Femtosecond laser fabrication of optimized multilayered volume diffractive optical elements

by

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A thesis submitted in conformity with the requirements for the degree of Doctor of Philosophy
Graduate Department of Electrical Engineering
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Abstract

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Diffractive optical elements (DOEs) serve an important function in many dynamic and static optical systems. The theory and design of surface diffractive structures are well understood and practically applied at high spatial and phase resolution for a wide range of optical applications in science and industry. However, these structures normally only harness phase modulation of uniform fields for the beam diffraction and therefore limit their range of application, as well as being susceptible to surface damage. Multilayered volume diffractive elements offer a powerful opportunity to harness both phase and amplitude modulation for benefits in diffraction efficiency and beam shaping. However, multilayered combinations have been difficult to fabricate and provide only weak diffraction for phase gratings with low refractive index contrast. The advent of femtosecond laser writing inside transparent media has enabled the facile embedding of optical devices such as waveguides and diffractive optics into novel three-dimensional geometries that offer advanced functionality with compact design. In this work, femtosecond laser writing is pushed to the limits of forming high resolution phase elements with sufficiently strong refractive index contrast on which to develop volume phase gratings with the highest diffractive efficiency. The formation of both positive and negative zones of refractive index contrast together with rapid Talbot self imaging inside weakly contrasting phase gratings are major challenges here diminish the efficiency of assembled gratings. A
method of strategic layering of otherwise weakly diffracting gratings onto Talbot planes is introduced to demonstrate, in FDTD models, the definitive enhancement of overall diffraction efficiency. A systematic optimization of laser writing in fused silica verify this enhancement or diminishment with weak volume gratings assembled on aligned or misaligned on Talbot planes. Advanced laser beam control methods were further demonstrated that underpin new direction for the facile assembly of highly functional DOEs that can exploit coherent light diffraction for opportunities in improving the performance of holographic devices and extend further to the powerful combination of phase and amplitude modulation control that is potentially available in a single optical device, thereby opening new directions for the design and fabrication of robust and strongly diffracting volume optical devices.
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Chapter 1

Introduction

The manipulation of light has been of interest as far back as three thousand years, which is evidenced by the Nimrud lens from ancient Assyria [12]. The first observation of diffraction by Francesco Maria Grimaldi (1618-1663) manifested as the fringes within the shadow of a rod illuminated by a point source. The understanding of diffraction through the application of wave theory to various obstacles and apertures have been further advanced by many distinguished scientists such as Huygens, Fresnel, Kirchhoff, Sommerfeld, Talbot, and Rayleigh [13].

An optical component that modifies wavefronts through segmentation and redirection of these segments by means of interference and phase control is commonly categorized as a Diffractive Optical Element (DOE). These DOEs can take many forms including kinoforms, which are smoothly varying surfaces that control phase, binary optics, which have discrete number of phase-controlling surfaces, and computer-generated holograms (CGH) or holographic optical elements, which depend on the interference generated by phase and amplitude manipulation [1]. While early optical design regarded diffraction as an undesirable phenomena that limited the resolution of an optical system, the advent of DOEs revealed the benefit of a single optical element that could provide the function of an array of lenses with equal efficiency and significant space savings. Further, phase
masking DOEs had the added advantage of using all the incident light and could modulate intensity patterns in the beam propagation direction.

The first man-made diffraction grating is commonly attributed to David Rittenhouse, who wound fine wires between a pair of pitch screws around 1785 [14]. Since then, the fabrication has advanced from physical processes, such as ruling and diamond turning, to modern techniques, such as optical or electron-beam lithography. These new approaches sought to overcome the limitations of feature size resolution, flexibility in choice of material, as well as time economy and cost reduction in fabrication.

The invention of the laser in 1960 [15] provided unprecedented high light intensities that have seen to induce non-linearity in optical materials. In 1996, Hirao et al. [16] demonstrated that the focusing of intense sub-picosecond pulses in bulk transparent material could result in permanent refractive index in a localized focal volume. Femtosecond laser direct writing allowed for mask-less fabrication of arbitrary three-dimensional paths in a variety of materials including glasses [16–18], crystals [19, 20], and polymers [21]. Though the application of femtosecond lasers has primarily focused on novel waveguide-based optical circuits [22], the induced refractive index contrast has also been successfully exploited for the fabrication of phase contrast DOEs [23–26].

In this work, a femtosecond laser was applied to fabricate multilayered buried DOEs inside bulk glass. Fused silica was an excellent candidate for volume DOEs due to its excellent transparency at visible wavelengths, low thermal expansion and high thermal diffusivity. In comparison to borosilicate glasses, fused silica has been traditionally challenging for refractive index modification due to its higher bandgap. However, femtosecond laser induced refractive index modification has also not revealed heat accumulation in fused silica due to the higher melting point and bandgap, which inhibits non-linear absorption. Consequently, finer pitch features are more readily available for phase elements in fused silica.

The main motivation was to harness, through intelligent design, the flexibility and
resolution available with femtosecond laser direct writing. In order to fully optimize the volume DOEs, refractive near field (RNF) microscopy was used to measure the refractive index profile of laser modification tracks and provide numerical data for theoretical modeling of phase grating efficiency. The resulting refractive index modification was found to have both positive and negative zones of index change. A surprising insight arose that showed the fine arrangement of such positive and negative zones could either enhance or diminish the overall diffraction efficiency of the phase gratings. This led to a deeper understanding of the resonant relationship between layer-to-layer separation of stacked gratings and diffraction efficiency, illuminating the substantial advantage for strategic alignment of grating layers to coincide with Talbot planes. The concepts of coherent stacking of low index contrast diffractive layers were then employed to design and laser-fabricate volume grating structures with high efficiency enhancement while exploring the optical response resolution limits available in fused silica glass.

In Chapter 2, relevant DOE design and fabrication is introduced. In addition, a review of femtosecond laser index modification is presented, along with fabrication challenges.

In Chapter 3, the experimental and characterization techniques are discussed. The exposure variations in the femtosecond laser fabrication of DOEs in fused silica and focusing conditions are described. Further, the microscopy tools and diffraction diagnostics used to assess the individual laser tracks and volume DOEs are detailed. Finally, the optical modeling tools used to analyze the diffracting behaviour of the DOEs are presented.

In Chapter 4, the key results of the design and fabrication of weak index contrast DOEs are presented. First, the fundamental limitations of weak index contrast gratings are discussed. Following this, the laser direct writing exploration in transparent glasses is detailed. The next two subsections detail the rigorous optimization of both the optical design and the laser fabrication of DOEs for NA = 0.55 and NA = 1.25 focusing conditions.

In Chapter 5, the enhancement in diffraction efficiency are explored through optical
modeling and verified with femtosecond laser fabrication of multilayered volume gratings. In Chapter 6, DOEs in two- and three-dimensions are discussed along with novel approaches to fabricating multi-dimensional volume elements.

Chapter 7 highlights the significant achievements of this thesis with comparisons to current state-of-the-art. Finally, the thesis concludes with a summary of the key findings, as well as an outlook for promising future research and application directions.
Chapter 2

Background

This chapter first presents the basics of diffractive optics, giving the literature context with respect to this thesis, as well as relevant theoretical background. The second section provides an overview of femtosecond laser direct writing inside glass that is directed at the challenges in fabricating diffractive optics.

2.1 Diffractive optics

Diffractive optics serve in many light systems for enhancing the performance of devices in beam shaping, pulse shaping, microscopy, optical tweezeing and 3D imaging [1, 27–29]. These DOEs are especially attractive in complex optical systems because they can perform the same functions with less space and equal efficiency, or can improve the optical resolution [1].

DOEs can be used for a variety of functions, from that of a classical refractive lens to complex wavefront transformers. An easy example to illustrate the difference between classical optical devices and DOEs is to consider the operation of a Fresnel lens compared to a basic plano-convex lens, as in Fig.2.1. A classical plano-convex lens, in (a), focuses a incident parallel rays into a focal point. Its Fresnel lens counterpart, in (c), can be generated by segmenting, in (b), the plano-convex lens and eliminating slabs of glass that
do not contribute to the bending of the light rays to the focal point. A further extension of this concept would be to approximate the Fresnel lens by using discrete levels to form a multiple level DOE, such as for 6-levels in (d).

Figure 2.1: Transformation of a (a) classic plano-convex lens through (b) segmentation to the (c) Fresnel lens counterpart and its (d) 6-level DOE approximation.

In more general terms, any wavefront transformation can be approximated in terms of diffracting rays with varying degrees of precision. For example, Fig. 2.2 shows a spot array generator that focuses a flat incident beam into an array of spots. Another common application is in the use of bean homogenizers (Fig. 2.3) based on an array of square, off-axis, continuous-relief diffractive microlenses to yield flat-top beam profiles for excimer laser systems. More complex farfield patterns can also be generated, such as in Fig. 2.4, where a 16-phase level DOE fabricated by F₂-laser micromachining of fused silica yields an image of the University of Toronto crest.

The study of surface diffractive structures have been widely applied because its design and underlying theory are well understood. Volume diffractive elements such as photorefractive volume gratings [23], computer generated holograms (CGH) [30], and laser direct
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Figure 2.2: 8-phase level diffractive spot array generator that outputs a $9 \times 9$ spot array [1].

Figure 2.3: Homogenizer microscope image on right that is arrayed into continuous-relief, square, off-axis diffractive microlenses that yields a uniform flat-top beam profile for beam homogenization of excimer lasers [2].

Figure 2.4: Atomic force microscope (AFM) image of a 16-phase level DOE fabricated by $F_2$-laser micromachining of fused silica to generate the farfield image of the University of Toronto logo [3].
written diffractive devices offer an attractive alternative that mitigates surface damage but requires new approaches to design and fabrication.

Conventional fabrication techniques include contact or proximity printing, projection lithography, direct writing with an electron beam or laser beam, gray-scale lithography [1,31–34] and direct writing, such as with lasers [35]. Conventional lithographic methods are well-established from the microelectronics industry and primarily relies on layer-by-layer approach to fabrication. This method is limited by the complexity of the fabrication process to only a few layers in the vertical direction and offsets between multi-layered devices requires a high degree of alignment and etching accuracy [36,37]. These processes are therefore highly time consuming, expensive and technically tedious for the fabrication of DOEs. Holographic lithography involves exposing a thick photoresist to a standing light wave pattern formed by the interference of multiple laser beams [38,39]. An example of this in Fig. 2.5 utilizes 3-beam interference generated by single laser beam exposure of a 3-level DOE to result in body centered tetragonal symmetry structures in SU-8 photoresist. The structures generated through this beam interference method are strictly of periodic structures only and require specific phase masks for forming the intended standing pattern. Similar holographic methods have also been used to expose photosensitive gel layers deposited as emulsion films, that post-processing produces a smooth and periodic modulation of index of refraction [40].

With direct writing methods, such as with lasers, diffractive optics can be written inside photoresists through multi-photon polymerization or inside transparent material through refractive index modification. For writing in photoresists, laser light is tightly focused to exceed the polymerization threshold through multi-photon absorption. After exposure, the resist is developed to reveal solidified polymer for the fabrication of three-dimensional structures such as in Fig. 2.6 [5,41]. These structures can be fabricated with great complexity, but the development requires interconnects between crystal layers that are sometimes difficult to achieve or undesired in the design.
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Figure 2.5: (a) Top and (b) Cross-sectional SEM images of body centered tetragonal symmetry structure in SU-8 generated by single laser beam exposure of the three-level DOE in the (c) AFM image using exposure configuration as in (d) [4].

Figure 2.6: (a) Forty layer 3D photonic crystal fabricated with direct laser writing in SU-8, with (b) side and (c) top view of a different broken structure showing 12 layers [5].

Direct laser writing inside transparent materials allows for the fabrication of DOEs without intermediate processing steps such as resist coating, exposure, and development. These writing methods follow from traditional mechanical processes for fabricating surface relief diffractive optics, such as ruled gratings or diamond turning. With direct laser writing of volume DOEs, laser light is focused tightly into bulk transparent material to
induce a positive or negative refractive index modification. Given the appropriate laser exposure conditions, these refractive index modified zones can be easily controlled and assembled into 3D optical devices [24–26,42], as described in further detail in Section 2.2. However, these fabrication techniques have primarily focused on the the stronger laser interaction with doped and borosilicate glasses to result in high refractive index change contrast, but also correspondingly larger physical structures relative to $\lambda$ [23,24] that preclude the demonstration of high-resolution diffractive optics. With femtosecond lasers, multilayered phase gratings formed inside fused silica have been demonstrated with low efficiencies of 25% due to increased grating thickness for 4 $\mu$m period gratings [25]. For the present objective of fabricating high-resolution phase gratings, research groups have not yet applied tighter focusing conditions successfully to generate strongly diffracting gratings when formed in a single layer array. Alternatively, a volumetric scattering model was used by [43] to optimize aperiodic volume optics, but was only valid for extremely weak diffracted or scattered wave fronts. Consequently, the challenge of harnessing weak refractive index modification for high resolution diffraction optics was recognized as a major hurdle in the laser fabrication of volume diffractive optics.

For low refractive index contrast DOEs such as written by lasers, dephasing of diffracted light over thick grating volumes imposes a fundamental restriction on diffraction efficiency that dramatically curtails their appeal. The limitations for weak refractive index contrast had not been fully understood and defined due to the absence of reliable fabrication methods as well as the challenge that most conventionally fabricated diffractive optics became inefficient when extended to the regime of very low refractive index contrast. The weak diffraction efficiency predicted for single layers of low contrast gratings were too low to be of much practical application. A noted exception to this prohibitively low diffraction efficiency is the specialized application of the Littrow configuration. Under the Littrow illumination, the diffraction efficiency has been shown experimentally to reach a high peak diffraction efficiency of 97% for samples of 0.6 $\mu$m
period and probe wavelength of 633 nm for a fused silica-air transmission grating ($\Delta n = 0.45$) [44]. While a very high diffraction efficiency can be obtained, the Littrow configuration is narrowly restrictive to specific probing angles and a single diffraction order, which prevent their general application to a broad range of DOE applications.

Alternative methods of improving diffraction efficiency have considered the extension to the layer-by-layer cascading of periodic structures, such as surface or volume gratings and DOEs. This effort to increase overall diffractive efficiency has been primarily focused on increasing the number of layers for overall longer diffracting length [26, 45, 46]. Multilayered volume Fresnel plates have also been demonstrated with moderately good efficiency of 60%, but only considered wide refractive index zones of 5 $\mu$m linewidth [26]. For the case of low refractive index contrast gratings, one must reconsider the multilayers in a theoretical context beyond a simple extension of the phase modulation range.

A curiously interesting observation was made in early work by Hargrove et al. [47], Malysh et al. [48] and Nordin et al. [49]. In particular, a periodic relationship appeared in calculations of the diffraction efficiency with respect to the separation between two layers of phase gratings. Hargrove et al. [47] noted, without giving physical insight, that a pair of acoustic gratings separated by periodic gaps of air resulted in strong enhancement of diffraction efficiency when the layer-to-layer grating separation was a multiple of $c_r$, given by

$$c_r = 2(n_r\Lambda^2)/\lambda$$

(2.1)

where $n_r$ is the base refractive index of the device, $\Lambda$ is the grating period, and $\lambda$ is the incident light wavelength. The modeling that led to Eq. 2.1 were based on scalar theory and was not of particular note because the diffractive structures in consideration were of sufficiently high index contrast (surface relief [48, 49] and acoustic waves [47]), where the high diffraction efficiencies were readily attainable with a careful consideration of the grating thickness. However, this periodic relationship would become key in the enhance-
ment of diffraction efficiency for weak index contrast phase gratings, a fundamental point that is exploited in this thesis.

The relationship in Eq. 2.1 arises from an analysis of the diffracting beams from two sinusoidal grating layers, described by the refractive profile

\[ n_m(x, t) = n_0 + n_m \sin 2\pi (mt/\lambda - mx/\lambda) + \delta_m/(2\pi) \] (2.2)

where \( n_0 \) is the base refractive index, \( \delta_m \) is the relative phase of the \( m^{th} \) harmonic, \( x \) is along the transverse grating length and \( t \) is time. Raman and Nath theory predicts that the \( q^{th} \) term (grating 2) from the \( p^{th} \) term (grating 1) will have light amplitude as given by the following equation

\[
\varphi = J_p(\nu)J_q(\nu)\frac{\nu_n\Lambda}{n\pi dsin\theta_p}\sin\left[\frac{n\pi d}{\Lambda}tan\theta_p\right]exp\left[-i(p+q)\delta_m\right]exp\left[-\frac{2\pi imp}{\Lambda}(d+l)tan\theta_p\right]
\]

\[
\times exp\left[-\frac{2\pi imq}{\Lambda}(d/2)tan\theta_p\right]exp\left[-\frac{2\pi in_0}{\lambda}(d+l)\cos\theta_p\right]
\] (2.3)

where \( \theta_p \) is the diffraction angle of the \( p^{th} \) term, \( d \) is the thickness of the gratings, and \( l \) is the separation between the gratings [47]. In order for a enhancement in the \( 1^{st} \) the diffraction order, a coherence of the phase component from the \( 1^{st} \) diffraction orders generated by the second grating (namely, ‘\( p = 0, q = 1 \)’ and ‘\( p = 1, q = 1 \)’ case). For this condition, a \( 2\pi \) phase shift from the separation between layers would result in a coherent addition of the orders to reveal the equation for \( c_r \) in equation 2.1. While this analysis was specifically demonstrated for plane wave illumination of sinusoidal gratings with scalar approximations, further analysis by other rigorous methods of optical modeling would reveal the same coherence effect for more general grating structures with appropriate layer-to-layer grating separation.

Equation 2.1 essentially describes the self-imaging length, or Talbot distance. The Talbot effect, first observed in 1836 by H.F. Talbot [50], occurs when a periodic object
is illuminated with spatially coherent light to produce a series of self-images of the illuminated object due to Fresnel diffraction. Talbot self-imaging has been exploited in many practical applications such as range sensing [51], Talbot spectrometers [52], Talbot interferometers [53, 54], and phase locking for generating coherent high power laser sources [55]. Talbot spectrometers depend on the difference in the distance between self-imaging planes, given by Eq. 2.1, for various wavelengths. Another well known application is in Talbot-Lau grating interferometers, which have been used in molecular, atomic, and x-ray interferometry [6]. Here, two planar gratings and a detector plane are arranged in parallel (Fig. 2.7) and illuminated by a low coherence, polychromatic source, where interference patterns from different wavelengths are phase-locked at the detector plane for interferometry [6].

