Direct Laser Writing of 3D Gratings and Diffraction Optics

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Abstract: We fabricate 3D gratings and diffraction optics using direct laser writing. Diffraction patterns of gratings agree with Laue theory. We demonstrate zone plates for visible wavelengths. Direct laser writing is promising for integrated diffraction optics.
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1. Introduction

Integrated diffractive optics has applications including beam shaping and control on the micro-scale[1] and is becoming prevalent in cutting-edge macro scale optical elements. Multi-layer devices are desireable; however fabrication is a challenge because 3D lithography is limited to layer-by-layer fabrication. Developments in direct laser writing enable fabrication of disconnected metal structures in a dielectric matrix with feature sizes below 100 nm across samples spanning millimeters[2,3]. This improves on two-photon polymerization used to fabricate 3D grating structures consisting of connected, free-standing structures with large filling fractions[4]. Laser-written disconnected metal structures are ideal for integrated micro-scale 3D diffraction optics due to the ease of fabrication and control of structure size, shape, and alignment. We demonstrate 3D gratings and diffractive lenses (zone plates).

2. Experimental methods

We fabricate samples by focusing 70-fs laser pulses with 11-MHz repetition rate centered at 795 nm into a thick (100-250 µm) polymer film doped with silver nitrate. Multi-photon absorption leads to reduction of metal ions and formation of silver structures at the focal point. By using a long-travel, high precision 3D translation stage, acousto-optic modulator, and adjusting exposure time and average laser power, shape and size of fabricated features can be controlled. Using a 0.8 NA objective, we have achieved <100 nm features and 0.5 µm resolution. The polymer is left in place after fabrication, providing a dielectric matrix to support disconnected structures.

Analogs of crystallographic structures are fabricated (simple and body-centered cubic and structures with a two-atom basis with different scattering strengths) using an exposure of 5-50 mW for 0.1-1 ms. Different scattering strengths are achieved by fabricating different size scatterers by varying the laser exposure parameters. Scatterers are spaced by 5-40 µm in order to observe multiple diffraction orders using visible wavelength illumination. Samples span several mm in plane and consisted of 2-12 layers in the *z*-direction. Diffraction patterns are measured in transmission using a 633-nm HeNe laser. Laue diffraction patterns are calculated for comparison with theory.

Zone plates with focal lengths ranging from 4 to 50 micrometers at 633 nm are fabricated using an exposure of 3-15 mW and stage translation speed of 5-200 µm/s. For comparison, zone plates of identical design are fabricated using standard 2D micro-fabrication techniques. These devices are tested in a transmission microscope using a white LED light source. The zone plate focal spots at different wavelengths are imaged by adjusting the microscope focal plane. Long-pass and short-pass filters are used to isolate specific wavelength ranges during imaging.

3. Results

Experimental results from 3D diffraction gratings are in good agreement with Laue theory. Locations of diffraction maxima and intensity variations follow calculations (Figure 1). Analogs of crystals with a two-atom basis with a strong and weak scatterer exhibit the expected intensity variations. However, bands from each diffraction order are wider than calculations predict for a given number of layers in the beam direction and weak signals are visible in some forbidden reciprocal lattice points.

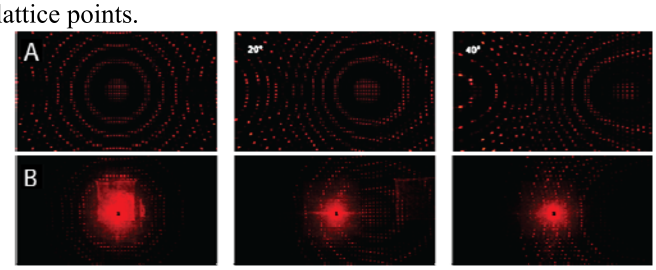

Figure 1 – A) Calculated diffraction pattern of a 4-layer cubic lattice and B) measured diffraction pattern of a 10-layer cubic grating at 633 nm. 0^{th} order transmission reduces signal to noise. Left to right, diffraction patterns with an incident beam angle of 0, 20, and 40-degrees from normal.

