F₂-laser microfabrication of multilevel diffractive optical elements

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Abstract. The 157nm F₂-laser drives strong and precisely controllable interactions with fused silica, the most widely used material for bulk optics, optical fibers, and planar optical circuits. A diffractive optical element (DOE) breaks apart wavefronts and redirects segmented beamlets through phase control for novel beam steering and shaping applications. This paper shows that precise excisions of 10-30 nm depth are available from the F₂ laser for the generation of efficient DOEs for the visible and ultraviolet spectrum. F₂-laser radiation was applied with beam homogenization optics and high-precision computer-controlled motion stages to shape up to 16-level, 256 × 256 pixel DOE devices on bulk glasses, with distinguishable level-to-level spacing of ~100 nm and surface roughness of ~13 nm. The 1st order diffraction efficiency was ~35%. The farfield pattern when illuminated with a HeNe laser was found to agree with simulations based on an iterative Fourier transform algorithm. Future improvements in the laser micromachining process and possible directions are also offered.

1. Introduction

Diffractive optical elements (DOE) are used to shape wavefronts by changing the phase of segmented beamlets and thereby provide a compact means for beam shaping [1]. DOE applications include optical computing, laser machining, optical communications, and biological sensors [2-5]. DOEs are especially attractive in complex optical systems because they can perform the same functions as multilenses with less space and equal efficiency, or can improve the optical resolution such as the phase-shift masks used in today’s lithography exposure tools for defining the critical gate dimensions of a transistor. Compared with traditional binary masks, DOEs have the further advantage of fully using all the incident light power and can modulate the light patterns in the third dimension (beam propagation direction). DOEs are usually fabricated through multi-step lithographic patterning and etching processes, molding techniques, or gray lithography [6-8]. While these processes serve well the high-volume batch fabrication of polymer elements and, in some limited cases, of glass materials, they lack the flexibility for rapid prototyping and other custom fabrication applications that are possible in laser nanofabrication systems.

One approach to custom writing of DOEs is a laser-induced backside wet etching method [9]. In this paper, the F₂ laser provides a direct ablation approach to writing DOEs with precise excisions of 10-30 nm depth for the visible and ultraviolet spectrum. F₂-laser radiation was applied with beam homogenization optics and high-precision computer-controlled motion stages to shape up to 16-level, 256 × 256 pixel DOE devices on bulk glasses, with distinguishable level-to-level spacing. The DOE devices were designed for HeNe laser wavelength by using an iterative Fourier transform algorithm (IFTA) [10].
2. F2-laser system
The optical processing system consisted of a commercial F2-excimer laser (Lambda Physik, LPF220i), a 157-nm beam delivery system by MicroLas Lasersystems, and a high-resolution micromachining station [11]. The F2-laser system provided uniform fluence of up to 7 J/cm² across a 250 μm × 250 μm target field. A 100-nm precision three-axis motion system (Newport TSP1100 with MM4006 controller) permitted accurate sample positioning. The fluence delivered to the precision motion stages were adjusted using two rotatable dielectric reflecting mirrors for tunable attenuation of the laser energy by 15 to 75%. The DOEs were fabricated pixel-by-pixel on fused silica substrates. A simple square aperture in an aluminium mask was used at the mask plane to provide a ~8 μm × 8 μm uniform exposure on the target plane. The pixels were overlapped approximately 0.5 μm on each edge to steepen the side walls of the pixels, yielding a final pixel size of ~7 μm × 7 μm. The fluence was selected for single pulse etching of the full depth of one phase level of the DOE. Although several pulses at lower fluence could be used to define each phase level, the single pulse approach reduced the processing time and improved the etch depth precision.

3. Results and Discussion
3.1 Surface Roughness
The smoothness of the laser formed DOE surface greatly affects the optical beam quality projected by the DOE. By improving the surface smoothness, the farfield pattern yielded by the DOE will be brighter and better defined. Figure 1(a) shows the DOE sample as formed after laser fabrication and a quick blowing with compressed air. The surface is covered with particulate of ~5µm size and the terraced structures of this 16-level DOE can barely be resolved. By immersing the DOE sample in acetone and applying indirect ultrasonic cleaning for ~1 hour, the pixel structure is clearly revealed and surfaces are much cleaner, as seen in figure 1(b). However, there remains a significant amount of finer soot (submicron) that is moderately adhered to the surface. As well, melt lips of ~200-300 nm are seen on the pixel edges. This sample was then placed in an EtOH bath with indirect ultrasonic cleaning for ~15 minutes. As seen in figure 1c, this second cleaning step removed the majority of the remaining soot and melt debris, leaving a relatively smooth and flat surface on each pixel. The edges are more clearly defined with the melt lip significantly reduced to ~10-20 nm size. The AFM profiles in figure 1 show the dramatic improvement in surface roughness made possible by post-laser cleaning.