![Figure 2.7: An illustration of a Talbot-Lau grating interferometer [6].](image)

In this thesis, the Talbot effect is first extended to explain the diffraction limitations within weak refractive index contrast phase elements and then exploited for the enhancement of the diffraction efficiency from multilayered DOEs.

### 2.2 Femtosecond laser direct writing

Femtosecond laser micromachining was first applied to the machining of surface relief structures in undoped polytetrafluoroethylene (Teflon) with 300 fs UV excimer laser
The tight focusing of femtosecond pulses inside transparent materials generates a combination of multiphoton absorption and avalanche ionization with such high intensities that there is a strong localized non-linear deposition of energy into the focal volume inside the bulk material [22, 62]. The laser-excited electrons transfer their energy to the lattice after several picoseconds and lead to a permanent material modification. The resulting modification can result in smooth refractive index change [63], form birefringent (nanograting) refractive index modification [64, 65] or microexplosions that result in nanovoids [66]. The modification regime depends on exposure parameters (energy, pulse duration, repetition rate, wavelength, polarization, focal length, scan speed, etc.), as well as material properties (bandgap, thermal conductivity, etc.) [22]. For pure fused silica, the three morphologies can be observed by changing the laser energy [67]. For the purposes of fabricating densely packed diffractive optics, it is advantageous to work within the regime of smooth and uniform refractive index modification as this results in the highest resolution and most repeatable modification zones.

Femtosecond laser writing at pulse energies just above the modification threshold results in the desired smooth refractive index modification in fused silica. Femtosecond laser material interaction is still not a completely understood mechanism, but is largely attributed to densification [68] and color centers [69], depending on the laser exposure conditions and the glass composition.

For femtosecond pulses focused with an external lens to achieve the desired micrometer sized focal size that is necessary for nonlinear absorption, the spatial intensity profile can be represented by the paraxial wave equation and Gaussian optics with spherical aberrations and non-linear effects neglected for simplicity. The diffraction-limited waist
radius, $w_0$, in a dielectric is therefore given by

$$w_0 = \frac{M^2\lambda}{\pi NA}$$

(2.4)

where $M^2$ is the Gaussian beam propagation factor or beam quality [70], NA is the numerical aperture of the focusing objective and $\lambda$ is the free space wavelength. The chromatic aberrations resulting from dispersion in the lens can be corrected with chromatic aberration-corrected microscope objectives and spherical aberrations from non-convergence of light rays, with multilens objectives or aspheric focusing lenses. For a $\Delta n = 0.46$ index mismatch when focusing for air into glass, spherical aberrations can be introduced, particularly for higher NA objectives [71], and contribute to strong depth-dependent focusing that distorts the femtosecond written buried structures [9, 65, 72]. One proposed solution for overcoming these spherical aberrations is to use oil immersion objectives for focusing the laser beam.

In the Kerr effect, a spatially varying refractive index is created by the spatial intensity variance in the Gaussian laser beam when propagating in dielectrics. The second order optical material non-linearity, $n_2$, is positive in most materials, resulting in a higher refractive index in the center of the beam which acts as a positive lens to focus the beam inside the bulk material to cause Kerr lens self-focusing. The collapse of the pulse in the focal point is predicted when the laser pulse exceeds the critical power for self-focusing given by

$$P_{\text{crit}} = \frac{3.77\lambda^2}{8\pi n_0 n_2}.$$  

(2.5)

In contrast, the non-linear ionization of the material produces a free electron plasma that behaves like a diverging lens. The self-focusing and plasma defocusing leads to filamentary propagation that results in an axially elongated refractive index structure, which is both a challenge and unexpected benefit for the fabrication of volume diffractive
optics. In fused silica, values of $\lambda = 532$ nm, $n_0 = 1.46$ and $n_2 \approx 3.5 \times 10^{-20} \text{ m}^2/\text{W}$ [22] yield a critical power of 0.83 MW that is readily obtainable with ultrafast lasers.

With the refractive index modification, form birefringence of periodic nanostructures result from interference of the laser field with the induced electron plasma wave [9, 64, 65, 73] that is expected to generate phase gratings with strongly differing polarization response [74]. Additionally, the laser material modification also has a strong scanning directional dependence, coined the quill effect by Kazansky and coworkers [75], that has been attributed to pulse front tilt that arises from the grating compressor in chirped-pulsed femtosecond lasers [76].

Further, it has been demonstrated there exists in-plane stress in femtosecond laser written waveguides in fused silica as well as surface swelling that occurs when waveguides are written close to the surface of the bulk material [77]. Both these factors will greatly affect the writing of volume DOEs in high resolution cases that require a high packing density of the index modification tracks. These factors are difficult to quantify for assembled DOEs because the observed changes in individual modification tracks cannot be directly translated into the laser written diffractive optics, due to uncertain responses when the tracks become partly over-lapping.

Previous work in waveguiding with similar laser exposure conditions had predicted refractive index change of $\Delta n \approx 0.01$ based on mode field matching [78]. While this predicted $\Delta n$ provides a good guide, it cannot be directly applied to laser-written volume diffractive optics as the mode field matching is based only on the guiding region of the modification track. In volume DOEs, the wavefront propagates along the entire cross-sectional length of the elongated tracks with multiple positive and negative regions of index contrast. While there is other work previously presented that predicts the refractive index contrast based on DOEs [25, 26], it has already been established that the morphology of the laser tracks are vastly different based on exposure conditions and need to be assessed in the context of the laser setup exposure conditions.
Chapter 3

Fabrication and Methods

In this chapter, the femtosecond laser direct writing arrangement is described, including lens and sample considerations. Section 3.2.1 describes the characterization tools used for examining both individual laser tracks as well as DOEs. Section 3.2.2 describes the optical modeling tools used for predicting diffractive optical intensity interference patterns and also projected farfield theoretical diffraction efficiencies.

3.1 Femtosecond laser direct writing

Laser modification tracks were fabricated inside fused silica (Corning 7980, $n_r = 1.46$) with a Yb-fiber amplified femtosecond laser (IMRA $\mu$Jewel D-400-VR) and formed into arrays and multi-level arrays to study 3D DOEs. The fibre laser is widely applied in industry and research labs due to an all-fibre approach, compact design and simple turn-key operation without the need for water cooling. To create the strongest refractive index contrast inside this wide band gap glass (9 eV), the laser system was frequency doubled with an LBO crystal (Newlight Photonics) to $\lambda = 522.5$ nm wavelength. The beam exposure conditions were 1 MHz repetition rate and pulse duration of 218 fs (FWHM), beam quality of $M^2 \approx 1.3$, and average peak powers of up to $P = 200$ mW, as measured with a thermal power meter (Ophir 12A). All Turning Mirrors (TM) and Flip Mirrors
(FM) (CVI Y1-1037-45) before the frequency doubling crystal (TM1-4 and FM1-2) were designed for high reflectivity at the fundamental wavelength of the femtosecond laser, $\lambda = 1045$ nm.

Precise writing of the 3D DOE structures with highly uniform exposure was provided by mounting the glass samples onto precise air-bearing $xyz$-motion stages (Aerotech ABL1000 and ALS130) each with 100 nm positioning precision that were mounted onto rigid granite arches together with the focusing beam optics. The laser power was varied and switched on or off with both an acousto-optic modulator (AOM, NEOS 23080-3-1.06-LTD) and a polarizer attenuator mounted on a rotation stage (Aerotech ART310). Refractive index structures were studied at various exposure powers ($P = 10$ mW to 200 mW) and sample scanning speeds, $v$, varied from 0.1 mm/s to the hardware limit of 100 mm/s found to induce modifications without undue damage to the glass. A flexible array of laser patterns together with power and scan velocity control were provided by a controller (Aerotech A3200) through computer programming (Aerotech AEROBasic).

The polarization of the laser was linear and perpendicularity or parallelism depended on the sample scan direction. A quarter-wave plate (QWP) provided circular polarization with an eccentricity of 0.3 or better. The laser beam could also be redirected into an Acousto-Optic Modulator (AOM, Neos 23080-3-1.06) powered by a Radio Frequency driver with a digital modulation input (Neos 21080-2DS) for quick modulation of the laser power that were precisely triggered user defined $xyz$-coordinates of the Aerotech stages through the Position-Synchronized Output (PSO). A maximum diffraction efficiency of 60% was obtained by angle tuning the AOM.

The intensity profile of the collimated laser beam prior to the focusing lens was characterized using a beam profiler (Spiricon Inc. LBA-USB v4.88). An example of this beam profile is shown in Fig. 3.1 which shows a $1/e^2$ elliptical Gaussian fit of $\sim 5.5$ mm and $\sim 4.2$ mm along the $x$- and $y$-axis, respectively, to overfill the focusing lens. The laser focus position on the sample was determined by imaging the Fresnel reflection directed
into a Firewire-interfaced CCD camera (Sony XCD-X710) with a zoom lens (Computar L5Z6004) for $\infty$-conjugate focusing. The smallest image size indicated a close proximity to focusing at the surface of the sample, which could be further improved to $\pm 2 \mu m$ precision by cross-calibrating with a minimum energy ablation threshold at best focus. The schematic of the optical delivery system from the fibre laser output to the target is shown in Fig. 3.2.

![Intensity profile of the fiber laser beam](image)

Figure 3.1: Intensity profile of the fiber laser beam (1 MHz, $\lambda = 522.5$ nm) at the target position without the focusing lens. The elliptical Gaussian fit of the laser beam shows a beam width ($1/e^2$) $\sim 5.5$ mm and $\sim 4.2$ mm along the $x$- and $y$-axis, respectively.

The laser beam was focused into the fused silica sample with the following lenses

1) Aspherical lens (Newport 5722-A) with numerical aperture of NA = 0.55

As noted in Section 2.2, aspherical lenses are beneficial to overcoming spherical aberrations. Additionally, the aspherical lens used here (Newport 5722-A) has chromatic aberration correction for use at $\lambda = 522.5$ nm. The focusing, based on equation 2.4, is expected to result in a focused spot size of $\sim 1 \mu m$. Spherical aberrations induced at the
Figure 3.2: Schematic of beam delivery system, where TM = turning mirror, HWP = half waveplate, FM = flip mirror, L = lens, A = aperture and HM = hot mirror [7].

Air-glass interface distorts the beam with deeper focusing that precludes the fabrication of deep structures. This is a particular limitation for volume DOEs due to the differences in refractive index properties as structures are fabricated at different depths. With a beam width entering the lens of \( \sim 5 \text{ mm} \), a power transmission of \( \sim 75\text{-}80\% \) through the lens can be expected, allowing for harnessing of the available laser energy.

2) Immersion microscope objective (Zeiss Plan 100X, NA 1.25, spot size \( \sim 0.3 \mu \text{m} \))

For oil immersion focusing, microscope objectives designed to work with index-matched oil were explored with focus here primarily on the Zeiss Plan 100× (NA = 1.25) lens. The main advantage of the oil immersed objective is the removal of spherical aberration, leading to the ability to fabricate diffractive elements uniformly through a large depth range in the glass. Further, with the tight focusing of an expected spot size \( \sim 0.3 \mu \text{m} \), much smaller index modification is expected from laser tracks fabricated with this objective. However, the use of a microscope objective that is not specifically intended for use in laser fabrication results in a relatively low transmission through the lens of only \( \sim \)
40-50%, depending on the amount of overfill employed at the entrance to the objective lens, which is $\sim 4$ mm - much smaller than the usual $\sim 5$ mm collimated beam of the femtosecond laser setup.

The use of an immersion objective required an index oil matched to fused silica ($n = 1.46$ for $\lambda = 522.5$ nm). For the purposes of this project, the following oils that were tested are listed in Table 3.1 along with pertinent physical properties as well as challenges for laser writing.

Table 3.1: Immersion oils and relevant physical properties for femtosecond laser writing.

<table>
<thead>
<tr>
<th>Manufacturer and item code</th>
<th>Viscosity and Boiling point</th>
<th>Transmittance at $\lambda = 522.5$ nm</th>
<th>Index of refraction, $n$ at $\lambda = 522.5$ nm</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cargille 18091 series A</td>
<td>130 cSt, $&gt;230$ °C</td>
<td>100%</td>
<td>1.460</td>
<td>• Partly soluble in Acetone&lt;br&gt;• Not soluble in water, Ethanol&lt;br&gt;• Clean with Ethyl Ether, Toluene</td>
</tr>
<tr>
<td>Cargille 06350</td>
<td>80 cSt, $&gt;343$ °C</td>
<td>100%</td>
<td>1.461994</td>
<td>• Partly soluble in Acetone&lt;br&gt;• Not soluble in water, Ethanol&lt;br&gt;• Clean with Ethyl Ether, Toluene</td>
</tr>
<tr>
<td>Cargille 50350</td>
<td>19 cSt, $&gt;262$ °C</td>
<td>100%</td>
<td>1.46202</td>
<td>• Partly soluble in Acetone&lt;br&gt;• Not soluble in water, Ethanol&lt;br&gt;• Clean with Ethyl Ether, Toluene</td>
</tr>
<tr>
<td>Carl Zeiss 462959</td>
<td>110 cSt, $&gt;130$ °C</td>
<td>100%</td>
<td>1.455</td>
<td>• Water soluble&lt;br&gt;• Clean with Acetone, IPA, Ethanol</td>
</tr>
</tbody>
</table>

The initial challenge of writing with oil immersion was the unexpected heating of the oil due to the incident laser energy, which resulted in bubbling that interfered with the fabrication of uniform structures. By first removing excess air through vacuum pumping, the bubbling was noticeably (through in-situ overhead camera observation) reduced and resulted in relatively uniform structures. However, further experimentation revealed that
a major culprit in the bubbling challenge was impurities present in waveguide matching optical-grade oils (Cargille 18091 series A). The switch to higher quality and purer index matching oils intended for microscope objective index matching as well as careful use of only disposable syringes for transferring the oil resulted in much more reliably repeatable experiments. In particular, the Carl Zeiss Immersion glycerine (462959) was found to result in the least noticeable surface bubbling and offered the most reproducible results over multiple laser writing experiments.

Following the writing of diffractive elements, it was necessary to clean the oil film on the fused silica samples. The appropriate solvents for efficient and complete cleaning are as outlined in Table 3.1. For the cleaning of Carl Zeiss Immersion glycerine (462959), Isopropyl alcohol (IPA, optical grade) resulted in the most complete removal of the immersion oil. However, glass substrates that underwent this cleaning procedure were not suitable for subsequent writing processes. The exact nature of this anomaly was not clear, but likely attributable to impurities introduced to the sample surface after the immersion oil and cleaning.

Other aspherical lenses (Newport 5720-A lens kit) with NA = 0.16 to 0.65 were also explored, but not extensively due to the lack of applicability for fabricating high-resolution diffractive elements. The observed trends of structures fabricated with different focusing clearly revealed much larger physical widths with lower NAs. Hence, this thesis focuses on presenting a comprehensive assessment of 0.55 and 1.25 NA for the fabrication of high resolution diffractive optics.

For the femtosecond laser writing, precise alignment was vital to manage the quill effect and other polarization effects during scanning (see Section 2.1). Therefore, magnets were used to register the sample edge firmly to the stage holder edge to ensure repeatable index modification tracks. Further, only a small amount of oil (< 0.1 mL) was found to be ideal with the immersion objective to reduce the possibility of the sample shifting by forces between the closely placed lens to the moving sample surface with ~50 - 150 µm
gaps. The optical aberrations at the glass interface restricted the formation of structures to depths of less than 150 µm from the sample surface.

The parameters considered for the optimization of volume gratings included periodicity (Λ), separation between layers (l), depth (z), and number of layers (N) as illustrated in Fig. 3.3. Additional considerations included incident laser power (P), polarization of the incident fabricating laser, and sample scan direction.

![Figure 3.3: Parameters for the optimization of volume gratings included periodicity (Λ), separation between layers (l), depth (z), and number of layers (N).](image)

Arrays of parallel laser tracks were scanned by the Aerotech stages to follow the G-code scripts such as in the example included in Appendix B. Further details on laser alignment and operation procedures for the femtosecond laser are described in detail in Shane M. Eaton’s Ph.D. thesis [11].

### 3.2 DOE diagnostics

#### 3.2.1 Characterization tools

Individual laser modification tracks were examined via optical (Olympus BX51), phase contrast and refractive near-field (RNF) microscopy (Exfo OWA9500) to assess morphology and refractive index contrast created transversely and in cross-section. For all the microscopy tools utilized, an optical resolution of 0.5 µm was anticipated. The optical microscope, with dry microscope objectives of 50× and 100× magnification, provided a
quick and qualitatively informative images of the laser tracks’ top and end-views. The phase contrast revealed images similar to that of optical microscopy, but was valuable in the interpretation of the induced index change mechanism. RNF microscopy provided detailed index profiling of the laser fabricated structures. The Exfo OWA9500 RNF microscope set-up for the measurement of laser written tracks in bulk material is shown in Fig. 3.4.

Figure 3.4: Schematic showing the set-up for refractive near field microscopy (RNF) by the Exfo OWA9500 instrument [8].

In the Exfo OWA9500, a collimated light beam from a laser source is focused with an objective lens to the endface of the fabricated laser track, which is placed vertical in the test cell. A silicon detector above the sample endface of the calibration block collects the portion of the beam refracted out of the laser track. The detected signal is inversely proportional to the changes in the index of refraction and, through interpolation, provides the refractive index profile of the laser track. The spatial resolution of the OWA9500 RNF microscope is $\sim 0.5 \, \mu\text{m}$ and offers refractive index characterization in the range of
A tabletop scanning electron microscope (SEM, Hitachi TM-1000) was also used to characterize the 3D photonic crystals fabricated through Ar\textsuperscript{+} exposure of SU-8 (MicroChem).

A procedure of optimizing scanning speed and exposure power was followed to examine the resolution limits for generating 1D phase gratings and other DOE designs having a high refractive index contrast for high potential diffraction efficiency. The DOE characterization was set-up on an optical table and the diffractive devices were formed over a $500 \times 500 \, \mu \text{m}^2$ area for this specific characterization setup. The sample was mounted on a custom holder on a rotary stage (Newport RSP-1T) and probed with a diode pumped solid state green laser (Lasermate GME-532-10FBP1, $\lambda = 532 \, \text{nm}$), collimated to a spot size of 300 $\mu \text{m}$ with two lenses of $f = 25 \, \text{cm}$ and $f = 10 \, \text{cm}$. The large laser diode linewidth of 0.1 nm precluded formation of Fabry-Perot fringes in the present sample thickness (1 mm). The schematic for the DOE characterization is shown in Fig. 3.5.

