected light approximately proportional to the graphics input intensity from the LCD that, in turn, ranges from 0 to 255. The LCD itself acquires the graphics pattern from the green connector of a VGA of a PC. The pattern previously has been displayed by graphics software. The pattern and graphics software are selected so that the pattern fills the entire display. The pattern is delivered to the actual SLM using F/40 optics to filter out the pixelation effect of the LCD. The details of construction of the SLM are reported in a reference.[10] The corresponding phase variation is slightly larger than 0 to 2π. The rise and fall times of the modulator add to about 190 milliseconds; hence no more than 5 pattern updates per second are feasible. Figure 2 shows the LCD, SLM combination.

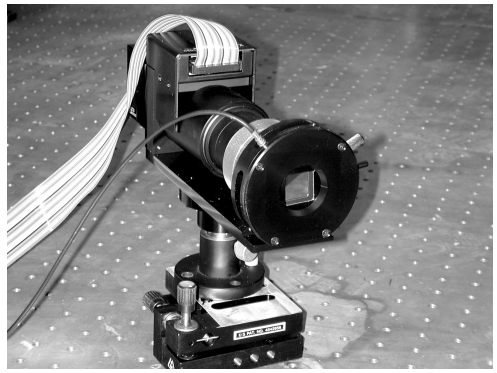

Fig. 2: LCD, SLM combination viewed toward the 20 by 20 mm adaptable mirror.

The process for using the LCD, SLM combination to control tweezers beams is easily stated. The first step is to compute the desired phase distribution $\Phi(x, y)$. This computation step in general depends on the particle scattering research mentioned in the **INTRODUCTION.** A simpler application to multi-tweezers-beam generation is discussed in the next section. The phase distribution can be calculated for control of the LCD, SLM at up to 480 by 480 points. The phase distribution is then converted to an intensity distribution using the calibration curve supplied with the LCD, SLM combination. The intensity-versus-phase calibration for the results to be reported is represented by the cubic

$$I = 4.10614 + 59.5342\,\Phi - 7.88323\,\Phi^2 + 0.675005\,\Phi^3. \tag{1}$$

A phase shift of 2π, for example, corresponds to a calculated intensity of 234 from eq. (1). The intensity distribution is then converted to an appropriate form, such as a TIFF file, for use with the graphics display software that communicates with the LCD, SLM via the VGA.

The performance of the phase modulator can be evaluated most easily by examining its use to generate multiple beams from a single input beam. Multiple and independently controllable reflected beams are potentially useful for many applications as well as tweezers.

2.2 Multiple Beam Generation

Figure 3 shows the simple setup used to test the multi-beam generation performance of the SLM. The beam from a $Nd{:}YVO_4$ laser is passed through a beam expanding telescope. The beam then traverses about 4 m before being reflected from the modulator. The reflected beams then pass back through the telescope and are observed, usually after reflecting them from a beam splitter onto a screen.

The simplest test of the quality of the SLM is to attempt to generate 3 beams, including a directly reflected beam and 2 beams from a $\cos(\Phi)$ pattern. The phase Φ cannot increase linearly with position, but must be restricted to the range 0 to 2π. A saw tooth phase pattern satisfying this requirement is generated from the expression

$$\Phi = 2\cos^{-1}\left[\cos\left(2\pi f x\right)\right]. \tag{2}$$

Here f is the spatial frequency of the saw tooth phase pattern (saw teeth per unit length).

This phase was calculated over a 400 by 400 array of points for 25 full cycles of the saw tooth and linearized using eq. (1). The pattern was converted to a TIFF image and supplied to the modulator through the VGA connector. TIFF images, unlike GIF images, occupy the full 0 to 255 range available to the SLM. In fact, there were 5 beams observed rather than 3 beams expected. Two end beams are fainter than those adjacent to the center beam and indicate some residual intensity modulation, a non-linearity in image creation, and/or the need for a positionally dependent calibration rather than the single expression in eq. (1). The performance of the SLM is degraded further to the extent of producing 7 beams rather than 3 beams, if eq. (2) is transformed linearly rather than through eq. (1). The performance of the SLM is quite sensitive to the details of the intensity-to-phase transfer function. If required by the tweezers setup, the calibration of the overall software and SLM system will be adjusted to reduce the intensities of the extraneous beams. In fact, simply reducing the contrast of the input pattern reduces the brightness of the extraneous beams.

