Micro-Optical Structures for Atom Lithography Studies

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ABSTRACT

Slow neutral beams of metal atoms can be manipulated using the intensity gradient of near-resonant light-fields enabling the deposition of atoms onto a substrate in a processes often referred to as atom lithography. A suitably shaped light-field gradient is used to control the path of metal atoms using the dipole force created by the interaction between atoms and the strong, near-resonant optical intensity gradient. Relatively simple patterns such as lines and dots have been created using optical standing waves while more complex light-fields might be created using computer generated optical elements (CGOE) to manipulate the laser beam.

In this paper we describe the microfabrication of spiral phase modulation structures used to create TEM^*_{01} fields, and diffractive optical structures used to create TEM_{01} fields. Static mask projection is used to machine the diffractive structure, and two different excimer laser ablation techniques are investigated to create the spiral structures. In the first a set of 15 separate patterns are prepared on a chrome-on-quartz mask, and the laser used to ablate each pattern to the required depth. This replicates photolithographic multi-step fabrication in that the final structure resembles a spiral staircase. In the second technique a more smoothly varying spiral ramp is ablated using a single mask that rotates about one of its vertices, a process called mask dragging.

Keywords: Excimer laser ablation, atom lithography, micro-optics

1. INTRODUCTION

Recent years have seen the field of atom optics expand and mature at a dramatic rate, with the demonstration of analogues to many conventional optical devices, from simple mirrors to the realization of coherent atom sources ("atom lasers")[1] One of the most useful devices in conventional optics is the lens and simple focussing of atoms has been demonstrated,[2] and there has been a continuing effort to extend on this in a project motivated by the potential advantages atom optics has over conventional optics[3]. Atoms are neutral, and can be cooled and trapped. They have large mass compared to photons, and are therefore sensitive to gravitational fields. Moreover, since thermal atoms have a short debroglie wavelength (typically angstroms or less), they can be focussed to the scale of tens of nanometers.

Although neutral atoms can be manipulated in a variety of ways, the interaction between atoms and lasers is particularly useful. Atoms in a near-resonant laser field experience two forces, the spontaneous and the dipole force, and it is the latter which is most useful for focussing atoms[4]. The dipole force acts along the direction of intensity gradients in the field, and in a direction dependent upon the detuning of the laser field from the atoms' resonant frequency. For light detuned above resonance, atoms will be pushed into dark regions of the field. Standing waves, which have a strong intensity gradient, have been used in just this way to deposit chromium onto a silicon substrate, and patterns of lines[5],dots[6] and hexagonal structures[7] have been created. The extension of this work to more general structures depends on the ability to shape and structure laser fields.

One way to create more complex light-fields is through the use of computer generated optical elements (CGOE)[8]. CGOEs can be used to modify either the phase or the amplitude of an incident light field (typically a gaussian field) in a controlled

way, and thus to produce a new, preferred light field. For the purposes of manipulating atoms, the creation of TEM_{01} and TEM_{01}^{*} fields, both of which have a dark central region into which slow atoms can be focussed, is of interest. The TEM_{01}^{*} field, commonly referred to as a "doughnut mode", consists of a bright region surrounding a dark central core. It has been used to focus atom beams[9], but the experimental arrangement for such work is awkward, requiring coaxial atom and laser beams as shown in figure 1.
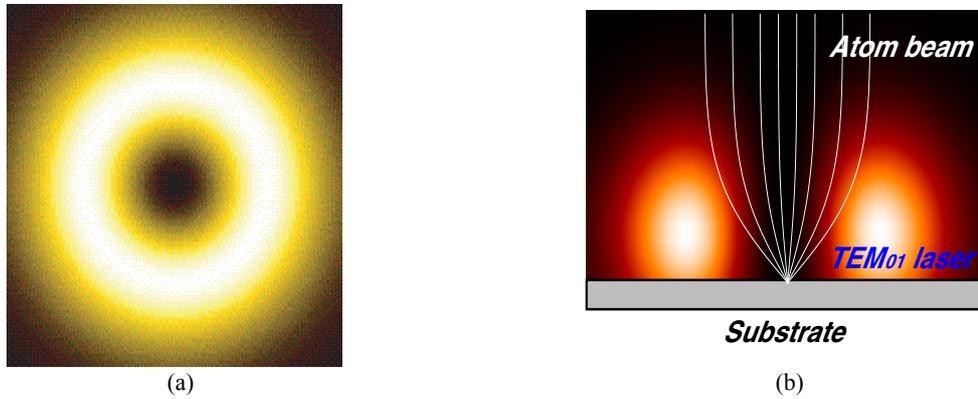

| (a) | (b) |

Figure 1. (a) Cross sectional view of the TEM_{01}^{*} field, and (b) schematic representation of atom lensing.