The optimization of the grating fabrication was primarily guided by measuring the efficiency of all available diffraction orders, with a low-power optical detector (Newport 818-SL) masked by a variable aperture to isolate individual diffraction orders of approximately 15 cm from the sample. Both reflected and transmitted orders were measured to assess scattering losses. The diffraction efficiency for each transmitted diffracted order is given as a percentage, resulting from the ratio of the measured power in the order over the measured probe power before the sample DOE. A similar procedure was also applied for additional probing the grating efficiency with a Ti:Sapphire laser ($\lambda = 800 \, \text{nm}$), a HeNe laser ($\lambda = 633 \, \text{nm}$) and a frequency tripled Nd:YAG laser ($\lambda = 355 \, \text{nm}$)

### 3.2.1.1 Diffraction efficiency measurement errors

The low-power optical detector (Newport 818-SL) has a spectral range from $\lambda = 400$ to 1100 nm, with an detector active diameter of 1.13 cm. The uniformity of response over
Figure 3.5: DOE characterization setup with the laser diode (Lasermate GME-532-10FBP1, $\lambda = 532$ nm) collimated through lenses, $f = 25$ cm and $f = 10$ cm, targeted at the DOE sample, which is mounted on rotation and $xyz$-stages.

the detector region is $\pm 2\%$ and the calibration uncertainty, with attenuator, is $1\%$ in the wavelength ($\lambda$) range of 400 to 940 nm. The rotary stage (Newport RSP-1T) on the sample holder controlled the beam probing angle of incidence with a resolution of $4$ arc min and sensitivity of $240$ arc sec.

In the measurement of optical diffraction efficiency, the laser fabricated devices were written over multiple days, due to the long fabrication time for an individual DOE design. For each separate exposure experiment, a baseline DOE consisting of a single layer of gratings with set laser writing conditions was fabricated to ensure consistency over a large number of experiments. The diffraction efficiency measurements were averaged over 3 to 5 devices and found to be repeatable within $5\%$ of the measured power. Changes in the femtosecond laser parameters, such as $M^2$ and pulse duration greatly affected the laser modification track morphology and corresponding fabricated DOEs. However,
these changes to the fundamental laser properties remained stable over the course of the majority of experiments described within this thesis and was not expected to significantly affect the repeatability of the data.

3.2.2 Optical modeling

The full vector field calculations of the far field diffraction efficiencies generated by the 1D phase gratings were made with commercial software (Grating Solver Development Company; GSolver 4.20c). The near-field interference intensity patterns anticipated from diffraction by single and multilayer phase gratings inside fused silica were computed by Finite Difference Time Domain (FDTD) using the FDTD Solutions program (Lumerical) and the interference electromagnetic fields from here were further propagated in free-space to determine the multi-order diffraction efficiencies. Sample coding and geometries used for both GSolver and Lumerical are included in Appendix C.
Chapter 4

Optimization of single volume grating layers

4.1 Talbot self-imaging limitation in weak index contrast gratings

In this section, the diffraction limitation in weak index contrast gratings are discussed and related to Talbot self-imaging inside the grating structure.

For traditional surface diffractive structures of binary rectangular grooves, scalar theory predicts that the diffraction efficiency can be controlled by the refractive index contrast ($\Delta n$) and the depth of the grating groove ($d$), which imparts a phase shift modulation of

$$\phi = 2\pi (\Delta n) d/\lambda$$  \hspace{1cm} (4.1)

on the phase front for probe wavelength, $\lambda$, for the case when $\Lambda \gg \lambda$. To predict the minimum grating thickness required for maximum diffraction efficiency, Eq. 4.1 is solved for $\phi = \pi$ to determine the grating depth $d_{\phi=\pi}$, that is valid only as long as scalar theory
is applicable to the phase mask and probe wavelength in question. For example, for standard fused silica surface relief gratings ($\Delta n = 0.51$) at probe wavelength of $\lambda = 244$ nm, a zeroing of the $0^{th}$ order (or maximization of the $1^{st}$ order) is desirable for writing Fibre Bragg Gratings and can be obtained for a grating depth of $d_{\phi=\pi} = 239 \mu$m. Here, the incident light wavelength to grating period ratio, $\lambda/\Lambda \sim 2$, falls near the edge of theory to ensure a strong $1^{st}$ order diffraction efficiency.

For the purposes of the FDTD calculations, the cross-section of the grating array is considered, such as shown in Fig. 4.1(a) for 6 grating periods. The hatched area represents the refractive index contrast ($\Delta n$), either positive or negative, in comparison to the background refractive index, $n_r$. The duty cycle of the phase grating as well as the grating period can be adjusted, as well as the refractive index profile along the grating depth. In the FDTD modeling, the single grating element is replicated over a large number of grating periods with boundary conditions and mesh sizes as described in Appendix C. The FDTD modeling is used to generate interference intensity profiles as shown in Fig. 4.1(b) for refractive index contrast of $\Delta n = +0.46$ in the hatched areas, which can then be projected into the farfield to determine the efficiency of all the diffracted orders. The coordinate convention of $xyz$ as shown in the bottom left will be used consistently throughout the results and discussion that follows.

Figure 4.2(a-d) shows the FDTD calculation (introduced in 3.2.2) of interference intensity pattern of light traversing through the narrow 1 $\mu$m zone of one volume phase grating period with $\Lambda = 1 \mu$m period and $d = 20 \mu$m thickness for probe wavelength, $\lambda = 532$ nm. The different refractive index contrast gratings, $\Delta n = 0.46$, 0.16, 0.06, and 0.02, with the higher refractive index volume demarked by the hatched region in the figures, were probed from the bottom ($z = 0 \mu$m) with $\lambda = 532$ nm light at uniform incident intensity $I_0 = 1$. For each grating case, the projected combined $1^{st}$ order diffraction efficiency, $\eta$, was calculated for increasing grating depths, $d$, as shown in Fig. 4.3.

In Fig. 4.2(a), the grating with an air-glass interface of $\Delta n = 0.46$ results in strongly
Figure 4.1: (a) Illustration of the cross-sectional view of a grating array with Λ = 1 µm period, 50% duty cycle, and thickness $d = 20$ µm. (b) FDTD intensity pattern example, with the refractive index contrast ($\Delta n = 0.46$) in the hatched area, as shown also in (a), and incident wavelength, $\lambda = 532$ nm, from the bottom.

contrasting intensity fringes (0 to 7.43$I_0$) with the first peak positioned at $z \sim 0.7$ µm that corresponds to a build up of $1.19\pi$-phase shift, based on Eq. 4.1. Should the grating be truncated at this $z = 0.7$ µm point, a peak diffraction efficiency of $\eta \sim 70\%$ is anticipated as shown in Fig. 4.3(purple). Here, a breakdown of scalar theory for such fine grating period ($\Lambda \sim 2\lambda$) leads Eq. 4.1 to underestimate the grating thickness for optimum diffraction efficiency [79,80]. The scalar expectation for the periodic oscillation of intensity fringes inside the grating structure is for the distance where $\phi = 2\pi$, or $d_{\phi=2\pi}$,
Figure 4.2: FDTD calculation for one phase grating period showing the interference intensity pattern of volume phase gratings of $d = 20 \, \mu m$ length (along $z$-axis) and 50\% duty cycle with period, $\Lambda = 1 \, \mu m$ (along $x$-axis) for refractive index contrasts (a) $\Delta n = 0.46$, (b) 0.16, (c) 0.06, and (d) 0.02. The white and red arrows represent, respectively, the Talbot oscillation distance, $c$, and the propagation distance for accumulating $2\pi$ phase contrast, $d_{\phi = 2\pi}$, along the phase gratings. Gratings probed from the bottom with $\lambda = 532 \, \text{nm}$.

As shown by the 2.65 $\mu m$ long red arrow in Fig. 4.2.

With decreasing refractive index contrast, the intensity contrast decreases strongly from Fig. 4.2(a) to (d) and, correspondingly, the diffraction efficiency also drops dramatically from 90\% (Fig. 4.3(purple)) to a maximum of only 4.4\% (Fig. 4.2(green)) for the weak contrast case regardless of the phase grating thickness. For the weak case of $\Delta n = 0.02$ (Fig. 4.2(d)), the constructive interference builds up to only a moderate intensity peak of $1.7I_0$ at grating depth $z = 2.65 \, \mu m$. An examination of Fig. 4.2(d) revealed that the periodic oscillation of the intensity pattern did not correspond to the scalar theory.
Chapter 4. Optimization of single volume grating layers

Figure 4.3: The projected efficiency of combined 1st order beams for varying grating thickness for $\Delta n = 0.46, 0.16, 0.06, \text{ and } 0.02$, for $\Lambda = 1 \mu m$ and $\lambda = 532 \text{ nm}$.

spacing of $d_{\phi=2\pi} = 21.3 \mu m$ (red arrow) as anticipated by Eq. 4.1.

In the high index contrast case of Fig. 4.2(a), there is strong containment of the light intensity within the higher index contrast region. This enables a build of strong intensity contrast between the high and low index contrast regions, along with sufficient phase modulation, to result in a strong first order diffraction orders as well as a nulling of the zeroth order. In the low index contrast case of Fig. 4.2(d), the light is not contained tightly in the high index contrast region. Therefore, the simple notion of phase delay between the high and low intensity regions is no longer applicable. The small intensity contrast from the rearrangement of light between the different refractive index zones limits the diffraction efficiency, as opposed to the traditional diffraction grating concept of phase delay.

With further insight, Chanda and Herman [81] noted that the interference pattern generated by a phase mask of period $\Lambda$, would lead to coherent combination of the diffraction orders on planes that repeated over a similar distance, $c$, identified as Talbot planes,

$$c = (\lambda/n_r)/(1 - \sqrt{1 - (\lambda/n_r \Lambda)^2})$$  \hspace{1cm} (4.2)
where \( n_r \) is the background index of refraction. Indeed, the periodic oscillation observed in Fig. 4.2(d) corresponds to this Talbot self-imaging separation, as indicated by the white arrow in the figure. For the gratings with high index contrast in Fig. 4.2(a), the oscillations within the grating length correspond more closely with the expected \( 2\pi \)-phase modulation distance given by \( d_{\phi=2\pi} \) (red arrow), which is significantly shorter than the Talbot plane separation, \( c \) (white arrow). As the refractive index contrast decreases (Fig. 4.2(a) to (d)), the \( d_{\phi=2\pi} \) (red arrow) length extends to beyond the Talbot spacing, \( c \) (white arrow) which limits the available diffraction efficiency as seen in Fig. 4.3, with corresponding decreasing intensity contrasts in Fig. 4.2(a) to (d).

The minimum grating thickness, \( d_{\phi=\pi} \), required for maximum 1\(^{st}\) order diffraction efficiency was also determined as anticipated by Eq. 4.1 and plotted in Fig. 4.4 over a broad spectrum. On the same graph, the first expected intensity fringe as predicted by Eq. 4.2, given by \( c/2 \), is also shown in black. The half-Talbot distance is independent of the index contrast (\( \Delta n \)), but rises strongly with decreasing probe wavelength. The fundamental limit of high diffraction efficiency is governed by the transition from classical diffraction where the \( \pi \)-phase contrast distance, \( d_{\phi=\pi} \), is found to exceed the half-Talbot plane distance, \( c/2 \). The fall off in diffraction efficiency occurs when the Talbot self-imaging oscillates on distances shorter than required for generating high contrast fringes on spacing \( d_{\phi=\pi} \), namely, when \( c/2 < d_{\phi=\pi} \). In this way, the grating thickness for the 1\(^{st}\) diffraction peak follows the \( d_{\phi=\pi} \) condition, increasing linearly with wavelength in Fig. 4.4 for all values of index contrast, until intercepting the \( c/2 \) line (black).

For the case of \( \Delta n = 0.02 \), this juncture at 269 nm wavelength turns over the optimum grating thickness to follow the \( c/2 \) curve towards longer wavelength as shown by the dashed green curve in Fig. 4.4. In the case of 532-nm probe wavelength, the half-Talbot self-imaging length of \( c/2 = 2.65 \, \mu m \) (Fig. 4.4(black)) is 4-fold shorter than the \( d_{\phi=\pi} = 10.6 \, \mu m \) distance (Fig. 4.4(green)) required for \( \sim \pi \)-phase shift, and insufficient phase shift of 0.25\( \pi \) is accumulated that limits the diffraction efficiency to peak at \( \eta = 4.4\% \) as
Figure 4.4: Minimum propagation distance for the first expected 1st order diffraction peak calculated versus probe wavelength for $\Delta n = 0.46$, 0.16, 0.06, and 0.02 phase gratings of $\Lambda = 1 \, \mu m$ period along with the half-Talbot oscillation length, $c/2$.

shown in Fig. 4.3(green). Hence, such uniform but weakly contrasting gratings cannot offer a high efficiency, even for large grating thicknesses.

For mid-range $\Delta n$ such as 0.06, the oscillations within the grating length follow the Talbot self-imaging planes, but shifts towards the expected $\sim 2\pi$-phase shift oscillations as anticipated by the calculations shown in Fig. 4.4. But outside the grating ($z = 0$ to $20 \, \mu m$), the three beam interference results in the Talbot self-imaging planes anticipated by Eq. 4.2. For high refractive index contrast of $\Delta n = 0.46$, the intensity in Fig. 4.2(a) oscillates on $d_{\phi=\pi} = 0.7 \, \mu m$ spacing, as the accumulation of maximum phase modulation occurs well before the Talbot self-imaging distance for all permitted diffracting wavelengths ($\lambda < 1 \, \mu m$) shown in Fig. 4.4(purple). Within the phase grating length ($z = 0$ to $20 \, \mu m$) in the case of $\Delta n = 0.46$, the oscillations observed followed the conventional $\sim \pi$-phase modulation, but outside the grating length, the diffracted orders interfere as anticipated by the Talbot self-imaging planes in Eq. 4.2.

Figure 4.2(a) also reveals finer fringe patterns (i.e. $\Delta z \sim 200 \, \text{nm}$) inside the Talbot self-imaging distance $c = 5.3 \, \mu m$ that arises from interference of the $m = 0$ and $\pm 1$ with the $m = \pm 2$ diffraction orders that undergo total internal reflection at the glass-air
interfaces. Continuous diffraction along the propagation length of the phase grating leads the 2\textsuperscript{nd} order beams to cause a longer range modulation of the peak intensity and the 1\textsuperscript{st} order diffraction efficiency that is apparent particularly for the high index contrast case of $\Delta n = 0.46$ case on distance $\Delta z = 7.3 \, \mu \text{m}$ in Fig. 4.2(a) and Fig. 4.4(purple). These 2\textsuperscript{nd} order beams cannot escape the grating due to total internal reflection.

The transition from conventional $\sim\pi$-phase modulation to Talbot self-imaging limitations is generalized for other grating periods in Fig. 4.5. In Fig. 4.5(a), glass gratings with background refractive index, $n_r = 1.46$, are considered with different probe wavelengths, $\lambda = 400, 532, \text{ and } 800 \, \text{nm}$. For the visible spectrum ($\lambda > 400 \, \text{nm}$), Talbot oscillation restricts the choice of index contrast to $\Delta n > 0.027$ for generating efficient gratings with $1 \, \mu \text{m}$ period. One can see that with longer period gratings, such as $\Lambda = 3 \, \mu \text{m}$, much lower index contrast of $\Delta n = 0.003$ will result in efficient gratings that can be optimized on the traditional $\sim\pi$-phase modulation condition. For smaller grating periods and weaker index contrasts, other approaches to improve the diffraction efficiency must be found.

Figure 4.5: (a) Minimum refractive index contrast in glass gratings ($n_r = 1.46$) before oscillation on Talbot self-imaging planes will curtail diffraction efficiency for cases of $\lambda = 400, 532, \text{ and } 800 \, \text{nm}$. (b) Minimum refractive index contrast in gratings for fused silica ($n_r = 1.46$) and TiO$_2$ ($n_r = 2.50$) gratings at $\lambda = 532 \, \text{nm}$ and Si ($n_r = 3.53$) gratings at $\lambda = 1.1 \, \mu \text{m}$ before oscillation on Talbot self-imaging planes will curtail diffraction efficiency.
In Fig. 4.5(b), the minimum refractive index contrast where Talbot oscillation restricts the diffraction efficiency is shown for fused silica ($n_r = 1.46$) and TiO$_2$ ($n_r = 2.50$) gratings at $\lambda = 532$ nm and Si ($n_r = 3.53$) gratings at $\lambda = 1.1 \, \mu m$ (the minimum transmitting wavelength for silicon). For TiO$_2$, which has higher refractive index compared to fused silica, a lower refractive index contrast is acceptable for all grating periods. For example, to generate efficient gratings at period $\Lambda = 1 \, \mu m$, a refractive index contrast of only $\Delta n > 0.029$ is required for TiO$_2$ compared with $\Delta n > 0.05$ for fused silica. For the case of Si, despite the higher base refractive index, $n_r = 3.53$, a higher refractive index contrast is required for $\sim \pi$-phase shift modulation regime due to the fact that the first transmitting wavelength is substantially higher at $\lambda = 1.1 \, \mu m$. Consequently, a large $\Delta n > 0.088$ is required for the generation of efficient gratings at $\Lambda = 1 \, \mu m$ in silicon.

The Talbot self-imaging oscillations, on distance $c$, are therefore the main limiting factor in determining the available diffraction from the combination of low refractive index contrast and high resolution gratings. For fused silica ($n_r = 1.46$) gratings of weak index contrast such as $\Delta n = 0.02$ available from femtosecond laser writing, a maximum of 4.4% combined 1st order diffraction efficiency is all that is available regardless of the total grating thickness, which precludes many practical applications. In order for volume diffractive elements to attain practical diffraction efficiencies, this thesis will study alternative methods of enhancing efficiency through intelligent design of multilayered gratings.

### 4.2 Laser direct writing in transparent glasses

Femtosecond lasers can be focused tightly inside transparent material to generate a combination of multiphoton absorption and avalanche ionization with such high intensities that there is a strong localized non-linear deposition of energy in the focal volume, as introduced in Section 2.2. In this Section, the types of transparent glasses studied with
the femtosecond fibre laser is detailed and assessed for fabrication of high resolution
diffractive optical elements.