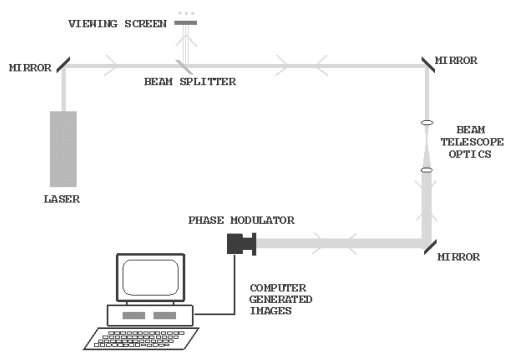

Fig. 3: Setup for generating and viewing multiple beams using the LCD, SLM combination.

A more interesting experiment is to test the ability of the modulator to generate multiple and independently controllable beams. Sending a rectangular grid pattern to the modulator easily generates large numbers of beams. A better test is to generate multiple cos(Φ) patterns summed to create the independently controllable beams. The phase modulation to accomplish this test is given by

$$\Phi = 2\cos^{-1}\left[\sum_{i=1}^{N}\frac{1}{N}\mathrm{Cos}\left(\Delta\Phi_i\right)\right], \tag{3}$$

where N is the number of patterns and

$$\Delta\Phi_i = \cos\left[2\pi\left(f_{xi}x + f_{yi}y\right)\right] \tag{4}$$

provides a directed cosine pattern in the xy plane. Varying (f_{xi}, f_{yi}) moves, and controls the magnitude and direction of motion, of the corresponding beam.

A test was conducted for 3 independently controllable beams. Actually 7 bright beams are generated by symmetry. The beams include the directly reflected beam and 3 pairs. The beams in a pair move together. Hence only three beams can be moved independently. The calculated phase assumed the form

$$\Phi(x,y) = 2\cos^{-1}\left[\frac{1}{3}\cos\left(2\pi f_1 x\right) + \frac{1}{3}\cos\left(\pi f_2\{x+y\}\right) + \frac{1}{3}\cos\left(2\pi f_3 y\right)\right]. \tag{5}$$

Patterns 1, 2 and 3 refer to the cosine functions with frequencies f_1, f_2, and f_3 in eq. (5). For the test to show the motion of 3 independently controllable beams, pattern #1 was stepped in units of 1 from 25 to 30 saw-tooth cycles; pattern #2 was stepped in units of 5 from 50 to 25 saw-tooth cycles; and pattern #3 was stepped in units of 1 from 30 to 25 saw-tooth cycles.

Figure 4 shows the first and last input patterns and the corresponding first and last beam arrangements recorded during this test. The conclusion is that independent motion of 3 or more beams is easily accomplished.

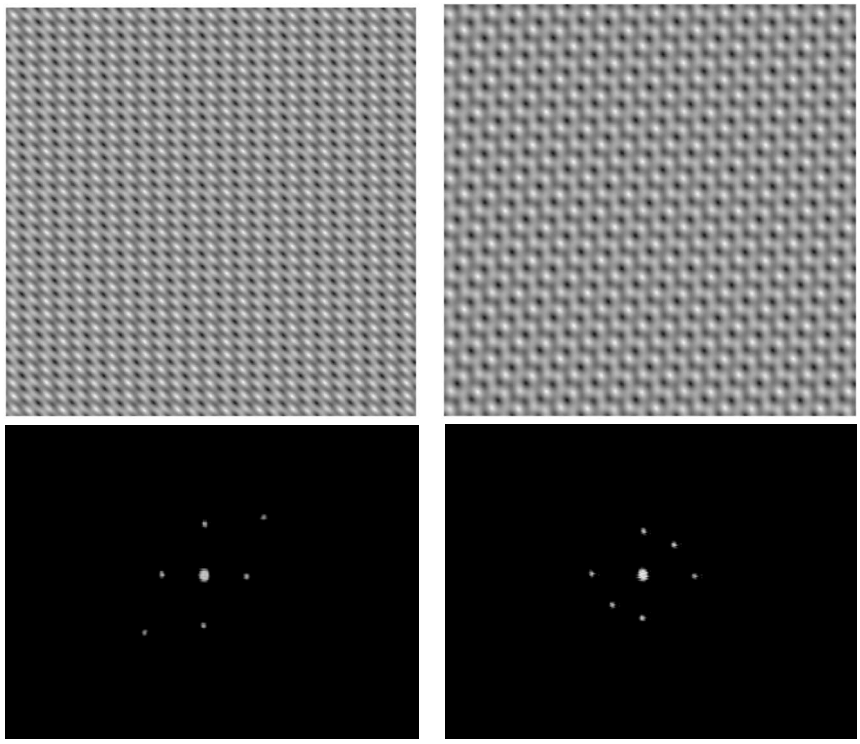

Fig. 4: First and last input patterns and corresponding beam patterns from setup in Fig. 3.