In contrast, the TEM_{01} field (back-to-back D-shaped spots separated by a central intensity minimum) permits the introduction of atoms transverse to the direction of beam propagation, which is much easier to realize experimentally. Two such beams can form a two-dimensional lens for atoms as shown in figure 2.

Atoms entering a TEM_{01} lens experience an intensity gradient which is relatively weak compared to the strong gradients in a standing wave. For this reason, in order to achieve reasonable focussing it is necessary to maintain high laser intensities and good optical quality in the beam. Given these considerations, transparent phase holograms are excellent candidates for creating the required laser fields.
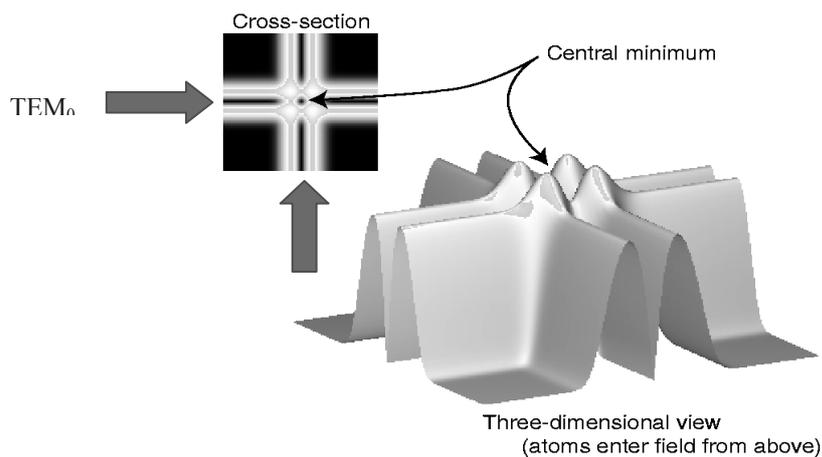

Figure 2 Dipole potential for lens formed from two TEM_{01} mode beams

2. THE MICRO-OPTICAL STRUCTURE

There are several approaches which may be taken to produce the required optical fields. The creation of a TEM_{01} field requires a very simple phase hologram such as that shown in figure 3. The hologram is made up of a series of ridges with a sinusoidal depth variation and a π-phase dislocation running through the pattern. This will produce a π-phase shift into one half of a gaussian input beam.
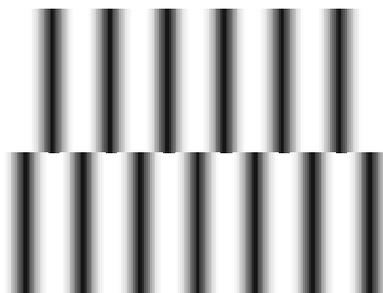

Figure 3. A diffractive phase pattern to produce a TEM_{01} field.

For a TEM_{01}^{*} field, the phase hologram will resemble a spiral. This will have the effect of radially shearing the phase of the gaussian input beam to produce a 2π-phase dislocation, and hence produce the TEM_{01}^{*} field shown in figure 4.
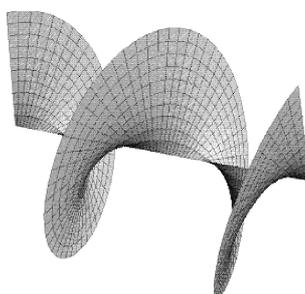

Figure 4. The ideal phase structure of a TEM_{01}^{*} beam (spiral)

The depth of the optical structure clearly depends upon the refractive index of the material and the wavelength of the light used. In this case our intention is to use 780nm laser radiation, hence for materials with a refractive index of 1.5, depths of 1.170μm would be required to produce a 2π-phase shift. Odd-Integer multiples of this depth are also acceptable provided the total depth does not exceed the coherence length of the incident light.