In borosilicate glasses, such as Corning EAGLE2000, strong index modification was
induced by femtosecond laser for fabricating waveguide devices [9]. With the femtosec-
ond laser detailed in 2.2, exposure conditions of variable repetition rate of 0.1 to 5 MHz
at $\lambda = 1045$ nm, $P = 200$ mW and 0.55 NA focusing, was tested in bulk EAGLE2000
glass to result in the morphological structures as seen in Fig. 4.6. Here, positive and
negative index change zones were observed along the propagation axis of the incident
laser. However, the heat accumulation effect dominates the refractive index modification
mechanisms, resulting in the material modification extending to a diameter $\sim 10 \mu m$ that
greatly exceeds the $w_0 = 1.6 \mu m$ focal volume. The heat accumulation modification was
formed by a slowly evolving near-Gaussian temperature distribution, where the over-
all size was determined by the maximum diameter where the temperature exceeds the
melting point ($985^\circ$). While the large cladding-like outer layer that was beneficial for
waveguiding, the overall large modification zone was unattractive for the fabrication of
high resolution DOEs on the order of $\sim 1 \mu m$, and other glass types were targeted for
DOE fabrication.

The femtosecond laser direct writing was also explored for other borosilicate glasses,
including Schott BK7. Previous work in BK7 reported negative refractive index change
from femtosecond laser fabrication [82–84]. With the IMRA femtosecond laser, cross
sectional microscope images were as shown in Fig. 4.7. The phase contrast images
in Fig. 4.7(a) revealed a very large spherical zone of negative refractive index change
of $\sim 10$ to $20 \mu m$ over the range of scan speeds tested, along with a small positive
index modification zone and surrounded by an outer-cladding zone similar to the heat
accumulation effects as seen for EAGLE2000 in Fig. 4.6. These overall large modification
structures were also deemed unsuitable for the fabrication of high resolution diffractive
optics.
Figure 4.6: Cross sectional refractive index profiles (from RNF) of laser modification tracks written inside EAGLE2000 with 200 mW power, 25 mm/s scan speed and repetition rates of 0.2, 0.5, 1, 1.5, and 2 MHz. The writing laser ($\lambda = 1045$ nm) was incident from the top and the refractive index scale is shown on the right [9].

Fabrication in high refractive index glasses, such as Ohara STIH-6 ($n \sim 1.81$), were also examined. In Fig. 4.8, the cross-sectional optical image of the laser modification tracks written in STIH-6 at 100 kHz and 522.5 nm are shown. The images reveal dark
regions of modification, which usually indicates a negative index change. Volume gratings of $\Lambda = 3$ to $5$ $\mu$m period were written in STIH-6, but optical proving resulted in a large amount of scattering noise surrounding the diffraction orders. The initial observation of scattering from volume gratings in STIH-6 suggested that in addition to the refractive modification, there was possibly also void formation inside the glass. Further examination of the laser modification tracks with phase contrast or RNF microscopy would be necessary to fully assess the modification mechanism inside STIH-6. The fabrication of 3-5 $\mu$m period gratings revealed combined 1$^{st}$ order diffraction efficiencies of less than 3% and were not expected to be a viable choice for fabricating high resolution diffractive optics.

Figure 4.8: Optical microscope cross-sectional images of laser modification tracks written in Ohara STIH-6 ($n \sim 1.81$) at 100 kHz, 522.5 nm, and NA = 0.55. Laser radiation was incident from the top.

The main motivation for laser direct writing in pure fused silica was the pursuit of smaller feature sizes. Previous work had observed that heat accumulation effects were
not observed in fused silica due to a two-fold weaker non-linear absorption in this wide bandgap material, as compared with borosilicate glasses [22]. Additionally, the working point temperature in fused silica is \( \sim 1.5 \)-fold higher than in borosilicate glasses, making melting and heat accumulation less likely in fused silica [42]. The absence of such thermal diffusion effects as seen in prior work was expected to offer much smaller feature sizes and, consequently, much higher resolution phase gratings.

The top-view images of femtosecond laser written modification tracks in fused is shown in Fig. 4.9 for exposure at 1 MHz, fundamental \( \lambda = 1045 \text{ nm} \), and 0.55 NA focusing over a range of laser powers and scan speeds. At these laser exposure conditions, the top-view reveals, at high scan speeds \( (v > 20 \text{ mm/s}) \), ‘pearl-chain’ structures as had been reported in other glasses with very high rep rate femtosecond lasers [22]. Although this ‘pearl-chain’ was not evident at low scan speeds \((v = 1 \text{ mm/s})\), very wide modification tracks were observed and deemed unsuitable for the fabrication of high resolution diffractive optics.

![Figure 4.9](image)

Figure 4.9: Optical microscope top-view of laser modification tracks written in fused silica at 1 MHz, 1045 nm, and NA = 0.55 for a range of applied laser powers and scan speeds.

With femtosecond laser writing at 100 kHz, fundamental \( \lambda = 1045 \text{ nm} \), and 0.55 NA focusing, the top-view morphology, as shown in Fig. 4.10 revealed large laser modification zones similar to that at 1 MHz, but without the ‘pearl-chain’ effect. Laser tracks written at the fundamental \( \lambda = 1045 \text{ nm} \) were weak and irregular for all exposure
conditions of scan speed, repetition rate, and pulse energy. Fig. 4.11 shows an overhead optical microscope image of typical tracks written with 1045 nm wavelength. Volume gratings written at the fundamental wavelength, were found to diffract poorly due to the irregularities as seen along the laser track length here.

![Image](image_url)

**Figure 4.10:** Optical microscope top-view of laser modification tracks written in fused silica at 100 kHz, 1045 nm, and NA = 0.55 for a range of applied laser powers and scan speeds.

![Image](image_url)

**Figure 4.11:** Overhead optical microscope images of laser modification tracks in fused silica written at 1045 nm wavelength with 1 MHz repetition rate, 175 mW power, 0.2 to 50mm/s scan speed, and NA = 0.55 for a range scan speeds [11].

Frequency-doubling the femtosecond laser to 522 nm, offered a theoretically 2-fold smaller focusing size that resulted in a higher maximum fluence and higher resolution when compared with the fundamental wavelength. Together with stronger multiphoton
ionization, the higher fluence was expected to contribute to the formation of higher contrast modification tracks [11] as well as finer pitched gratings.

For the purposes of fabricating high resolution transmission volume gratings, fused silica was found to be the ideal choice in the pursuit of smallest feature sizes with maximum refractive index modification, as detailed in the following sections. In addition, fused silica had very high transparency over all visible wavelength spectrum and laser induced modification structures remained highly stable at over a long lifetime (years). Further, fused silica was widely available and inexpensive to obtain in a variety of dimensions.

In the next section, the frequency doubled femtosecond laser optimization for volume grating fabrication was explored together with comparisons of optical modeling.

4.3 Low 0.55 NA focusing

The femtosecond laser direct writing in fused silica glass with $\lambda = 522.5$ nm and focusing at $\text{NA} = 0.55$ was explored with an aspherical lens (detailed in Section 2.2). This section will first assess the morphology of individually written laser modification tracks on which to build a model for optical diffraction calculations from arrays of such tracks. This section builds towards the optimization of linear volume gratings with respect to laser exposure conditions that offer high resolution gratings with strong diffraction.

4.3.1 Single modification track morphology and optical modeling

The physical structure of the refractive index modification inside glass was controlled primarily by the sample scan speed, the applied laser power and the focusing power of the lens, which determined the net amount and spatial distribution of laser energy deposited along the laser track. Following previous work of weak laser focusing to write buried optical waveguides [42], modification tracks with strong refractive index contrast
were first assessed for the aspherical lens (NA = 0.55), yielding the cross-sectional end views of single laser written tracks for the range of sample scan speeds and applied laser power as shown in Fig. 4.12.

Figure 4.12: Optical microscope cross-sectional end view of refractive index modification tracks formed at various laser powers and writing speeds for λ = 522 nm and NA = 0.55. Writing laser incident from top. Light regions indicate positive index change and dark regions indicate negative index change.

The dark and bright regions seen under backlighting in these optical microscope images were confirmed through RNF to correspond to negative and positive index change,
respectively. For high exposure (low scan speed, \( v = 1 \text{ mm/s} \) and high applied laser power, \( P = 173 \text{ mW} \)) in the top left of Fig. 1, the incident laser induced a series of positive (light regions) and negative (dark regions) index changes inside the material through multiple cycles of self-focusing and plasma defocusing effects as expected when the peak power of the femtosecond laser approached the critical power \( P_{\text{crit}} = 0.8 \text{ MW} \) for self focusing [22]. As the net laser exposure decreased with increasing scan speed and/or decreasing applied laser power, the size and contrast of the overall fabricated structure decreased from \( 3 \mu\text{m} \times 25 \mu\text{m} \) \((P = 173 \text{ mW}, v = 1 \text{ mm/s})\) to \( 1 \mu\text{m} \times 5 \mu\text{m} \) \((P = 50 \text{ mW}, v = 10 \text{ mm/s})\), approaching the diffraction limited waist radius of \( 0.6 \mu\text{m} \) and \( \sim3 \mu\text{m} \) depth of focus. In addition, lower power lead to weaker self focusing and therefore fewer cycles of positive and negative index change, that ended with only one positive and one negative index region being generated for the case of \( P = 50 \text{ mW} \) in Fig. 4.12. For the purpose of writing high resolution and efficient gratings, the morphological trends in Fig. 4.12 demonstrated a trade off. One may select the low contrast tracks (i.e. bottom right of Fig. 4.12) that pack more tightly but offer lower diffraction efficiency, while the high index contrast modification tracks (i.e. top left of Fig. 4.12) may coalesce through stress relaxation into weakly contrasting phase gratings when assembled too densely.

A higher resolution quantitative characterization of the refractive index contrast of these laser tracks was provided by RNF microscopy, yielding the cross-sectional image in Fig. 4.14(a)(left) for the case of \( P = 173 \text{ mW} \) and \( v = 1 \text{ mm/s} \) laser exposure. The RNF image shows a good correspondence of the high and low index regions to match respective light and dark zones in with the slightly lower resolution optical microscope image in Fig. 4.12(top left). Further, the phase contrast microscopy of these same laser written tracks confirmed that there was no scattering that would have been indicative of damage centres or micro-voids within its length, as seen in Fig. 4.13 which compares optical, phase contrast and RNF microscopy of individual laser tracks written with similar laser exposure conditions. The phase contrast and RNF microscopy show greater detail...
of the laser track morphology, but confirm that the optical microscopy is a good indicator of the presence of positive (light) and negative (dark) refractive index modification.

Figure 4.13: Comparison between (a) optical microscopy, (b) phase contrast microscopy, and (c) RNF microscopy images of NA = 0.55 individual laser tracks written at $P = 150$ mW, $v = 1$ mm/s and circular polarization.

![Comparison between (a) optical microscopy, (b) phase contrast microscopy, and (c) RNF microscopy images of NA = 0.55 individual laser tracks written at $P = 150$ mW, $v = 1$ mm/s and circular polarization.](image)

The refractive index profile from RNF measurements also confirmed the formation of multiple positive and negative index regions, over a total modified area of $\sim 3$ $\mu$m width and 25 $\mu$m length with index contrast varying from $\Delta n = -0.013$ to $+0.015$. One can anticipate forming linear arrays of such laser tracks to form high contrast phase gratings. A microscope image of the cross-sectional end view (Fig. 4.14(b)(right)) of a grating formed by patterning a $\Lambda = 1$ $\mu$m periodic array of similar tracks to that in Fig. 4.13(b) revealed a potential reduction of lateral refractive index contrast. While such small $\Lambda/2 = 0.5$ $\mu$m phase elements were not clearly resolved at the optical resolution limit of the optical microscope, $1^{st}$ order diffraction from this device appeared at the expected $32^\circ$
angles with combined efficiency of $\eta = 9\%$. Similarly, optical resolution limits in the 
RNF also precluded an reliable recording of index profile for this high-resolution phase 
grating array (Fig. 4.14(a)(right)).

When stitching together such laser modification tracks, one anticipates a melding of 
positive and negative index regions laterally when the cross-sectional width exceeds the 
period. Figure 4.15(red) shows the refractive index profile expected laterally across the 
laser modification track (Fig. 4.14(a)(left)) when averaged over the axial length. Due to 
the deep negative refractive index zones seen in Fig. 4.15, the averaged refractive index 
profile was found to have an overall negative $\Delta n$, which may be contrary to waveguiding 
expectations which generally look to guide in the peak positive index change regions. 
However, for the purposes of diffractive optics, an overall negative or positive index 
contrast was less important than the relative index contrast generated by these arrayed 
gratings. The average refractive index profile is well represented by the 0.78 $\mu$m wide 
(FWHM) Lorentzian profile in Fig. 4.15(thin black) having a peak refractive index 
contrast of $\Delta n = -0.009$. A simple linear superposition of this refractive index profile for 
a 1 $\mu$m periodic array of individual tracks (blue lines in Fig. 4.15) is seen to lead to a 
60% lower refractive index contrast ($\Delta n_{AC} = 0.017$) for such phase gratings together with 
an increased overall net decrease in the refractive index background of $\Delta n_{DC} = -0.010$.

While this average refractive index approximation provided a useful guideline for the 
prediction of overall diffraction efficiency, for the purposes of optical modeling, it was 
necessary to consider the refractive index profile of the entire laser track as shown in Fig. 
4.14. To reduce the computational effort in the FDTD modeling, the multiple cycles of 
positive and negative index changes of the laser written track in Fig. 4.14(a)(left) were 
simplified into various block representations as shown in the left of each frame of Fig. 
4.14(b-e), with the main motivation of matching experimentally measured diffraction 
efficiencies. The refractive index contrast in each block was matched to the average value 
of index contrast observed in the RNF measurement (i.e. Fig. 4.14(a)(left)). These
Figure 4.14: (a) Refractive near-field microscopic image of the laser-track cross section, laser written with $P = 173$ mW, $v = 1$ mm/s scan speed, and 0.55 NA focusing, with refractive index contrast scale on left, and corresponding end-view of assembled array of 1 µm period gratings in fused silica. (b) Simplified block representations of the index profile arrayed into 1 µm period grating (left) with the interference intensity pattern from FDTD calculations for 532 nm light incident propagation from top (right) and corresponding far field combined 1st order diffraction efficiency, $\eta$(bottom). (c-e) Block representation of a single track (left), corresponding intensity pattern (right), and grating efficiency (bottom).
blocks were then formed into linear arrays as seen in Fig. 4.14(b)(left) for the case of slicing the profile into a half-period width of 0.5 μm (50% duty cycle) with refractive index zones varying as $\Delta n = -0.008, +0.0034, -0.0085, \text{ and } +0.0101$ from top to bottom.

In the FDTD modeling, the non-uniform laser track morphology could not be imported into the FDTD modeling tools directly and required discretation of the RNF profile. Further, the simplification of the complex non-uniform laser track morphology to averaged uniform blocks was necessary due to computational time restrictions. The complexity of a fine variances in index change would result in an exponential increase of computational complexity, rendering the modeling of multilayered DOEs impractical.
The uniform blocks of refractive index change provided a good approximation of the real RNF profile and particularly for the examination of index change with respect to Talbot self-imaging planes, which is only dependent on the refractive index of the bulk glass.

With fused silica ($n_r = 1.46$), the Talbot separation is given by Equation 4.2 as $c = 5.4 \, \mu m$. Small variations of $\sim 0.001$ is expected not to change the oscillation period of the interference intensity pattern as long as the refractive index contrast does not flip from positive to negative or vice versa. Therefore, the simulations can be satisfactorily approximated by uniform averages of the refractive index change.

The intensity interference pattern expected by FDTD calculation for 532 nm wavelength light propagating downward through the phase array (Fig. 4.14(b)(left)) is shown in Fig. 4.14(b)(right), where the 1 $\mu m$ horizontal length was stretched dramatically against the 30 $\mu m$ vertical thickness of the phase grating for better viewing of the interference fringes.

In Fig. 4.14(b), the contrast of the intensity interference pattern first grows and then diminishes before the end of the phase grating ($z = 25 \, \mu m$), resulting in a combined 1$^{st}$ order diffraction efficiency of $\eta = 2.4\%$ which was significantly smaller than the experimentally observed $\eta = 9\%$. Figures 4.14(c-e)(left) were block representations with increasing complex patterns of refractive index contrast that better conform to represent the wider index zones of the single track RNF profile (Fig. 4.14(a)(left)). This served to reduce the net accumulated phase contrast with the surprising benefit of increasing 1$^{st}$ order diffraction efficiency from $\eta = 2.8\%$ to 5.4$. However, these simple models failed to match the observed $\eta = 9\%$ efficiency as well and the resolution was not sufficient to determine an accurate representative arrangement of the refractive index profile. The present method to superimpose refractive index profiles (Fig. 4.14(a)(left)) into 1 $\mu m$ period arrays (Fig. 4.14(b)(left)) cannot account for effects such as stress relaxation and refractive index saturation as manifested in the blurring of laser written gratings.
as observed in Fig. 4.14(a)(right) and require development of higher resolution RNF techniques to underpin more precise FDTD and diffraction calculations.

The interfering intensity contrast, $I(x,z)$, developing through the phase grating for the case of Fig. 4.14(b) was re-examined in Fig. 4.16 by overlaying this intensity pattern (Fig. 4(a)) with the refractive index contrast pattern, $n(x,z)$ (hatched area). Here, the axial dependence of the peak refractive change, $n(x = 0.25 \, \mu m, z)$ from RNF data (Fig. 4.14(a)) is plotted (Fig. 4.16(b)) together with the axial index profile from the simplified block representation (Fig. 4.14(b)) as indicated by positive (green hashed) and negative (red hashed) refractive index change zones. Following the axial dependence in $I(x,z)$, the theoretical 1st order diffraction efficiency, $\eta(z)$, was extracted and plotted in Fig. 4.16(c). The intensity contrast and diffraction efficiency here do not increase monotonically along either of the long positive or negative index zones. For example, $\eta(z)$ appears constrained in value, oscillating in a small range of 2.4% to 6% in the long positive index zone of $z = 14$ to $24 \, \mu m$ as both constructive and destructive interference limits the maximum available diffractive efficiency despite the large thickness of a weak contrast volume grating.

For weak phase gratings, continuous diffraction into and out of adjacent zones of index contrast reduces the net phase contrast that can be imparted on the traversing wavelet. A dephasing of the diffracted and zeroth order beams thus prevents the desired $\approx \pi$-phase shift to accumulate as required for maximum diffraction efficiency. Further, when zones of negative and positive index appear in tandem, one can find strong constructive interference effects to arise under certain conditions, for example, in the $z = 0$ to $8 \, \mu m$ range where $\eta$ increases from 0 to 2.6%, or similarly, from $z = 11$ to $16.5 \, \mu m$ where $\eta$ increases from 0.74% to 6%. Such surprising constructive interference from alternating zones of phase delay and advancement suggest a powerful opportunity to strategically arrange the index of refraction zones to coincide with the periodic intensity profiles seen in Fig. 4.16(a) for enhancement of diffraction efficiency.