The uses of the SLM to generate phase modulated beams for interferometry and multiple interfering beams are discussed in the next subsection.

2.3 SLM as an interferometer component of an optical tweezers

The SLM acts as an adaptive mirror to generate multiple interfering beams by itself, but the intended application envisions that most of the tweezers power will remain in the original laser beam. That beam will be combined in an interferometer with a lower power beam reflected from the SLM. The arrangement shown in Fig. 1 tested a rudimentary form of this configuration. Figure 5 shows the results of combining the expanded laser beam with a beam reflected from the SLM. The SLM constituted one mirror of a Twyman-Green interferometer for that demonstration. The interferometer was set up in finite-fringe mode with the pattern shown in Fig. 5a. Five saw-tooth cycles (Fig. 5b and Fig. 5c) were delivered to the VGA of the PC connected to the SLM. The effect on the finite-fringe pattern shows clearly (Fig. 5d). Figure 5e shows the pattern reflected from the SLM alone with the reference beam blocked.

The SLM can function as a local-reference-beam interferometer by itself. The performance was tested by passing the SLM-transformed beam through a classical spatial filter in order to isolate a pair of reflected beams whose interference pattern was then recorded. The SLM was supplied with the phase (after transformation by eq. (1)) given by

$$\Phi = 2\cos^{-1}\left\{\frac{1}{2}\cos\left[2\pi f_{x1}x\ \mathrm{sign}\left(\cos\left[2\pi f_{x1}x\right]\right)+2\pi f_{y1}y\right]+\frac{1}{2}\cos\left[2\pi f_{y2}y\right]\right\}. \tag{6}$$

where sign(x) = 1 when x ≥0, and sign(x) = –1 when x<0. The f_x and f_y denote spatial frequencies in the x and y directions. Figure 6 shows an interference pattern from a pair of beams selected by spatial filtering.

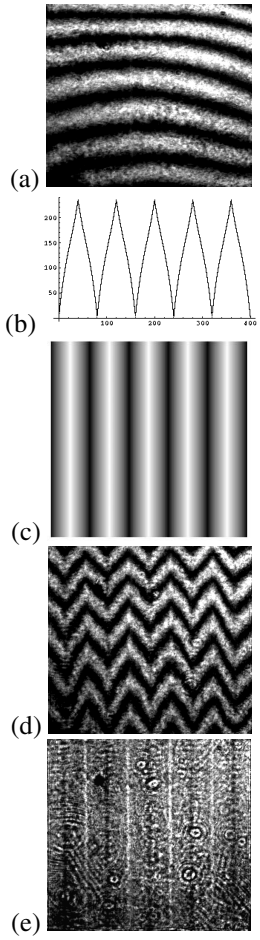

Fig. 5: (a) Carrier fringes; (b) saw-tooth phase; (c) input pattern; (d) finite-fringe pattern; (e) SLM-reflected beam.

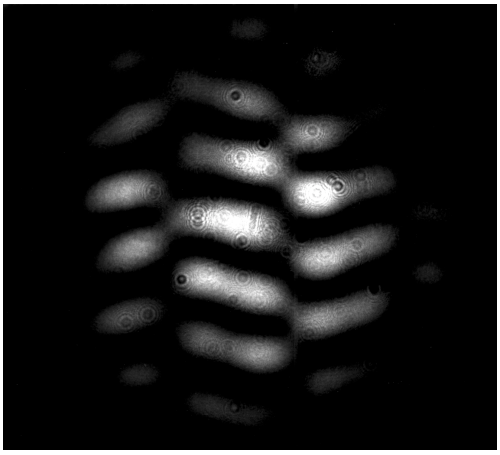

Fig. 6: Interference of pair of beams selected by spatial filtering.

The frequency f_{y1} was selected to correspond to about 18 saw-tooth cycles and f_{y2} was selected to correspond to 30 saw-tooth cycles. The frequency f_{x1} was selected to correspond to about 3.5 saw-tooth cycles.

The tweezers beam still requires a controller, assuming that the phase modulator is adequate and that the fringe patterns are correctly calculated. One intended application of the tweezers is automated assembly of nano-structures. Neural-net processors have proven to be effective for interpreting fringe patterns and generating process control decisions from fringe patterns. As outlined in the next section, we intend to investigate the use of neural nets to direct the interferometer controlled tweezers beams.