![Figure 1](image_url)

**Figure 1.** AFM images of DOE fabricated with F2 laser (a) before cleaning, (b) after acetone bath, and (c) after EtOH bath. Probe area is 60 μm x 60 μm. Top shows 3-D profile of the 7 μm × 7 μm pixels.

The graph in figure 2 shows the root mean square (RMS) surface roughness, measured over ~60% of the central pixel area, plotted as a function of the etched depth for a 16-level DOE. The sample was cleaned by both acetone and EtOH baths. When the sample was cleaned only with acetone (figure 1(b)), the average RMS roughness was approximately 42 nm, whereas the subsequent EtOH cleaning step (figure 1(c)), yielded an average RMS roughness of 13 nm. This 3-fold improvement significantly
reduces the amount of scattered light from the DOE pixels. Figure 2 further shows no apparent dependence of surface roughness on the pixel etch depth.

3.2 Accuracy and Reproducibility
The ~3-5% (RMS) pulse-to-pulse energy fluctuation of the F2-laser (measured over 10,000 pulses) contributes an expected 2-3 nm variation in the targeted etch depth for the observed logarithmic etch depth dependence on fluence. This small factor enabled highly reproducible etch depth over a large number of pixels and phase levels as conveyed by the narrow range of etch depth data within each phase level as shown in figure 3. The graph clearly distinguishes 16 different phase levels with a maximum scatter within one phase level of only 55 nm (maximum to minimum). Although an 87-nm phase step was required for 633 nm probe light, the observed 104 nm etch depth difference (slope in figure 3) arose from slightly higher on-target fluence than desired and possible overetching during the post-laser cleaning step. A random sampling of pixel etch depth revealed a highly linear dependence with the desired design phase level, \(N\), without evidence of ablation-rate incubation effects. The pixel depth was accurately controlled by the single-pulse etch depth (104 nm) multiplied by the number of laser pulses (\(N = 0\) to 15). These attributes of high linearity and small variance amongst thousands of pixels clearly demonstrate controlled fabrication of 16 distinguishable and evenly spaced phase levels in fused silica glass. This control is essential for generating the desired farfield DOE patterns with minimum scattering loss.

3.3 Farfield DOE-Generated Patterns
By illuminating the laser-patterned DOE area of the substrate with a collimated and spatially filtered HeNe laser beam, one obtained a farfield pattern such as shown in figure 4(b). This pattern compares favourably with the theoretically expected farfield pattern shown in figure 4(a). The larger features of the crest were accurately defined in figure 4(b) and only the finely detailed Latin phrase (bottom of crest) was unresolved. The diffraction-limited angular resolution of the DOE is given by

\[
\frac{\lambda}{2^N \times b} = 0.0004 \ \text{radians},
\]

where \(\lambda = 633\ \text{nm}\) is the wavelength of probe light, \(2^N \times 2^N\) is the total number of pixels \((N = 256)\), and \(b = 7\ \mu\text{m}\) is the pixel size. The observed angular resolution in figure 4(b) is within a factor of two of this calculated diffraction value. The observed pattern also reproduces the grainy noise expected outside the crest window (angles > \(2^N\) in figure 4(a)) but shows higher speckle noise in the detailed crest features than predicted in the ideal DOE design. Further reduction of surface roughness and increase of the number of pixels would improve the angular resolution of both the design and experimental far-field pattern. Larger number of pixels could not be tested due to mechanical instability of the optical system beyond the present 3 hour fabrication time.
The light defining the University of Toronto crest in figure 4(b) only represented ~34.3% of the total incident laser power. A large part of the light was lost to 1st order grating spots (not shown in figure 4(b)) of less than 13.3% efficiency in each order. Such grating spots should not be present in a perfectly fabricated DOE and is attributed to over-etched pixel depth (104 nm versus 87 nm) for the present 633 nm probe light. Additional losses arise from scattering in both the forward and backward directions that originates with the 13-nm surface roughness and non-vertical pixel walls (figure 1(c)).

Figure 4. Theoretical (a) and experimentally observed (b) farfield patterns generated by a 256×256-pixel 16-level DOE. The University of Toronto crest is centred at 0th order. The axes are labelled with the angle of diffraction.

4. Conclusion

F₂-laser micromachining was successfully demonstrated to fabricate DOEs in fused silica substrates that yield farfield diffraction patterns in good agreement with simulated design results. Sixteen distinguishable phase levels with precise and reproducible etch depth were generated, yielding an overall diffraction efficiency of 34%. Post-fabrication solvent cleaning improved the pixel surface roughness to 13 nm (RMS). The results show F₂-laser ablation is a promising approach for the rapid fabrication of custom designed multilevel DOEs. Further improvements in the DOE efficiency is centred on improving the wall steepness between pixels and reducing the surface roughness with alternate laser processing and chemical cleaning recipes.

Acknowledgements

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