The near-field intensity patterns within fused silica based grating structure was ex-
Figure 4.16: (a) FDTD calculate intensity pattern for 532 nm light incident from top through a periodic ($\lambda = 1 \mu m$, 50\% duty cycle) array of refractive index elements with hashed area following the index contrast as indicated by the axial profile in (b) showing the approximation (black) to the RNF data (blue) obtained Fig. 4.14(a). (c) The resulting combined 1st order diffraction efficiency, $\eta$, developing along the z axis in (a).
plored in Section 4.1. For \( n_r = 1.46 \), the interfering intensity oscillations within the grating thickness will be limited by the Talbot self-imaging planes, given by Eq. 4.2, at \( z = c = 5.3, 10.6, 15.9, \ldots, \mu \text{m} \). In Fig. 4.16(a), long zones of exclusively positive or negative index contrast, such as from \( z = 11 \) to \( 16.5 \mu \text{m} \), that straddle several cycles of \( c \), constructive and destructive interference are responsible for the oscillating \( \eta \) values observed in Fig. 4.16(c), as anticipated by previous optical modeling in Fig. 4.2. Conversely, there is a growth in the diffraction efficiency observed for \( z = 0 \) to \( 8 \mu \text{m} \) grating thickness. This corresponds to alternating regions of positive and negative refractive index change that coincide with the Talbot half-planes, \( c/2 \).

Further evidence for such cycles of constructive and destructive interference that repeat on Talbot planes manifest in a strong wavelength dependence in \( c \). This was anticipated by the wavelength dependence explored in Section 4.1, Fig. 4.4 which shows the turnover point from classical \( \sim \pi \)-phase modulation to Talbot self-imaging limitations. Here, we explored this wavelength dependence in the context of femtosecond laser written phase gratings with NA = 0.55 focusing. The combined 1\(^{st}\) order diffraction efficiency and the associated intensity interference patterns calculated by FDTD for the block representation of the refractive index profile given in Fig. 4.14(d) are shown in Fig. 4.17(a) and 4.17(b), respectively, for a wide range of probe wavelengths, \( \lambda = 157 \) to 1500 nm. The diffraction efficiency rises dramatically with decreasing wavelength to peak at \( \eta = 79.4\% \) for \( \lambda = 157 \) nm, demonstrating high wavelength sensitivity to the fixed arrangement of positive and negative index zones in the theoretical model.

At short wavelengths, \( \pi \)-phase shift is readily attainable for short grating lengths as anticipated by conventional scalar diffraction theory, thus resulting in strong diffraction which manifests as high contrast interference fringes repeating on \( \Delta z = \lambda/2\Delta n = 3.9 \mu \text{m} \) distances for \( \lambda = 157 \) nm as compared with much longer distances of \( c = 5.3 \mu \text{m} \) between Talbot planes (Eq. 4.2). With increasing wavelength, the classical fringe separation, \( \Delta z = \lambda/2\Delta n \) increases past the rapidly decreasing distance \( c \) (represented by
Figure 4.17: (a) Combined 1\textsuperscript{st} order diffraction efficiency, $\eta$, calculated (blue) and observed (red) for different probe wavelengths through a periodic array of refractive index blocks shown in (b)(left) that represents the laser track of Fig. 4.14(a). The corresponding calculated (FDTD) interference intensity pattern at the indicated wavelengths propagating through a 1 $\mu$m periodic array of refractive index blocks. Intensity scale (right) is normalized for incident intensity $I_0 = 1$ except for the 157 nm case where 0.5$I_0$ was used. Arrows represent the Talbot length of $c$ for the given wavelength.

The arrows in Fig. 4.17(b)) such that the multiple oscillations now follow along closely spaced Talbot planes, constraining the intensity contrast long before $\pi$-phase shift can be accumulated. Wavelengths longer than 1000 nm were above the diffraction limit for the
\( \Lambda = 1 \ \mu \text{m} \) period. The wavelength dependence of 1st order diffraction efficiency from the present single-layer phase grating (exposure conditions in Fig. 4.14(a)) was measured experimentally at wavelengths, \( \lambda = 355, 532, 633 \) and 800 nm, and showed relatively good correspondence in Fig. 4.17(a) with the predicted theoretical trends given the simplifying assumptions of the block representation for FDTD modeling.

For all wavelengths, the experimentally measured values of diffraction efficiency were higher than the theoretically modeled values, as expected by the previous mismatch between theoretical and experimental observed in Fig. 4.14. For visible wavelengths, \( \lambda = 532 \) and 633 nm, the experimentally measured valued were evaluated to be 9.4% and 4.2%, respectively, as compared with theoretically modeled values of 4.2% and 1.16%. At \( \lambda = 355 \) nm, there is a better correspondence of 3.7% experimentally and 2.6% theoretically. At \( \lambda = 800 \) nm, the theoretically expected value was 0.056%, but experimental power measurements were in the noise of the power meter and the experimental expectation could only be capped to a maximum of 0.3% based on visually absent diffraction orders as compared with the observed laser beam through appropriate neutral density filters.

The theoretical modeling in this section provided insight into the mechanisms involved in the assembly of gratings formed by femtosecond laser direct writing. The complexity of the refractive index morphology induced by laser writing led to a significant observation that the serendipitous location of the negative and positive index zones with respect to the Talbot planes of self-imaging could lead to enhancements in the observed diffraction efficiency. Further, it was observed that despite the overall large size of the induced index of refraction change, it was possible to stitch together gratings of relatively small \( \Lambda = 1 \ \mu \text{m} \) period. These observations would be applied to the optimization of gratings written with NA = 0.55 as well as provide groundwork understanding for fabrication of higher resolution gratings with the NA = 1.25 focusing lens to follow in later sections.
4.3.2 Optimized linear volume gratings

In this section, the various laser exposure conditions will be explored to write phase grating arrays with the final objective of fabricating the highest resolution gratings with highest efficiency using the NA = 0.55 aspherical lens.

4.3.2.1 Exposure optimization

The overall morphology of the alternating positive and negative modification zones of the laser tracks was seen in Fig. 1 to vary widely with laser power and scan speed that would dramatically affect the diffraction efficiency when assembled into high resolution volume phase gratings. The two main laser exposure conditions that could be easily controlled through software programming were the applied laser power and the sample scan speed.

In Fig. 4.12, the applied laser power and sample scan speed have a clear effect on the morphology of the fabricated laser track. The size and contrast of the overall fabricated structure decreased from $3 \mu m \times 25 \mu m$ ($P = 173$ mW, $v = 1$ mm/s) to $1 \mu m \times 5 \mu m$ ($P = 50$ mW, $v = 10$ mm/s), which is expected to strongly affect the overall diffractive behaviour of the assembled volume gratings. In Section 4.3.1 the unpredictability of assembled volume gratings efficiency was seen to be complicated by the finely structured variations in the induced refractive index contrast. The trade-off between the strength of the induced refractive index contrast and the size of the modification track cannot be accurately predicted solely on the individual laser tracks in Fig. 4.12. Consequently, it is necessary to assess the assembled volume gratings by measuring the diffraction efficiency experimentally in order to determine the most efficient gratings. To this end, the volume gratings were probed at $\lambda = 532$ nm and the combined $1^{st}$ order diffraction efficiencies were plotted as shown in Fig. 4.18 for varying applied laser powers in (a) and varying sample scan speeds in (b).

In Fig. 4.18(a), the combined $1^{st}$ order diffraction efficiency, $\eta$, is shown for a varying applied power, $P$, between 50 mW and 200 mW, with fixed period of $\Lambda = 1 \mu m$ and
Figure 4.18: Combined 1st order diffraction efficiency, $\eta$, for (a) varying laser power at $v = 1$ mm/s and (b) varying scan speed at $P = 150$ mW for single layers of volume gratings written with $\Lambda = 1$ $\mu$m and $\text{NA} = 0.55$ focusing, probed at $\lambda = 532$ nm. Error bars indicate worst case of diffraction efficiency measurement inaccuracy.

$v = 1$ mm/s. While volume gratings were formed and resolvable visually for $P < 50$ mW, these gratings did not diffract efficiently enough to be definitively measured. The combined 1st order diffraction efficiency, $\eta$, in Fig. 4.18(a) increases monotonically over the range $P = 50$ to 150 mW before leveling off at values of $\sim 9-9.5\%$, possibly owing to saturation of refractive index change and stress relaxation from the close overlapping of the large laser track (Fig. 4.12). The expected trade-off between small structures at low powers versus high index contrast at higher powers, points to the value of the much higher index contrast available for $P > 150$ mW.

With decreasing scan speed, there was an observed stronger morphological change (Fig. 4.12) which translated to an increase in the diffraction efficiency that peaked at $\eta = 9\%$ for $v = 1$ mm/s as seen in Fig 4.18(b). However, similar to fabrication with high laser power, the diffraction efficiency diminished to 4.2% for $v = 0.5$ mm/s. While it is advantageous to write at higher scan speeds to minimized the overall fabrication time of the volume gratings, it was determined that the ideal scan speed was $v \sim 1$ mm/s
for the most efficient diffractive gratings, an exposure condition that is strikingly similar to observed ideal conditions for fabricating waveguides in fused silica [11]. Therefore, the combination of moderate scan speed and relatively high laser power resulted in an optimum available diffraction efficiency at a high resolution limit of 1 \( \mu \text{m} \) period for 0.55 NA focusing.

### 4.3.2.2 Polarization and scan direction optimization

Zones of birefringent refractive index change has been previously observed in femtosecond laser written modification tracks in fused silica glass. The form birefringence has been attributed to periodic nanostructures resulting from interference of the laser field with the induced electron plasma wave that is expected here to generate phase gratings with strongly differing polarization response, as introduced in Section 2.2. The assessment of this birefringence was examined by writing linear volume gratings with polarizations parallel, perpendicular, and circular, in comparison to the writing scan direction as shown in Fig. 4.19.

![Figure 4.19: Example to illustrate experimental setup of parallel, perpendicular, and circular polarization.](image)

Figure 4.19: Example to illustrate experimental setup of parallel, perpendicular, and circular polarization.

Figure 4.20(a-c) shows the morphology of single layer grating structures of 1 \( \mu \text{m} \)
Chapter 4. Optimization of single volume grating layers

period written with identical exposure \( (P = 150 \text{ mW}, \; v = 1 \text{ mm/s}) \) with polarization parallel (Fig. 4.20(a)), perpendicular (Fig. 4.20(b)) or circular (Fig. 4.20(c)) to the laser scan direction. The combined 1\textsuperscript{st} order diffraction efficiency for parallel and circular polarizations were very similar at \( \eta = 6.0 \) and 5.8\%, respectively, in contrast with only \( \eta = 1.4\% \) for perpendicular polarization. This lower efficiency was attributed to higher scattering losses from the less uniform morphology seen in Fig. 4.20(b) in contrast with the other polarizations. The end view of individual laser written tracks appear similar in optical (Fig. 4.20(d)) and phase contrast microscopy (Fig. 4.20(e)) that show a stronger resemblance between writing with parallel and circularly polarization than with the perpendicular case.

Figure 4.20: Top-down view of gratings generated by writing arrays of parallel laser modification tracks of \( \Lambda = 1 \mu \text{m} \) with (a) parallel, (b) perpendicular, and (c) circular incident polarization at \( P = 150 \text{ mW} \) and writing speed, \( v = 1 \text{ mm/s} \), and corresponding (d) optical and (e) phase contrast microscope end views of single isolated tracks.

In other work within the Herman group, femtosecond laser writing has revealed both form and stress birefringence [85, 86]. However, changing the probing laser polarization
did not reveal any observable birefringence. This is possibly due to the fact that effects of the nanogratings are washed out by the larger modification contrast of the written phase gratings. Stress birefringence for closely written laser tracks were determined to be up to $\Delta n \times 10^{-4}$ [85], which is a magnitude less than the index contrast anticipated from the phase gratings.

Based on the diffraction efficiencies, parallel polarization written gratings offered the best performance. However, circular polarization provided a wider flexibility for directionally invariant fabrication of 2D or curved structures, such as required in Fresnel lenses. Aside from the polarization effects, the laser material modification also had a strong scanning directional dependence, coined the quill effect that has been attributed to pulse front tilt in the femtosecond laser beam which aligns with our present $y$-direction scanning, outlined in Section 2.2. We did not have the resources to measure this pulse front tilt, and efforts to compensate for this tilt by varying the compression gratings for the laser system did not appreciably affect the observed quill effect. In Fig. 4.21, the sign convention for $+x$- and $+y$ scanning directions are shown as observed when facing the $xyz$-stages that hold the bulk fused silica sample.

The experimental results in Fig. 4.22 show the combined 1$^{st}$ order diffraction efficiencies measured through phase gratings written in the $\pm x$- and $\pm y$-directions for $P = 50$ to 195 mW exposure. There was a general rise in efficiency with increasing power, with the best efficiencies found for scanning in the $+x$- and $+y$-direction, while the reverse directions generated devices with approximately 50-60% lower efficiency. To fabricate symmetric two dimensional gratings (i.e. $x$ and $y$ orientations), this strong directional dependence was compensated by two approaches:

1) **Dynamically varying the laser power with direction**: In this approach, the laser power is reduced for scanning in the $+x$ and $+y$ directions to match the diffraction efficiency anticipated for the negative directions. With dynamic variation, this method can be applied to the fabrication of curved structures with some success, but requires
Figure 4.21: Example to illustrate experimental setup to show scan direction as viewed facing the sample holder on stages.

intensive programming of the stages and the AOM.

(2) Selecting only positive (\(+x\) and \(+y\)) writing directions: Here, the fabrication is done in only the positive writing directions, which requires either lifting the laser focus out of the bulk material or shutting off the laser on each traversing cycle to write the next line feature.

The first method can result in excess stress due to the unavoidable writing in the vertical direction, which in turn leads to stress fractures or unintended changes to the endpoints of the diffractive optics. The second method is the preferred method in this thesis especially for the moderate focusing condition of \(NA = 0.55\) where a significant amount of observed cracking due to the accumulated stress of assembling dense volume gratings as seen in Fig. 4.23. This method adds additional fabrication time that does not contribute to writing volume structures, but can be greatly minimized by translating the motion stages at a high speed (\(v \sim 50 \text{ mm/s}\)) in the negative writing directions.
This second method has proven to result in volume gratings with diffraction efficiencies similar to method (1), without causing stress-induced edge cracks.

Figure 4.22: Laser directional writing dependency (+x and +y) of the combined 1st order diffraction efficiency, η, at different laser writing powers for a single layer of gratings with Λ = 1 µm and v = 1 mm/s. Gratings probed at λ = 532 nm. Error bars indicate worst case of diffraction efficiency measurement inaccuracy.

Figure 4.23: Multilayered gratings with Λ = 1 µm and v = 1 mm/s showing stress cracks on the edge of the volume gratings.

4.3.2.3 High resolution phase gratings

In the pursuit of high resolution phase gratings with period, Λ < 1 µm, the focusing lens of NA = 0.55 did not seem promising as evidenced by the overall large size of the laser written tracks (Section 4.3.1). However, as previously described in Section 4.3.2, gratings were successfully written with the expected diffraction angles, albeit with somewhat limited diffraction efficiencies. Here, the optimization of the grating period will be explored.

In Fig. 4.24, a power and scan speed range similar to that in Fig. 4.12 show the refractive index modification tracks in an optical microscope top view. Here, multiple regions of index change are observed, similar to heat accumulation effects observed in femtosecond laser written tracks within borosilicate glasses such as BK7 [10] or Eagle
Figure 4.24: Optical microscope top view of refractive index modification tracks formed at various laser powers and writing speeds for $\lambda = 522$ nm and NA = 0.55.

2000 [87], as described in Section 4.2. However, from the cross sectional end views (Fig. 4.12), the heat accumulation effects are indeed absent from laser tracks written inside pure fused silica in contrast with our previous studies in other glasses [11]. The absence of these heat accumulation effects allows for the fabrication of high resolution diffractive optics in fused silica. The overall large size of the individual laser tracks are attributed to only small sized index change regions along the length of the track. But the narrowest regions are outside the optical resolution of microscopy and therefore anticipated to be smaller in the range of $\sim0.5 \mu m$.

Following subsections 4.3.2.1 and 4.3.2.2, the ideal writing conditions was anticipated for strong high resolution phase gratings to be at reasonably high applied laser powers ($P \sim 150$ mW), scan speed of $v = 1$ mm/s, and circular polarization. In Fig. 4.25, the combined 1st order diffraction efficiency, $\eta$, is shown for varying periods, $\Lambda = 1$ to $3 \mu m$. The diffraction efficiency rises gently from $\eta$ of 9.4% for 1 $\mu m$ period phase gratings to 10.2% for 2 $\mu m$ period phase gratings. The diffraction efficiency rises quickly to 13% for
\( \Lambda = 3 \ \mu m \) and is expected to rise for longer period gratings. Unsurprisingly, the overall large laser tracks anticipate that densely assembled gratings result in an overlapping between adjacent tracks, as anticipated by the Lorentzian approximation shown in Fig. 4.15. Grating periods smaller than 1 \( \mu m \) resulted in volume gratings that did not diffract efficiently enough to be measured accurately. Another major limitation of fabricating at \( NA = 0.55 \) is the large stresses caused by densely packing these large laser tracks, as previously shown in Fig. 4.23 and also explored later in Section 5. Hence, 0.55 NA focusing had a sharp resolution cutoff of 1 \( \mu m \) period for writing diffractive volume gratings.

Figure 4.25: Combined 1st order diffraction efficiency, \( \eta \), measured from single layer phase gratings with varying period formed with \( v = 1 \ \text{mm/s} \) for \( P = 175 \ \text{mW} \) and circular polarization. Gratings probed at \( \lambda = 532 \ \text{nm} \). Error bars indicate worst case of diffraction efficiency measurement inaccuracy.