3. NEURAL-NET-DIRECTED CONTROL

Artificial neural networks have been used successfully to direct the alignment of a Gaussian-beam-smoothing spatial filter;[6] to perform flow-visualization-pattern to flow-visualization-pattern transformations and direct control actions in a wind tunnel;[7] and to perform sensitive detection of changes in electronic holography patterns[8,9] for non-destructive evaluation. The studies have shown that the sensitivity and training of feedforward nets to learn pattern data can be improved greatly by using the correct intensity dependent transformations of the input patterns.[9] The nets can be trained with both experimental and model-generated training records. It seems feasible to use model and experimental-pattern trained neural networks for tweezers-beam interference-pattern-to-interference-pattern transformations.

The neural nets can easily handle the 5-pattern-per-second processing rate imposed by the phase modulator. The major current restriction is that the interference patterns are limited to between 1,000 and 10,000 inputs or outputs of the feedforward nets. But the information needed to generate, for example, eq. (5) is considerably less at 3 spatial frequencies. The most difficult task is anticipated to be experimental: the detection of the scattering-modified interference patterns for neural-net interpretation. The scattered light is very hard to access.

4. CONCLUDING REMARKS

We noted that the feasibility of using a changing interference pattern to move a tweezers-held particle has been established experimentally. We hypothesized that the practical exploitation of this effect for nanotechnology requires an adequate programmable phase modulator, some new computations of the near field scattering from a tweezers-held tip or tool, and a neural-net process control system. The major conclusion reported herein is that the phase modulator selected for interferometer control appears to perform adequately. The modulator is easy to use to generate multiple and independently controllable beams. The modulator is easy to program and performs well as an adaptable mirror in an interferometer. The modulator in fact performs well enough that the scattering computations and the adaptation of the neural-net process-control methods appear to be justified.

5. REFERENCES

1. Jih-Fen Lei, *NASA/Project Plan, Nanotechnology Project, Aerospace Propulsion and Power Program (R&T Base),* Nov. 8, 2000.
2. M.V. Salapaka, D.J. Chen, and J.P. Cleveland, "Linearity of Amplitude and Phase in Tapping-Mode Atomic Force Microscopy," *Phys. Rev. B* **61**, pp. 1106–1115, 2000.
3. R. Seibel, "Manipulation of Micro Scale Particles in an Optical Trap Using Interferometry," *NASA/TM* in progress.
4. HAMAMATSU SLMM X7550 LCD Lens-Coupled PAL-SLM Module (Parallel Aligned Liquid Crystal Spatial Light Modulator).
5. F. Gittes and C.F. Schmidt, "Interference Model for Back-Focal-Plane Displacement Detection in Optical Tweezers," *Opt. Lett.* **23,** pp. 7–9, 1998.
6. A.J. Decker, "Self-Aligning Optical Measurement Systems," *Appl. Opt.* **31**, pp. 4339–4340, 1992.
7. A.J. Decker and A.E. Buggele, "Automation of Some Operations of a Wind Tunnel Using Artificial Neural Networks," *AIAA J.* **34**, pp. 421–423, 1996.

8. A.J. Decker, "Optimization of Training Sets for Neural-Net Processing of Characteristic Patterns From Vibrating Solids," *Optical Diagnostics for Fluids, Solids, and Combustion, Proc. SPIE*, C.R. Mercer, S.S. Cha, and G. Shen, eds., vol. 4448, pp. 209–217, 2001.
9. A.J. Decker, "Neural-Net Processing of Characteristic Patterns," *Topics on Nondestructive Evaluation Series, Automation, Miniature Robotics and Sensors for Nondestructive Evaluation and Testing,* Yoseph Bar-Cohen, Technical Editor, vol. 4**,** chapter 7.1, The American Society for Nondestructive Testing, Inc., 2000.
10. Y. Kobayashi, Y. Igasaki, N Yoshida, N. Fukuchi, H. Toyoda, T. Hara, and M.H. Wu, "Compact High-Efficiency Electrically-Addressable Phase-Only Spatial Light Modulator," *Diffractive/Holographic Technologies and Spatial Light Modulators VII, Proc. SPIE*, I. Cindrich, S.H. Lee, and R.L. Sutherland, eds., vol. 3951, pp. 158–165, 2000.

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13. ABSTRACT ***(Maximum 200 words)***
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