3. FABRICATION TECHNIQUE

The fabrication of the micro optical elements can be approached in any one of a number of ways. Early techniques involved the reduction of a computer-generated pattern into a photographic emulsion[10]. High resolution can be achieved using electron-beam lithography or laser-writing techniques, [11] which involve the exposure of a resist, followed by chemical etching. Methods designed to reduce or remove the necessity of etching have also been investigated[12]. There has also been considerable interest in the use of spatial light modulators for the rapid production and modification of kinoforms .[13]

In this study we are investigating the utility of excimer laser ablation to fabricate micro optical elements. Excimer laser ablation techniques have been widely applied in both industrial and research applications for the fabrication of 3D microstructures. [14,15] The short pulse (20ns), ultra-violet beam from an excimer laser makes it ideal for rapidly machining materials, particularly polymers, with excellent depth resolution. Since the beam from an excimer laser is large (about 20 x 10mm in cross section), multimodal and rather more divergent than most other industrial lasers, the beam from the laser is usually used as an illumination source for projection mode machining. The system used for this study is a Mask Projection Micromachining System (Exitech Series 8000) [16] using a Lambda Physik LPX210i Krypton Fluoride Excimer laser operating at 248nm. The beam delivery system incorporates a double fly's eye homogenizer that provides uniform illumination of the mask plane with an intensity variation of ±5% RMS. The projection lens has a demagnification factor if 10x, a numerical aperture of 0.3 and field of 1.2mm diameter. The beam delivery system incorporates a motor driven attenuator that can be controlled by the main Computer Numerical Controller (CNC) of the system to provide continuously variable transmission from 5% to 99%. The motion of the 4 axis (XYZ and rotation) workpiece holder, and the two axis open frame mask stages are all controlled by the same CNC system which also drives the beam attenuator and synchronizes the firing of the laser using Position Synchronised Output (Aerotech Inc). Both the workpiece and mask motion stages are fitted with servo controlled drives using a linear glass encoder providing 50nm resolution and ±1μm accuracy over the full stage travel.

The mask spatially defines the pattern cut into the workpiece, and the depth is determined by the number of laser pulses used and the fluence, in J/cm^2, of the laser pulses. Masks may be fabricated using conventional semiconductor lithography techniques in chrome-on-quartz, or for structures which do not require such high resolution, may be readily made using thin metal shims or photochemically etched shims. Metal shims may be used at almost all fluences without damage, however fluences on chrome-on-quartz masks must be kept below 150 mJ/cm². With a 10x projection lens this means that the maximum achievable workpiece fluence is around 15 J/cm^2 which greatly exceeds the fluences of 1 to 2 J/cm^2 typically used to machine polymers.

3.1 DIFFRACTIVE MICRO OPTICAL STRUCTURE

Laser ablation to produce the diffractive phase mask required to produce a TEM_{01} field may be performed using static mask projection. In this case the chrome-on-quartz pattern is a series of solid, or opaque, black bars arranged in the configuration shown in figure 3. If the ablation process is performed to produce structures which are close to the optical resolution limit of the ablation projection lens (around 0.8μm in our case), the resulting bar structures will have sloping walls which may approximate the sinusoidal depth variation required. In any case, excimer laser ablated features always display some degree of taper of the side walls, dependent upon the NA of the optical system and the ablation fluence[17,18], and this too may be used to control the slope of the structures.