This section outlined the optimization of assembled volume gratings written at \( NA = 0.55 \) with respect to theoretical expectations, as well as laser conditions such as applied laser power, sample scan speed, polarization, scan direction and grating period. The
exposure conditions herein described will be extended to the fabrication of multilayered gratings later in Section 5.
4.4 High 1.25 NA focusing

The femtosecond laser direct writing at $\lambda = 522.5$ nm with focusing at NA = 1.25 was explored with microscope objective as detailed in the 2.2 section. This section will first assess the individually written laser modification tracks on which to establish a model for the refractive index profile and thereby facilitate optical modeling of the grating arrays. The section will finish with the optimization of linear volume gratings with respect to laser exposure conditions at limits of high resolution.

4.4.1 Single modification track morphology and optical modeling

Similar to the trends found for aspherical lens focusing in Section 4.3, the applied power and scan speed greatly affect the morphology of the induced laser modification inside bulk fused silica. The individual laser tracks produced cross-sectional endviews as shown in Fig. 4.26.

As previously observed, the dark regions correspond to negative refractive index change and the light regions to regions of positive index change. The highest applied laser power was $P = 72$ mW, which is significantly lower than the applied power at NA = 0.55 focusing due to much lower lens transmission and also overfilling of the incident laser beam size ($\sim 5$ mm) at the lens entrance window ($\sim 4$ mm). However, this 3-fold stronger focusing through a 1.25 NA oil immersion lens, as compared to NA = 0.55, offering the generation of smaller and more strongly contrasting modification tracks as seen in Fig. 4.26 compared with Fig. 4.12 for NA = 0.55. The tracks reveal the general trend of increasing refractive index contrast, increasing size, and increasing number of positive and negative zones of index change as exposure increased, similar to the trends of Fig. 4.12 for NA = 0.55 focusing, but with much smaller physical sizes. At the highest exposure of $P = 72$ mW and $v = 0.1$ mm/s, a large $\sim 12 \mu$m diameter symmetric structure
Figure 4.26: Backlit optical microscope cross-sectional end view of refractive index modification tracks formed at various laser powers and writing speeds for $\lambda = 522$ nm and $\text{NA} = 1.25$. Writing laser incident from top. Light regions indicate positive index change and dark regions indicate negative index change.

having strong positive index contrast is observed that suggested a micro-explosion inside the bulk material. With higher scan speeds ($v = 1$ to 10 mm/s), the symmetrical bright structure exists in conjunction with an elongated structure that is typically observed for femtosecond laser writing in fused silica.

For moderate powers, $P = 54$ and 36 mW, elongated structures with multiple cycles of positive and negative refractive index change regions are noted to extend over lengths...
of \( d = 10-15 \ \mu m \). For low power, \( P = 18 \) mW, only one positive and one negative zone of refractive index change was observed. A small central zone of positive index contrast that approaches the expected laser spot size of \( \sim 300 \) nm is found against a much larger \( \sim 6 \ \mu m \) zone of negative refractive index contrast.

For the purposes of studying the individual laser tracks for fabricating high resolution gratings, a moderate applied power of 36 mW and 1 mm/s scan speed was chosen for further analysis. The RNF assessment for this modification track is shown in Fig. 4.27 alongside the corresponding optical microscope end-view. For this laser track, the total laser modification zone for both the positive and negative refractive index change was \( \sim 2 \times 11 \ \mu m^2 \). Figure 4.27(b) shows the raw RNF measurement that revealed a lot of extraneous striations, possibly from light refracting out of the modification centre, as well as an overall sloping gradient of index contrast from the top to bottom due to an inherent measurement artifact. This image was digitally flattened with the use of MATLAB to unravel the \( \Delta n \) in Fig. 4.27(c). The RNF measurement implies a peak refractive change of \( \Delta n = +0.024 \) with no negative index change. Based on previous observations with waveguiding measurements [88] and also the optical microscope measurements, a negative index change is expected at the top of the laser track as well as several refractive index variations along the track length. However, the narrow width together with the smaller variations within the laser track lie below the optical resolution of the RNF microscope \( \sim 0.5 \ \mu m \) and therefore, the detailed refractive index profiles could not be determined. The coarse estimate of peak refractive index change of \( \Delta n = 0.025 \) provided a useful guide for optical modeling of the diffraction efficiency to match with experimental measurements.

A cross-sectional averaging over the vertical thickness of the RNF images in Fig. 4.27(c) is shown in Fig. 4.28(a) in red. A good correspondence to a 0.7 \( \mu m \) wide (FWHM) Lorentzian fit shown in black. A simple linear superposition of this refractive index profile for a 1 \( \mu m \) periodic array of individual tracks (blue lines in Fig. 4.28) would then lead
Figure 4.27: (a) Optical microscope cross-sectional end view of refractive index modification tracks formed at $P = 36$ mW and $v = 1$ mm/s, (b) corresponding raw RNF measurement of the same laser track and (c) Digitally flattened RNF measurement with refractive index scale along the right hand side.

to a much lower refractive index contrast ($\Delta n_{AC} = 0.0058$) for such phase gratings along with a $\Delta n_{DC} = 0.01$ refractive index background increase. In Fig. 4.28(b), the same RNF measurement is shown in red again, but with a 25% narrower Lorentzian fit that results in a $\Delta n_{AC}$ of 0.007 and $\Delta n_{DC} = +0.0036$. The increase in the $\Delta n_{AC}$ is clearly very sensitive to the width of the laser track and consequently, inaccuracies in the RNF measurements will directly reduce the corresponding inaccuracy in the prediction of the real refractive index contrast.

Figure 4.29 shows a comparison between the optical microscope cross-sectional end-view of laser tracks written with NA = 0.55 in (a) and 1.25 in (b) for a measured applied power on target of $P \sim 50$ mW. This comparison clearly reveals much larger sized structures for NA = 1.25, which is a result of the 3-fold tighter focusing with NA = 1.25 when compared to NA = 0.55. With this high NA, the same pulse energy is seen to deposit more energy into the fused silica with the more tightly focused beam, generating multiple zones of positive and negative refractive index zones, which a clear sign of self-focusing and plasma defocusing. A consideration of the NA = 1.25 track written at $P = 18$ mW in Fig. 4.29(c) shows a laser track with dimensions similar to the cross-section found for NA = 0.55 at $P = 50$ mW (Fig. 4.29(a)), with one clear positive and negative index zone. However, the refractive index zones are sharper and shorter,
Figure 4.28: (a) Cross-sectional refractive index profile averaged over axial length of laser modification track (red) from RNF measurement (Fig. 4.27(c)) and a Lorentzian representation (black). A periodic array of index profiles (blue) of $\Lambda = 1 \, \mu m$ period and their summation predicting the refractive index profile of the buried phase grating (heavy black). (b) A 25% smaller Lorentzian approximation (black) with the $\Lambda = 1 \, \mu m$ period periodic array in blue and their summation predicting the refractive index profile of the buried phase grating (heavy black).

which can be attributed to the much smaller depth of field at $NA = 1.25 \, (\sim 0.67 \, \mu m)$ versus $NA = 0.55 \, (\sim 3 \, \mu m)$.

The morphology shown in Fig. 4.27 reveals fundamental resolution limits in the RNF measurements that make the determination of the refractive index profiles difficult to measure absolutely. The focus spot size with $NA = 1.25$ is supposed to 3-fold smaller than that at $NA = 0.55$, which would suggest a correspondingly smaller track width as well, which is not evident based on the comparisons of the Lorentzian FWHM fits ($0.7$ for $NA = 1.25$ versus $0.78$ for $NA = 0.55$). This suggests that higher resolution RNF measurements would be required for correct prediction of the laser track morphology. Without sufficient resolution to reveal the expected index variations along the laser focal axis, an accurate model individual laser tracks for the prediction of the diffracting behaviour could not be explored as it was in the low $NA = 0.55$ focusing case in Section 4.3.1. However, the
Figure 4.29: A comparison between optical microscope cross-sectional end-view of laser tracks written with (a) $NA = 0.55$ and (b) 1.25 focusing lens for a measured applied power on target of $P \sim 50$ mW and (c) with $NA = 1.25$ focusing at $P = 18$ mW for $v = 1$ mm/s.

peak and average RNF measurements provided a useful baseline for optical modeling of diffraction.

For the purposes of optical modeling, it was observed that the refractive index variations along the vertical length of the laser focal axis are much smaller than the Talbot self-imaging distance, $c = 5.3 \, \mu m$ for $\Lambda = 1 \, \mu m$ period. Consequently, accounting for these fine variations were not essential for the modeling, as had been previously observed in Section 4.3.1 where the refractive index variations were significant factors at lengths comparable with $c$. Figure 4.30(a) shows the same optical microscope in Fig. 4.27 for $P = 36$ mW and $v = 1$ mm/s along side the calculated FDTD intensity pattern in (b) and (c).

In Fig. 4.30(b), the interference intensity pattern is shown for a 7 $\mu m$ thick grating of $\Delta n = +0.025$ with $\Lambda = 1 \, \mu m$ period with 50% duty cycle, resulting in a peak intensity of $1.708I_0$. When projected into the farfield, the combined 1st order diffraction efficiency is predicted to be 4.26%, which is lower than the experimentally measured $\eta = 5.2\%$. When a thin 3 $\mu m$ grating layer with a $\Delta n = -0.005$ is introduced above the positive refractive index change, the peak intensity increases to $1.796I_0$ and results in a $\eta$ of 6.22%, which is
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Figure 4.30: (a) Optical microscope cross-sectional end view of refractive index modification tracks formed at $P = 36$ mW and $v = 1$ mm/s, (b) FDTD calculated intensity pattern for 532 nm light incident from bottom through a periodic ($\Lambda = 1$ µm, 50% duty cycle) array of positive refractive index change elements and (c) the same grating array with an additional thin layer of negative refractive index change elements. The hashed area represents the zone of index change with higher (light) and lower (dark) refractive index contrasts. The color bar on the right indicates the intensity for the FDTD calculations with the incident intensity of $I_0 = 1$ probed at wavelength $\lambda = 532$ nm from the bottom. The diffraction efficiency, $\eta$ is shown at the bottom.

higher than the experimentally measured value. This indicates that an anticipated fine structured refractive index profile can significantly alter the diffraction efficiency. However, many variations of these negative index change zones can be fashioned to match the measured diffractive efficiency with a single fabricated grating structure and a definitive determination either by RNF or optical modeling was not possible. The diffraction efficiency from the optical modeling of multilayered phase gratings was compared to experimentally measured values for an estimation of the effective refractive index contrast,
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4.4.2 Optimized linear volume gratings

Although the refractive index profiles could not be precisely assessed for the NA = 1.25 focused laser tracks, individually or assembled, a systematic exploration of the diffraction efficiency was possible. Based on RNF and optical microscopy, the laser modification at NA = 1.25 was found to be much smaller than those fabricated with NA = 0.55 (2 μm × 10 μm versus 3 μm × 25 μm). Consequently, the diffraction efficiencies measured were also expected to be lower in value. In this section, the volume gratings will first be assessed based on variations in applied laser power and sample scan speed. This will be followed by an exploration of laser polarization and scan direction dependence and optimization of the phase gratings. Finally, the fabrication of high resolution phase gratings will be examined.

4.4.2.1 Exposure optimization

As in Section 4.3.2.1, a range of applied laser power and sample scan speed was studied to assess the effect of the laser exposure conditions on the diffraction efficiency of phase gratings fabricated with NA = 1.25 focusing. In Fig. 4.26, the morphology of the individual laser tracks were observed to have both positive and negative refractive index change zones. Assembly of these individual tracks into phase gratings confirmed that the formation into coherent volume gratings with appropriate diffraction angles for a period of Λ = 1 μm.

In Fig. 4.31(a), 1 μm volume gratings were fabricated at a fixed scan speed of \( v = 1 \text{ mm/s} \) for the power range of \( P = 8.75 \) to 50 mW. There is a steady increase in the combined 1st order diffraction efficiency from \( \eta = 1.8\% \) at \( P = 8.75 \text{ mW} \) to \( \eta = 5.2\% \) at \( P = 35 \text{ mW} \) before the efficiency plateaus to \( \eta = 5.17\% \) at \( P = 50 \text{ mW} \). Volume gratings were explored at higher powers (\( P \sim 70 \text{ mW} \)), but did not result in efficiently
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diffracting structures. This observation is expected when assessing the morphology of the laser tracks in Fig. 4.26, which reveals structures too large (∼12 µm) for the assembly into high resolution volume gratings of Λ = 1 µm period.

Figure 4.31: Combined 1\textsuperscript{st} order diffraction efficiency, η, for (a) varying laser power at \(v = 1 \text{ mm/s}\) and (b) varying scan speed at \(P = 35 \text{ mW}\) for single layers of volume gratings written with \(Λ = 1 \mu\text{m}\) and NA = 0.55. Error bars indicate worst case of diffraction efficiency measurement inaccuracy.

For the fabrication of volume gratings, a moderate power of \(P = 35 \text{ mW}\) was selected as higher laser powers did not correspond to much higher measured diffraction efficiencies (Fig. 4.31(a)). In Fig. 4.31(b), 1 \(\mu\text{m}\) volume gratings were fabricated at \(P = 35 \text{ mW}\) for \(v = 0.1\) to 5 mm/s. For the low scan speed of \(v = 0.1 \text{ mm/s}\), the diffraction efficiency was too low for accurate measurement. However, at \(v = 0.5 \text{ mm/s}\), a combined 1\textsuperscript{st} order diffraction efficiency, η, of 5.3% was observed. At \(v = 1 \text{ mm/s}\), the efficiency lowers slightly to η = 5.2%. At higher scan speeds of \(v = 2\) and 5 mm/s, the combined 1\textsuperscript{st} order diffraction efficiency decreased rapidly to η = 2.1%. Previous waveguiding work confirmed that the ideal scan speed for good guiding laser tracks at similar laser conditions were found for \(v = 0.5 \text{ mm/s}\) [88]. However, for the purposes of assembling volume gratings, this low scan speed would be equivalent to a four-fold increase in the fabrication time, compared with writing at \(v = 1 \text{ mm/s}\). Therefore, for the purposes of this thesis, a moderate power of \(P \sim 35 \text{ mW}\) and scan speed of \(v = 1 \text{ mm/s}\) was chosen.
4.4.2.2 Polarization and scan direction optimization

Following similarly with the results for NA = 0.55 (Section 4.3.2.2), parallel and circular polarization for NA = 1.25 focusing was found to result in volume gratings of similarly high diffraction efficiency compared with gratings formed with perpendicular polarization. Volume gratings were written at $P \sim 35\,\text{mW}$ and scan speed of $v = 1\,\text{mm/s}$ for parallel, circular, and perpendicular polarization. The combined 1st order diffraction efficiency for parallel and circular polarizations were very similar at $\eta = 5.4\%$ and $5.2\%$ respectively. With perpendicular polarization, a slightly lower $\eta$ of $2.35\%$ was measured.

In Fig. 4.32, the combined 1st order diffraction efficiencies measured through phase gratings written in the $\pm x$- and $\pm y$-directions is shown for $P = 8.75$ to $50\,\text{mW}$ exposure with circular polarization. For all applied laser powers, it was found that positive ($+x$ and $+y$) scan directions yielded an average of $22.5\%$ higher combined 1st order diffraction efficiencies when compared to negative ($-x$ and $-y$) scan directions. As with NA = 0.55 focusing in Section 4.3.2.2, the volume gratings at NA = 1.25 focusing were preferentially written by using only positive ($+x$ and $+y$) writing directions.

4.4.2.3 High resolution phase gratings

Based on the estimation of the $0.7\,\mu\text{m}$ wide (FWHM) Lorentzian fit of the laser modification track in Fig. 4.28 at the resolution limits of the RNF, submicron grating periods were anticipated with NA = 1.25 focusing. As such, the diffraction efficiency of such gratings were tested for decreasing period.

In Fig. 4.33, the combined 1st order diffraction efficiencies as measured for grating periods $\Lambda = 0.6$ to $4\,\mu\text{m}$ are presented. Unlike the limit of $\Lambda > 1\,\mu\text{m}$ period for volume gratings written with NA = 0.55, the gratings written with NA = 1.25 resulted in measurable diffraction to $\Lambda = 0.6$ and $0.75\,\mu\text{m}$. However, the prohibitively low diffraction
Figure 4.32: Laser directional writing dependency of the combined 1st order diffraction efficiency, $\eta$, at different laser writing powers for a single layer of gratings with $\Lambda = 1 \mu m$ and $v = 1 \text{ mm/s}$. Error bars indicate worst case of diffraction efficiency measurement inaccuracy.

Efficiencies of $\eta = 0.72\%$ and $0.94\%$, respectively, were unattractive for practical applications. A broader examination into the scaling of applied laser power and scan speed could improve diffraction efficiency at these small periodicities.

For $\Lambda = 1 \mu m$ a diffraction efficiency of $\eta = 5.2\%$ was measured for $P = 35 \text{ mW}$ exposure, which is smaller than the $9.4\%$ measured for gratings written with $\text{NA} = 0.55$ focusing for the same grating period. The combined 1st order diffraction efficiency increased to $\eta = 6.82\%$ for $\Lambda = 1.5 \mu m$, but decreases to $\eta = 6.47\%$ for $\Lambda = 2 \mu m$ and further to $\eta = 2.45\%$ for $\Lambda = 4 \mu m$. The peak of the diffraction efficiency at $\Lambda = 1.5 \mu m$ implies that this is the location of 50% duty cycle. This corresponds to an anticipated phase element width of $0.75 \mu m$, which is very close to the $0.7 \mu m$ wide (FWHM) Lorentzian fit anticipated in Fig. 4.28. A deeper examination into the relationship between diffraction efficiency and grating period could prove to pinpoint the exact element width fabricated with this focusing length, in the absence of higher resolution microscopy tools.

The previous sections have established the laser exposure conditions to provide a
Figure 4.33: Combined 1st order diffraction efficiency, $\eta$, for single layers of phase gratings with varying period with $v = 1 \text{ mm/s}$ for $P = 35 \text{ mW}$. Black trendline is a guide to the eye. Error bars indicate worst case of diffraction efficiency measurement inaccuracy.

A moderate value of diffraction efficiency at the limit of resolution available from $\text{NA} = 0.55$ and $1.25$ focusing. The conditions were carried forward to the examination of multilevel diffraction gratings based on exposure of single layer gratings. The vertical thickness and lateral widths of the laser modification track is critical for the precise manipulation of multilayered phase gratings aligned on the Talbot self-imaging planes.
Chapter 5
Multilayered volume gratings
arrayed on Talbot planes

This chapter will describe the optical modeling of multilayered volume gratings for coherent light building, followed by the femtosecond laser fabrication of these multilayered gratings.