Zone plates fabricated by laser writing and electron beam lithography exhibit the expected focusing behavior (Figure 2A and B). Laser fabricated zone plates have lower signal-to-noise; however, optimization of the laser writing parameters can greatly increase their efficiency. Slow write speeds (10-15 µm/s) at moderate to low laser power (6 mW) provide the cleanest features and best zone plate efficiency. The focal point of zone plates is strongly wavelength dependent with the opposite dispersion of lenses made from common optical materials. Longer wavelengths are focused closer to the zone plate. Wavelength selectivity has been achieved using laser-written zone plates with pinholes placed above at the focal point of specific wavelengths (Figure 2C and D). Different wavelengths can be selected by changing the separation between the zone plate and pinhole.

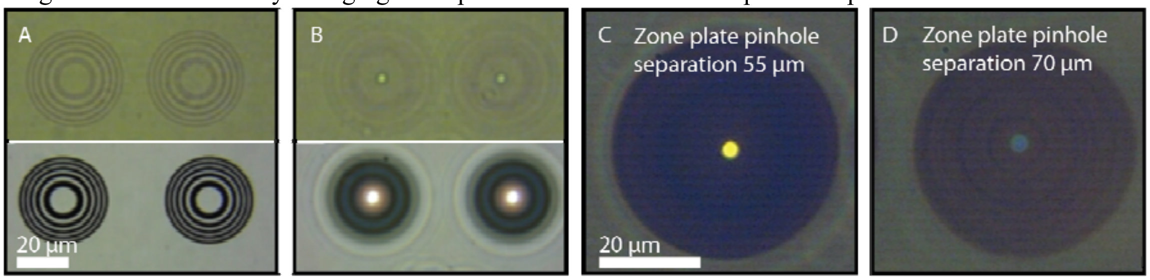

Figure 2 – A) Top, laser written zone plates and bottom, lithographically defined zone plates. B) The focal plane is shifted 50 µm above the zone plates to image the designed focal point for 633-nm light. C) Transmission of yellow (550-600 nm) light transmitted through a pinhole positioned 55 µm above a zone plate and D) transmission of blue (425-475 nm) light through a pinhole 70 µm above a zone plate. Both the zone plates and pinholes in C and D are laser-written.

4. Discussion and conclusion

Some discrepancies between experimental and calculated diffraction patterns were expected. We expect irregularities and multiple scattering events because the scattering cross sections are large and silver structures are elongated, rather than point scatterers. Additionally, structures with a large number of layers ($n \geq 4$) in the illumination direction appear to suffer from shadowing effects. The observed diffraction patterns are more-consistent with a structure consisting of fewer layers than are present in the fabricated structure. Wider bands are present in each diffraction order. In some cases, signal is visible at forbidden reciprocal lattice points, likely because of non-ideal scatterers. 3D gratings demonstrate that direct laser writing of disconnected metal structures can be used to produce 3D diffractive elements that can be described using diffraction theory.

Some reduction in quality was expected for laser-written zone plates compared to zone plates defined by electron beam lithography. Silver formed by laser writing consists of an agglomeration of silver nano-particles, reducing the opacity of the structure relative to pure silver. This structure also leads to roughness at the edges of features.

Fabrication and testing of diffractive elements provides an avenue to investigate the quality of laser-written silver structures and could provide rapid feedback for optimization of the laser writing process. Discrepancies from calculated responses of structures could be used to estimate roughness along the edges of features and the filling fraction of silver within structures. Further improvements to the laser writing process, such as use of higher NA objectives and aberration correction when fabricating deep (>50 µm) within the polymer layer, could further enhance the feature size, resolution, and quality of structures for applications.

Fabrication of relatively simple diffraction optics components, such as zone plates, demonstrates the utility of direct laser writing for diffractive optics. We have also shown that this technique can be used to fabricate integrated, bulk diffractive components with arbitrary spacing in the *z*-direction by demonstrating stacked layers of zone plates and pinholes. Adding additional layers in *z* and fabricating components at different *z*-positions is trivially easy. These structures would be difficult and costly to fabricate using lithography techniques because a full series of fabrication steps is required for each layer and dielectric spacer material must be deposited for each layer.

5. References

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