3.2 SPIRAL PHASE STRUCTURES

Two alternative approaches have been used to fabricate the spiral structure required to produce the TEM_{01}^{*} beam. The first process simply uses a series of masks, some of which are shown in figure 5, which are individually indexed and overlaid by the Excimer Laser Micromachining System. The process is simple and rapid. The depth of each of the "steps" in the "spiral staircase" is easily varied simply by changing the number of laser pulses used per mask pattern by the CNC program.
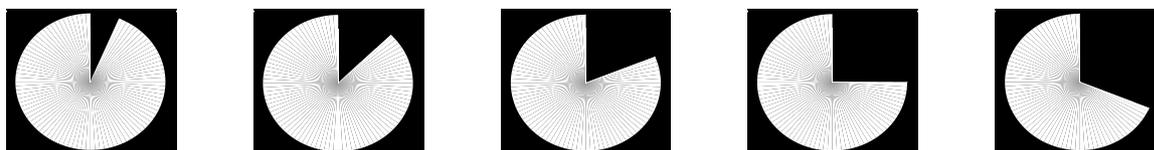

Figure 5. Five of the 15 indexed mask patterns used ablating a "spiral staircase"

In the second approach a single mask was prepared which was about a 20th segment of a circle. This was placed onto a holder which could rotate the mask under CNC control causing the segment to scribe a full circle. The rotation axis can be co-ordinated with the laser firing so that the number of laser pulses, and hence the depth of the cut, can be varied.

4. RESULTS AND DISCUSSION

Our first step was to calibrate the excimer laser etch rate for the candidate materials. We particularly concentrated on obtaining data for near-threshold ablation since these conditions give the lowest ablation rate and, at least in principle, the finest depth control.

4.1 MACHINING DEPTH

The measured ablation rate curves are shown in Figure 6. These are typical curves for excimer laser ablation showing a threshold fluence below which no ablation occurs, followed by an increasing etch rate with increasing fluence.
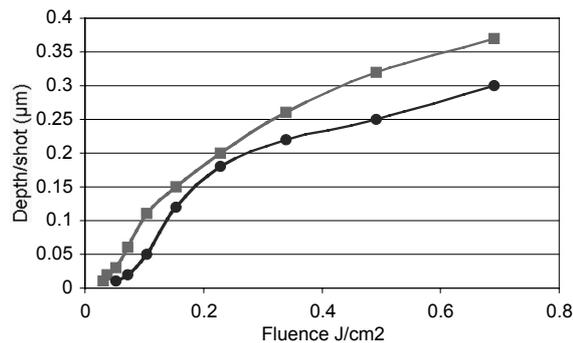
Figure 6. Single-shot etch rate measurements for Polycarbonate (upper line) and PET (lower line) for 248nm radiation.

The etch rate was measured by ablating a series of test structures using 100 laser pulses, measuring the depth of ablation, and dividing by 100 to determine the single shot ablation rate.

4.2 DIFFRACTIVE MICRO OPTICAL STRUCTURES

Fluences of less than 100 mJ/cm^2 produce average ablation rates of less than 50nm per shot, however such low fluences are not useful for machining since the ablation rate is not homogeneous. Higher fluences, nearer 1 J/cm^2, are required to produce smoother features. This can be seen in figure 7, which shows microstructures at the bottom of the ablation site typical of near-threshold machining. The microtexture is more pronounced at smaller ablation fluences.
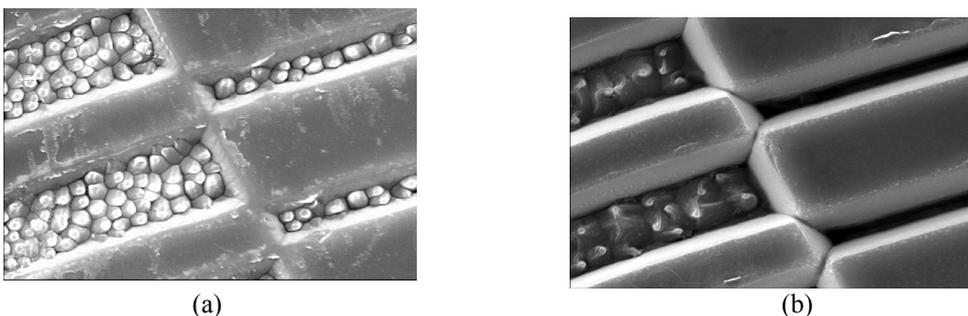
| (a) | (b) |

Figure 7. Diffractive structures machined into polycarbonate using 248nm at (a) 340 mJ/cm^2 and (b) 690 mJ/cm^2.