In Section 4.3.1, the diffraction efficiency for the optically modeling based on 0.55 NA laser track morphology was observed to be enhanced when the positive and negative index contrasts modulated on distances matching the half-Talbot plane, $c/2$. For NA = 0.55 focusing, the $\sim 25 \mu m$ vertically elongated laser tracks consisting of multiple cycles of positive and negative index change zones. However, with NA = 1.25 focusing, a vertical thickness of $\sim 10 \mu m$ was observed for moderate applied laser power, $P = 35$ mW, and scan speed of $v = 1$ mm/s in Section 4.3. The smaller modification zones as well as the avoidance of spherical aberrations with the oil immersion 1.25 NA lens, were particularly suited for the exploration of multilayer grating alignment on Talbot planes of self-imaging given by $c = 5.3 \mu m$ for $\Delta n = 0.025$ and incident wavelength, $\lambda = 532$ nm. The following sections detail the coherent light building with multilayered volume gratings in relation to Talbot planes.
5.1 Optical modelling - coherent light building

Due to the limited resolution of the RNF measurements for the case NA = 1.25 focused laser tracks, an effective index change region equivalent to the positive refractive index change thickness of 7 µm was first considered to represent the index profile such as was presented in Fig 4.27. With the inferred grating thickness of $d = 7 \mu m$, an estimated $\Delta n = +0.025$ zone was stacked vertically, beginning with spacing of $l = 7 \mu m = 1.3c$ offsets to represent ‘continuous’ phase gratings shown in Fig. 5.1 by the hatched zones for one layer (Fig. 5.1(a)), two layers (Fig. 5.1(b)) and three layers (Fig. 5.1(c)) of phase gratings. The FDTD modeled interference intensity pattern resulting from these volume gratings for incident wavelength of $\lambda = 532$ nm are shown for an incident intensity $I_0 = 1$ propagating upward from the bottom ($z = 0$).

![Figure 5.1](image)

Figure 5.1: FDTD simulation of intensity pattern generated through $N = (a) 1$, (b) 2, and (c) 3 layers of gratings with $d = 7 \mu m$ thickness and layer-to-layer separation of $l = 1.3c$, where $c = 5.3 \mu m$ to form ‘continuous’ gratings. The gratings have periodicity, $\Lambda = 1 \mu m$, base refractive index, $n_r = 1.46$, refractive index contrast, $\Delta n = 0.025$, and were probed with incident wavelength, $\lambda = 532$ nm.
In Fig. 5.1(a-c), the intensity interference patterns evolving axially are found to oscillate periodically on the Talbot plane spacing, \( c = 5.3 \, \mu m \) both inside and beyond the grating zones. The intensity contrast for the continuous grating peaked at a maximum contrast of \( 1.6I_0 \) regardless of the grating length. The diffraction efficiency depended precisely on where the grating ended, yielding high contrast interference and high diffraction efficiency as in Fig. 5.1(a) when the grating ended approximately at a peak intensity fringe (i.e. \( z = 1.5c = 7.95 \, \mu m \)) or yielded low contrast and low diffraction efficiency as in Fig. 5.1(b) when the grating ended at a position of low intensity contrast (\( z = 2.6c = 14 \, \mu m \)). The corresponding diffraction efficiency varied from the peak of \( \eta = 4.4\% \) that is approximately represented in Fig. 5.1(a) to \( \eta \sim 0\% \) for the 3-layer thick grating in Fig. 5.1(c). This result demonstrates the low diffraction efficiency expected from weak uniform phase gratings as first introduced in Section 4.1.

A coherence similar to that shown in Fig. 4.3.1 for coherent combination of \( 1^{st} \) order diffraction beams with the varying refractive index contrast is proposed here for multilayered gratings constructed by segmenting the thick volume grating into thin phase grating layers. Here, the same phase elements are separated with centre-to-centre spacing of \( c \), or multiples thereof, to match the interference intensity patterns in Fig. 5.1. First, the calculated diffraction efficiency for continuous phase gratings of increasing thickness is shown in Fig. 5.2(solid black), as previously introduced in Section 4.1, but restated in terms of number of layers, \( N \). The diffraction efficiency oscillates periodically with increasing grating length corresponding to the expected Talbot plane separation, \( l = c = 5.3 \, \mu m \), and is limited to a maximum of \( \eta = 4.4\% \). The peaks and troughs are, therefore, predictable by half-integer and integer multiples of \( c \) respectively, as represented in Fig. 5.2 by the dotted and solid vertical lines, respectively.

Breaking the phase gratings into two and three layer phase gratings is shown in Fig. 5.3(a). The intensity contrast builds to \( 2.2I_0 \) at two layers where the second layer is located at \( z = 10.6 \, \mu m \), in comparison with the case of weak intensity contrast (\( 1.6I_0 \))
Figure 5.2: Calculated combined 1\textsuperscript{st} order diffraction efficiency, $\eta$, for a continuous grating layer in terms of number of layers, $N$, where a single layer corresponds to $d = 7 \, \mu m$. The gratings have periodicity, $\Lambda = 1 \, \mu m$, base refractive index, $n_r = 1.46$, refractive index contrast, $\Delta n = 0.025$, and were probed with incident wavelength, $\lambda = 532$ nm. Vertical lines show half-integer and integer multiples of $c$.

found for the continuous grating layers in Fig. 5.1(b) of identical refractive index modified thickness. Further, the diffraction efficiency can be enhanced or diminished based on the relative spacing between the two layers. In Fig. 5.4, the calculated combined 1\textsuperscript{st} order diffraction efficiency, $\eta$, is shown for varying layer-to-layer separation by the triangles, along with a sinusoidal fit to the data.

In previous work, Hargrove et al. [47] had predicted in equation 2.1 a periodic enhancement and diminishment of the diffraction efficiency based on the layer-to-layer separation of strongly contrasting phase gratings. Their result for $c$ (Equation 2.1) is here identified as an approximation of the Talbot plane separation we introduced in Equation 4.2 that assumes the grating period is much larger than the incident wavelength ($\Lambda \gg \lambda$). This coherent enhancement of diffraction efficiency when satisfying the Talbot separation condition was confirmed by the far-field diffraction efficiencies calculated in Fig. 5.4. The combined 1\textsuperscript{st} order diffraction efficiency generated for increasing separation, $l$, between the grating layers yielded the sinusoidal-like modulation from 0% to 13.6% efficiency, with
the maxima aligned with grating separations matched precisely to the Talbot planes at multiples of $c = 5.3 \, \mu m$, $2c = 10.6 \, \mu m$, and $3c = 15.9 \, \mu m$. Correspondingly, the first order beams from each grating layer are interfering destructively for half-integer layer separations $3c/2$, $5c/2$, ..., attesting to the powerful coherent Talbot alignment effects present in multi-layered gratings.

Figure 5.3: FDTD simulation of intensity pattern generated through $N =$ (a) 2, (b) 3 (c) 8 and (d) 15 layers of gratings with $d = 7 \, \mu m$ thickness and layer-to-layer separation of $l = 2c = 10.6 \, \mu m$. The gratings have periodicity, $\Lambda = 1 \, \mu m$, base refractive index, $n_r = 1.46$, refractive index contrast, $\Delta n = 0.025$, $d = 7 \, \mu m$, and were probed with incident wavelength, $\lambda = 532$ nm. The $3I_0$ and $3.6I_0$ intensity scales apply to (a)(b) and (c)(d), respectively.

These benefits of diffraction efficiency enhancement can be further extended to multiple layers of gratings. In Fig. 5.3(b), three ($N = 3$) layer gratings are separated by the same $l = 2c = 10.6 \, \mu m$ and found to build to $3.0I_0$ intensity contrast at three layers ($l = z = 21.2 \, \mu m$) with a correspondingly higher $\eta = 16.2\%$ in contrast with the two layer case of $1.6I_0$ and $\eta = 16.2\%$ as represented in Fig. 5.3(b). Extending to $N = 8$ layers as shown in Fig. 5.3(c), the diffraction efficiency rises to a peak of $\eta = 95\%$ and manifests in high intensity contrast that peaks at a maximum of $3.6I_0$ at $z = 16c = 84.8$
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Figure 5.4: FDTD calculated combined 1\textsuperscript{st} order diffraction efficiency, $\eta$, (triangles) for a two grating layers with respect to varying layer-to-layer separation, $l$, with sinusoidal fit. Vertical lines show half-integer and integer multiples of $c$. The gratings have periodicity, $\Lambda = 1 \mu m$, base refractive index, $n_r = 1.46$, refractive index contrast, $\Delta n = 0.025$, $d = 7 \mu m$, and were probed with incident wavelength, $\lambda = 532$ nm.

$\mu m$. This diffraction efficiency enhancement is graphed in Figure 5.5 for multiple grating layers with ideal layer-to-layer separation, $l = 2c = 10.6 \mu m$.

By extending further the phase grating in Fig. 5.3 to $N = 15$ layers, there is a reversal of this building intensity contrast together with diminishing first order diffraction efficiency to zero at 15 layers as seen in Fig. 5.5. Therefore, the intensity contrast oscillates with increasing Talbot layers, but are enveloped by the trend such as seen in Fig. 5.2 for continuous phase gratings that yield oscillating maxima ($8$ layers = $16c$) and minima ($15$ layers = $30c$). The finer scaled periodic intensity modulations (i.e. $\sim 1 \mu m$) observed in Fig. 5.3(c) and (d) also arise from weak 2nd order diffracted beams present only inside the glass substrate due to total internal reflection.
5.2 Laser fabrication of multilayered volume gratings

The direct-writing techniques afforded by femtosecond lasers permit formation of very small refractive index structures that can be arbitrarily spaced on optical wavelength dimensions inside bulk transparent glasses. Such laser writing presents a unique opportunity here to systematically study the Talbot effects and the predicted enhancement of diffraction efficiency for multilayered diffractive structures.

In Fig. 5.6, the combined 1st order diffraction efficiency, $\eta$, was measured for 2 grating layers written with $NA = 0.55$ and varying layer-to-layer separations, $l$ for periodicity, $\Lambda = 1 \, \mu m$, and different applied laser power ($P$). For high powers such as $P = 150$ and $200$ mW, there were diminishing gains to the double grating layers when compared to single grating layers due to the anticipated overlapping of the elongated laser modification. For example, for the case of $P = 150$ mW, a peak efficiency of 7.4% was measured at $l =$
15 µm as opposed to η = 9% that was measured for a single layer. Extending to longer layer-to-layer separations did not result in a higher diffraction efficiency, possibly due to the varying morphology of laser tracks with deeper focusing that results for spherical aberration with the NA = 0.55 lens.

Figure 5.6: Combined 1st order diffraction efficiency, η, for 2 grating layers with varying layer-to-layer separations, l, for periodicity, Λ = 1 µm, and different applied laser power (P) for NA = 0.55 focusing and scan speed, v = 1 mm/s. Error bars indicate worst case of diffraction efficiency measurement inaccuracy.

Stitching of layers on Talbot planes writing were mostly inconclusive with NA 0.55 focusing, possibly owing to the much stronger saturation effects of index contrast in the assembly of much larger laser tracks on 1 µm periodicity. Further, the non-uniform refractive index modulation over the large grating thickness due to variances in the deposited energy as well as spherical aberrations made the stitching of these elongated structures challenging to accurately assess.

An assessment of the gratings fabricated with the low power of \( P = 50 \text{ mW} \), however, revealed an interesting trend. The morphology of the individual laser tracks in Fig. 4.12 revealed a small vertical thickness of \( d \sim 7 \mu\text{m} \). The gratings assembled at this applied power showed a measured increase of 1.8-fold in diffraction efficiency for 5, 10, 15 and 20 µm in Fig. 5.6. This tracks well with the anticipated enhancement of diffraction
efficiency anticipated by alignment on the Talbot planes. For this reason, multilayered
gratings formed with NA = 1.25 focusing promise to better demonstrate the multilayered
enhancements due to the shorter grating thickness and much higher diffraction efficiencies
found for moderately low applied laser powers such as \( P = 50 \text{ mW} \).

To approximate the model of continuous phase grating in fused silica, individual
grating layers were stitched together vertically by laser writing with NA 1.25 focusing at
\( P = 35 \text{ mW} \) and \( v = 1 \text{ mm/s} \) with a layer-to-layer separation of \( l = 1.3c \) to represent
the cases in Fig. 5.1. As previously observed in Section 4.4, the diffraction efficiencies
measured for powers higher than 35 mW did not result in appreciable diffraction gain.
Thus, a moderate power (\( P = 35 \text{ mW} \)) was selected for the additional benefit of compact
vertical stacking due to the vertical thickness of the individual laser tracks as observed
in Fig. 4.26.

The measured combined 1st order diffraction efficiency, \( \eta \), for \( N = 1 \) to 4 layers of
‘continuous’ gratings is shown in Fig. 5.7(triangles) to be weak (\( \eta = 5.1 \) to 5.4\%) despite
increasing thickness, as expected theoretically from a continuous volume grating (Fig.
5.2(solid line)). The data failed to follow the predicted oscillation due to the imprecise
matching of the non-uniform refractive index change (Fig. 4.14) relative to the uniform
phase grating model used in Fig. 5.3. Further, the diffraction efficiency is very sensitive
to small errors in the grating layer position or the assessment of the refractive index
profile of the laser tracks.

A more comprehensive approach to study the multilayered gratings is to systemat-
ically vary the separation of two identical phase grating layers. Figure 5.8(blue) shows
the diffraction efficiencies measured for double layer phase gratings with various layer-
to-layer separations over the range of \( l = 7 \) to 29 \( \mu \text{m} \). The experimental data follow the
general trend of the modeling results with periodic cycles that peak at separations of \( l
= 11, 16, 21, \) and 27 \( \mu \text{m} \), which align closely with the expected Talbot plane multiples
at \( 2c = 10.6, 3c = 15.9, 4c = 21.2, \) and \( 5c = 26.5 \mu \text{m} \) separations.
Figure 5.7: Calculated (solid line) and measured (triangles) efficiency of both first order diffracted beams ($\lambda = 532$ nm, $\Lambda = 1$ $\mu$m, $\Delta n = 0.025$) for a ‘continuous’ grating of 7, 14, 21 and 28 $\mu$m thickness representing $N = 1, 2, 3,$ and 4 grating layers respectively. The experimentally measured volume gratings were written with $P = 35$ mW, $v = 1$ mm/s, NA 1.25 focusing, and circular polarization.

The matching of the simulated diffraction efficiency (red triangles) to experimental values as seen in Fig. 5.8 was found for an index contrast of $\Delta n \sim 0.025$ across an inferred grating thickness of 7 $\mu$m. This strong refractive index contrast exceeds the $\Delta n = 0.015$ value reported for waveguides written with similar exposure conditions [88] and may suggest that the positive index contrast zone is longer than the 7 $\mu$m inferred here or that other factors such as the formation of weak negative index zones between the laser tracks are also contributing to the enhancement of the diffraction efficiency. For example, the negative and positive refractive index zones seen in Fig. 4.26 are fortuitously aligned to near the half-Talbot plane separation distance, $c/2 = 2.65$ $\mu$m, and are expected to contribute a strong in-phase enhancement similar to the $c$ alignment between zones of positive index change.

For the same laser writing conditions as used in Fig. 5.8, multi-layered phase gratings were written at the optimal separation of two Talbot planes ($l = 2c = 10.6$ $\mu$m), yielding the measured combined 1$^{st}$ order diffraction efficiencies plotted in Fig. 5.9(blue). Figure
Figure 5.8: Calculated (red triangle) and measured (blue square) efficiency of both first order diffracted beams ($\lambda = 532$ nm, $\Lambda = 1$ $\mu$m, $\Delta n = 0.025$) for two layers of 7 $\mu$m thick gratings with increasing layer-to-layer separation, $l$.

5.10 shows the enhanced 1\textsuperscript{st} order diffraction generated by the 10 layered grating over the single layer grating. The efficiency rises strongly from 5.2\% of the single layer to a peak of 35\% at 8 layers (Fig. 5.9(blue)), which falls short of the 95\% value expected theoretically. Beyond 8 layers, the diffraction efficiency falls off only gently to 26\% at 15 layers, where a null was expected theoretically. Several factors may underlie a growing discrepancy between experimental and theoretical data for high number of grating layers (>3). The multiple negative and positive zones of refractive index change as observed in the single track of Fig. 4.26 suggest more complex diffraction phenomena underlie the optical propagation than accounted by the uniform rectangular contrast phase grating model applied to the FDTD analysis in Fig. 5.3. This simplified representation of the single layer phase grating was found to accurately illustrate the coherent layering effect on Talbot planes for the two-layer phase grating data presented in Fig. 5.8, but may
become a factor for the efficiency discrepancy in Fig. 5.9(b) at four or more grating layers.

Alternatively, we have observed the overall stress generated in glass to increase dramatically as large volumes of laser tracks were woven into small volumes, possibly limiting the net index contrast obtainable as the overall glass structure saturates to a maximum obtainable refractive index contrast. Thus, the intermediate layers in many layered grating structures may contribute lower overall refractive index contrast and grating efficiency than that available from the top and bottom layers. To bypass this fundamental limit of forming strongly contrasting grating structures, a less dense arrangement with vertical layer-to-layer separations of $l = 3c$ or $4c$ may be considered, but could not be tested here due to the limited working distance of the present objective lens.

An assessment of the fabricated grating optical losses yielded a 1.5% Fresnel reflection loss from the combination of two air-glass boundaries together with single-layer grating scattering losses of 1% attributed to submicron graininess in the laser formed grating lines. However, such losses could only account for a quarter of the efficiency discrepancy in Fig. 5.9. Alternatively, the stitching accuracy of the grating layers both laterally and vertically, with motion stage positioning precision of $\pm100$ nm, may cause blazing effects as well as randomization of the diffraction efficiency that may reduce the peak of each 1st order diffraction efficiency by no more than 20% in calculations, and could also not fully explain the observed trends in Fig. 5.9. For example, in the extremely unlikely case of 100 nm misalignment of adjacent grating layers, FDTD simulation shows the diffraction efficiency to only fall from 95% to 77.2% over 8 layers of volume gratings. The presence of both positive and negative refractive index changes (Fig. 4.26) together with a complex combination of the above variances possibly underpins this discrepancy in diffraction efficiency. An accurate profiling of the refractive index contrast on a high resolution scale of $<200$ nm is required to better assess and fully harness laser direct writing for generating highly efficient multi-layered phase gratings.
Figure 5.9: Calculated (red triangle) and measured (blue square) efficiency of both first order diffracted beams ($\lambda = 532$ nm, $\Lambda = 1$ $\mu$m, $\Delta n = 0.025$) for increasing number of layers, with ideal layer-to-layer separation, $2c$.