This observation means that it is necessary to machine using a single laser pulse the sub-micrometer depth structures required for the diffractive element. Multiple pulses at lower fluences do not produce an acceptable surface finish. The fluence used for single-pulse patterning can be adjusted to provide an ablation depth in polymers which is approximately

that required for the structure. The Scanning Probe Microscope cross sectional plot shown in Figure 8 is that of a sample which received a single laser pulse producing a smoothly varying groove 0.614µm deep and about 8µm wide.
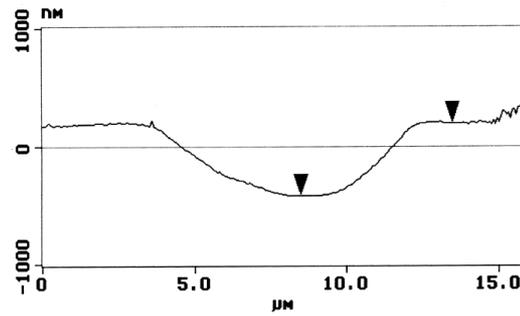

Figure 8. Cross-Section of single shot ablation in Polycarbonate

An alternative to single-shot machining of polymers is to fabricate the structure into a material whose etch rate is significantly lower. Ablation rates for glass are generally an order of magnitude smaller than for polymers and require fluences an order of magnitude greater. We have repeated these trials on glass and found that for fluences of 3.6 J/cm^2 we were able to machine more than 2µm deep using 500 laser pulses. The surfaces of these preliminary structures were unacceptably rough and, although this method has potential for shallow machining, it clearly requires further development.

4.3 SPIRAL PHASE STRUCTURES

Both of the methods used to fabricate spiral staircases in polymers produced encouraging results. Structures made using the indexed masks and the rotating mask are shown in figures 9 and 10 resp.
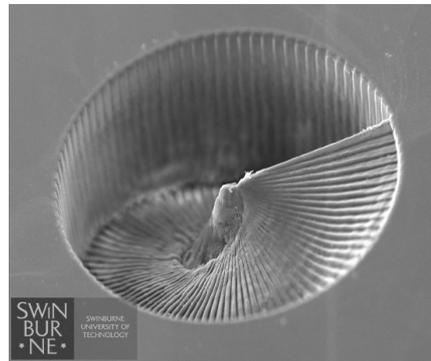

Figure 9. Spiral fabricated using indexed mask   Figure 10. Spiral fabricated using rotating mask

In each case the diameter of the structure is 1mm. In figure 9 the staircase clearly shows the 15 discrete levels produced by the mask set. Structures with a total depth of about 5µm have been fabricated. The structure shown in this figure has been ablated using 10 laser pulses per mask producing a total depth of about 45µm enabling the profile to be more easily imaged by the Scanning Electron Microscope.

The structure in figure 10, ablated through the rotating mask, produced a more gradual variation in depth. The total machining process requires more than 100 pulses to form the full profile, so that the minimum depth for the completed structure is of the order of 10µm.

In both cases the minimum structure depth is significantly greater than that required to produce a 2π-phase change in the incident light field assuming the wavefront propagates directly into air. One way to overcome this limitation is to tailor the difference in refractive index by the use of index matching fluids such as microscope objective immersion oil. For example, for a polymer with a refractive index of 1.59 and an immersion oil with a refractive index of 1.54, the structure depth required to produce a 2π-phase change for 730nm is 23µm. Not only does this mean that the total structure depth is easily achievable, but the effect of surface roughness is ameliorated.

5. CONCLUSION

Excimer laser mask projection produces microstructures directly without the need for wet processing, resist patterning or plasma etching. With only simple changes to the CNC program controlling the machine we have been able to rapidly investigate many different processing protocols.

In this investigation of the fabrication of micro optical elements we have demonstrated the potential for three different machining methods. Fabrication of both diffractive and phase micro optical structures is achievable using direct ablation of polymer materials. The challenges in this process stem from the minimum ablation depth achievable by laser ablation while maintaining an acceptable level of surface roughness. The use of a refractive index matching oils offers a simple solution since it increases the depth of the structure required. Other alternatives include ablation of the structure into glass, making use of its lower etch rate, or the use of single shot ablation into polymers.

6. REFERENCES

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