Figure 5.10: Digital image of farfield diffraction ($0^{th}$ and $\pm 1^{st}$ orders) from a single grating layer and 10 grating layers at an ideal $2c$ layer-to-layer separation.
The coherent enhancement of multilayered gratings was also experimentally observed for \( \Lambda = 600 \text{ nm} \) for an ideal layer-to-layer separation, \( 3c = 5.32 \mu\text{m} \), as shown in Fig. 5.11. For this high resolution case with \( P = 35 \text{ mW} \) and \( v = 1 \text{ mm/s} \), the single layer combined 1\(^{st}\) order diffraction efficiency, \( \eta = 0.71\% \) was observed to increase monotonically to a peak of \( \eta = 10.8\% \) for \( N = 5 \) layers. This observed enhancement again verifies the benefits of coherent building of efficiency when the gratings are aligned on Talbot self-imaging planes, but would require further optimizing of the laser fabrication process for diffractive elements for practical applications.

![Figure 5.11: Measured efficiency of both first order diffracted beams (\( \lambda = 532 \text{ nm}, \Lambda = 0.6 \mu\text{m}, P = 35 \text{ mW}, v = 1 \text{ mm/s} \) and NA 1.25 focusing with circular polarization) for increasing number of layers, with ideal layer-to-layer separation, \( 3c = 5.32 \mu\text{m} \). Error bars indicate worst case of diffraction efficiency measurement inaccuracy.](image)

The efficiencies reported for the present multi-stacked gratings (NA = 1.25), both theoretical and experimental, demonstrate the significant potential for the fabrication of high efficiency low index contrast phase gratings inside bulk transparent media that have not been previously available for such high resolution gratings.
Chapter 6

Diffractive optical elements

In previous chapters, only linear volume gratings that cast diffraction into a single plane were considered. Here, multilayered gratings were explored in 2-dimensions that can generate 2-dimensional diffraction patterns, presenting an alternative method for fabricating DOEs.

6.1 2D multilayered volume gratings

A logical extension of the multilayered gratings in Section 5 was to consider layered arrays of gratings written in both $x$- and $y$-directions of sample scanning. In the first iteration of this investigation, the layers in both directions were written with the same applied laser power. As anticipated by the scan direction dependence in Section 4.4.2.2, the same applied power in both scan directions are expected to result in gratings of differing diffractive efficiencies. For the focusing condition of $NA = 1.25$ and an applied power of $P = 35 \text{ mW}$ with circular polarization, the measured diffraction efficiency from the individual grating layers of $\Lambda = 1 \mu \text{m}$ period were $\eta = 5.2\%$ versus $4.44\%$ for $+x$ and $+y$-directions, respectively.

Figure 6.1 shows the measured combined 1st order diffraction efficiencies, $\eta$, for multilayered arrays of gratings written at $P \sim 35 \text{ mW}$ with circular polarization on $\Lambda = 1 \mu \text{m}$
period. The legend axes, $x$ and $y$, in the graph refers to the diffraction orders generated by the gratings written in the $x$ and $y$ sample scan directions, respectively. Similarly, $P_x$ refers to the writing power of the gratings in the $x$-direction and $P_y$ refers to the writing power of the gratings in the $y$-direction.

In Fig. 6.1(a), six layers of gratings were written with $z = c = 5.3$ µm layer-to-layer separation between alternating $x$- and $y$-direction gratings starting with the $y$ scan direction at the bottom. For this fabrication configuration, the combined 1st order diffraction efficiencies were unbalanced with $\eta_y = 9.6\%$ from the $y$-direction gratings and $\eta_x = 17.3\%$ for the $x$-direction gratings.

The same alternating layers were considered as in Fig. 6.1(b), but formed with laser exposure beginning with the $x$ scan direction at the bottom. Here, the combined 1st order diffraction efficiencies flipped such that the $y$-scan direction yielded a higher efficiency of $\eta_x = 8.6\%$ versus $\eta_y = 17.1\%$.

Alternatively, the $x$ and $y$ gratings can be fabricated on the same plane, such as in Fig. 6.1(c). The higher diffracting axes depended on which grating layer was written last. For the $y$-$x$-$y$-$x$-$y$-$x$ configuration, the measured diffraction efficiency was $\eta_x = 20.8\%$ versus $\eta_y = 10.4\%$. This reversed for $x$-$y$-$x$-$y$-$x$-$y$ configuration, where the measured diffraction efficiency was $\eta_y = 20.6\%$ versus $\eta_x = 15.7\%$.

In all of the multilayered configurations considered above, it was observed that the measured diffraction efficiency was lower than the corresponding diffraction efficiency measured for the 3-layered linear volume gratings in Fig. 5.9 of $\eta = 21.7\%$. Further, a higher diffraction efficiency was measured for the grating layer formed last in the device, suggesting a partial erasure of the first written grating layer by the 2nd adjacent layer.

Symmetric $\pm x$ and $\pm y$ diffraction orders are often desirable for 2D diffraction gratings. One approach to achieve this symmetry for the present case of 2D grating writing is to adjust the laser power applied for one axis while holding the applied power in the other axis. Similar to the alternating layers in Fig. 6.1(a) and (b), three layers were fab-
Figure 6.1: Measured combined 1st order diffraction efficiencies, $\eta$, from two-dimensional gratings written in the $x$- and $y$-directions of sample scanning with corresponding geometries in (a-c) showing writing configuration based on laser incident from the top. The legend axes, $x$ and $y$, in the graph refers to the diffraction orders generated by the gratings written in the $x$ and $y$ sample scan directions, respectively.
ricated in the $x$ and $y$ scan directions. Fig. 6.2 shows the combined 1st order diffraction efficiency, $\eta$, for varying power in the $y$ direction, while the power was set at $P = 35$ mW for the $x$ direction.

Figure 6.2: Combined 1st order diffraction efficiency, $\eta$, for three alternating layers each in the $x$ and $y$ axes, as shown in Fig. 6.1(a) and (b). For both cases, a power of $P_x = 35$ mW was applied in the $x$ axis while the applied power was varied in the $y$ axis.
For the case of ‘x-y-x-y-x-y’ stacking, the diffraction efficiency for both axes varied widely between $\eta = 9$ to $22\%$. For low powers in the $y$ axis, such as $P = 10 \text{ mW}$, the diffraction efficiency from the $x$ axis gratings diffracted with $20\%$ efficiency, similar to expectations for linear volume gratings. Not unexpectedly, the diffraction efficiency from the $x$ axis remained consistently higher than from the $y$ axis. With increasing applied power in the $y$ axis, the higher diffraction efficiency on the $x$ axis gratings switches over to show higher diffraction efficiency from the $y$ axis gratings. The turnover point for this behaviour occurs between the applied power of $P = 30$ to $35 \text{ mW}$.

From the previous observation in Fig. 6.1, it was observed that the last fabricated layer would define the dominant axis of diffraction. Consequently, the results in Fig. 6.2(a) are consistent in that symmetric $x$ and $y$ diffraction orders are generated when slightly lower applied power is used in the $y$ axis for ‘x-y-x-y-x-y’ configuration.

When the writing order is changed to ‘y-x-y-x-y-x’ as in Fig. 6.2(b), the measured data revealed a higher diffraction efficiency from the $x$ axis gratings, regardless of the laser power applied in the $y$ axis grating layer. With the $x$ axis as the last layer formed, the $\eta_x$ diffraction efficiency remains higher than $\eta_y$.

A similar analysis was conducted for fixed power scanning in the $y$ direction while varying the applied power in the $x$ axis scanning. For the ‘y-x-y-x-y-x’ configuration, the diffraction efficiencies were measured for a power of $P_y = 35 \text{ mW}$, as shown in Fig. 6.3. For this case, symmetric diffraction orders were observed for a much lower applied power of $P_x$ between $20$ to $30 \text{ mW}$. Again, the last fabricated layer was found to be the dominant diffracting layer.

The dominance of the last fabricated layer suggests that each written layer has an effect on the previously written grating layers. These effects are not as evident with multilevel linear volume gratings in Section 5, but become obvious with the different diffracting efficiencies measured here for directions of $\pm x$ and $\pm y$. In order to obtain symmetric orders with maximum diffraction efficiency, a systematic exploration of the
Figure 6.3: Combined 1st order diffraction efficiency, \( \eta \), for three alternating layers each in the \( x \) and \( y \) axes, as shown in Fig. 6.1(a). For both cases, a power of \( P_y = 35 \) mW was applied in the \( y \) axis while the applied power was varied in the \( x \) axis.

parameter space would be necessary, with variations of the power at each layer. These observations suggest that orthogonal writing of grating layers induces longer reaching stress zones that are preferentially designed to reduce the index contrast. The formation of submicron nanogratings are well known [9, 64, 65, 73] to exist for such femtosecond laser writing that cause a strong form birefringence that may underlie their strong index contrast erasing effects.

An alternative configuration of fabricating 2D multilevel DOE is shown in Fig. 6.4. Here, the stacks of linear gratings are treated as isolated entities, similar to the gratings written in Section 5. The long range separation of the \( x \) and \( y \) orientated grating layers is expected to remove the erasure effects observed above for smaller vertical spacings.

With this method of fabrication, it is necessary to write significantly deeper into the bulk material, which can introduce depth related variances in the volume gratings index contrast. The measured diffraction efficiency from 3-layers stacked with \( x \) followed by \( y \) directions, at \( P = 35 \) mW, \( v = 1 \) mm/s and 1.25 NA focusing, yielded \( \eta_x = 16.9\% \) and
\( \eta_y = 11.1\% \), which is lower than with alternating layers (\( \eta_x = 17.1\% \) and \( \eta_y = 12.6\% \)). Lowering the applied power in the \( x \) direction to \( P = 20 \) mW helped to create more symmetric diffraction efficiencies of \( \eta_x = 14.1\% \) and \( \eta_y = 11.1\% \). An increase to 4 layers in each direction, with \( P_x = 20 \) mW and \( P_y = 35 \) mW, yielded a diffraction efficiency of \( \eta_x = 18.9\% \) and \( \eta_y = 15\% \), with power moderation in the \( x \) direction. The addition of another layer in \( y \) direction (4 layers in \( x \) and 5 layers in \( y \), with \( P_x = 20 \) mW and \( P_y = 35 \) mW) yielded slightly higher diffraction efficiency in the \( y \) direction to balance the efficiency to \( \eta_x = 18.8\% \) and \( \eta_y = 16.1\% \). With further finesse, more symmetric orders could be expected. However, the maximum diffraction efficiency would be less than its optimum potential due to the limits of assembling large number of grating layers together without the erasure effects above.

Figure 6.4: Example of segmented \( x \) and \( y \) oriented linear gratings on \( 2c \) separation and isolated by \( l_{\text{stack}} \).

### 6.2 DOEs for photonic crystals

The configuration in Fig. 6.4 was useful for demonstrating a specific application of such 3D DOEs. In the fabrication of photonic crystals with a single laser beam, 3D
interference patterns can be generated in the near-field to expose photoresists such as SU-8 [4]. The standing interference pattern generated is controlled by a phase shift (i.e. separation) between two orthogonal gratings that is difficult to control or apply precisely with conventional gratings. One approach to address this problem is through the custom fabrication of multileveled linear gratings with a $c/4$ layer-to-layer separation, which has been previously demonstrated to be favourable in generating diamond-like woodpile structures [81], which is the preferred structure for strong stop bands in all 3D directions. However, such custom fabrication poses two major problems: the practical limitation in precisely controlling this layer-to-layer separation together with the high cost and challenges of producing high resolution DOEs.

The femtosecond laser direct writing inside fused silica defines a flexible approach to separate orthogonally aligned linear gratings and manually adjust the layer-to-layer separation. Otherwise, alignment of two separate physical gratings is challenging on the micron level precision. Specifically, for 1 $\mu$m period gratings, a layer-to-layer separation of $c/4 = 1.3$ $\mu$m would be necessary for generating diamond-like crystal structures. Shifts in the layer-to-layer separation could result in the less attractive body-centered tetragonal (BCT) symmetry. The volume DOEs proposed in this thesis is extremely attractive for the fabrication of these photonic crystals for several reasons: (1) flexibility in specifying layer-to-layer separation, (2) fixed orthogonality of the grating layers, (3) quick fabrication speed, and (4) robustness against contact exposure with the photoresist during the fabrication of the photonic crystals.

To this end, multilevel gratings, such as in Fig. 6.4, were fabricated with varying separations between the stacks of $x$ and $y$ layers. For the exposure of SU-8 photoresist generating a moderate the diffraction efficiency of all the 1st diffraction orders is important to ensure sufficient pattern contrast to overcome the polymerization threshold. Consequently, for this project, a more forgiving grating period of $\Lambda = 1.5$ $\mu$m was used, where the Talbot self-imaging was expected at $c = 12.6$ $\mu$m, which requires writing
deeper into the bulk material. For four layers of gratings formed in each of the $x$ and $y$ directions, a combined 1$\text{st}$ order diffraction efficiencies of $\eta_x = 19.8\%$ and $\eta_y = 17.6\%$ were measured.

![Figure 6.5: (a) Top view SEM of developed Ar$^+$ laser fabricated photonic crystal templates formed from 2D laser written phasemasks with varying separation between stacks of $x$ and $y$ gratings, with total variation in $l_{\text{stack}}$ of $c/4$. (b) and (c) Magnified views of sample structure #7.](image)

A series of such DOEs were fabricated with varying separation between the $x$- and $y$-oriented grating layers in the range of 0 to $c/4 = 3.15 \, \mu m$, which under exposure into SU-8 photoresist (work by colleague, Leon Yuan) with an Ar$^+$ laser at $\lambda = 514.5 \, \text{nm}$ would result in shifts of the crystal structure from body-centered-tetragonal (BCT)
to diamond-like woodpile structures having tetragonal (TTR) symmetry. Due to the relative weakness of the diffraction orders ($\eta_x = 24\%$ and $\eta_y = 18\%$) in comparison with commercially produced DOEs, the exposure window for forming highly contrasting 3D PC templates is extremely narrow between the limits of thin interconnects between layers to closing of the open voids. Further, the large grating period of $\Lambda = 1.5 \mu m$ meant that the vertical period of the photonic crystal structure, which also corresponds to the Talbot self-imaging, would be large at $c = 12.6 \mu m$. This long vertical period can be problematic for supporting the 3D network structure without sufficient interconnects. A parameter scan of the Ar$^+$ exposure times and SU-8 development defined a range of 3D periodic photonic templates over the varying offsets between the $x$ and $y$ grating layers, as seen in Fig. 6.5. The structures from the SEM top views are observed to vary widely over the offset range, but no discernable trend could definitively assign BCT or diamond-like symmetry.

A magnification of one of the sample structures reveal a top layer periodic structure that corresponds to the expected 1.5 $\mu m$ period pillars, in Fig. 6.5(c), with vertical connections to deeper layers. Further work is in progress to assess these structures by cleaving the sample to examine the template cross-section, and verify if appropriate crystal symmetries are formed by this newly proposed phase mask technique. These initial experiments suggests great potential for the use of femtosecond laser fabricated volume DOEs to create photonic crystals and other 3D devices by tailoring the fabricated refractive index profiles.

### 6.3 Single scan 2D volume DOEs

For a more flexible and efficient fabrication process, a simple laser modulation method centered of exploiting the AOM in the femtosecond laser beam path. The AOM could be triggered through computer programming to coincide with the sample-holding motion
stages positions. With appropriate triggering, both symmetric and asymmetric layers of 2D diffracting elements could be fabricated. For example, in Fig. 6.6(a), the spacing between laser tracks defines $\Lambda_x$ period and AOM triggering with respect to the laser scan speed defines the $\Lambda_y$ period to form a 2D phasemask structure. By shifting the AOM modulation pattern, such as in Fig. 6.6(b), the 2D structure can approximate a hexagonal shape with diagonal $\Lambda_{xy}$. Further customization of the triggering can also be used to introduce varying asymmetries to customize formation of voids or optical defects.

Figure 6.6: (a) Laser scanned with track-to-track spacing of $\Lambda_x$ and AOM triggering to form $\Lambda_y$ period and (b) with a shift of the AOM modulation pattern, such that 2D hexagonal structures can be structured with $\Lambda_{xy}$ periodicity.

Circularly polarized incident laser light focused with the 0.55 NA lens at 175 mW power and 1 mm/s scan speed yielded the 2D DOE structure shown in Fig. 6.7(a). This optical microscope image of a 2D phase grating was formed with the laser scanning along the $y$ axis under $\Lambda_y = 5 \, \mu m$ periodic modulation and with track-to-track spacing of $\Lambda_x = 1 \, \mu m$. This structure yielded asymmetric diffraction efficiencies of $\eta_y = 19\%$ and $\eta_x = 1\%$, which corresponded closely with FDTD calculated values of $\eta_y = 20\%$ and $\eta_x = 1.3\%$ based on the refractive index profile anticipated from Section 4.4.1.

Two-dimensional DOEs could also be fabricated with hexagonal-like symmetry, as in Fig. 6.7(b), that resulted in weak diffraction of $\eta_{xy} < 2\%$ efficiency that arose from imperfect synchronization between the laser triggering and the motion stages that shifted the phase elements diagonally. While not explored here, one may apply the multilayered
Figure 6.7: Optical microscope images of single layer DOEs written by computer controlled 2D patterning showing orthogonal gratings (a) of $\Lambda_y = 5$ $\mu$m and $\Lambda_x = 1$ $\mu$m period and hexagonal patterned gratings (b) with diagonal period $\Lambda_{xy} = 5$ $\mu$m.

fabrication methods as described in Section 5 and dramatically increase the efficiency of such DOEs with coherent phase alignment of such layers onto Talbot planes.
Chapter 7

Significance and Conclusion

7.1 Significance

The insight into the Talbot self-imaging oscillation first presented in Section 4.1 revealed a fundamental restriction on the available diffraction efficiency from high resolution, low refractive index contrast phase gratings. An in-depth exploration of the range identifying the limits of Talbot self-imaging was presented for the first time, defining the practical limiting factors for diffraction efficiency from weak index contrast DOEs, which is of particular interest when fabricating volume phase elements with direct laser writing.

For direct laser writing of volume diffractive optics, the stronger laser interaction with doped and borosilicate glasses resulted in high refractive index change contrast, but also correspondingly larger physical structures [23,24], that have precluded the demonstration of high resolution diffractive optic devices in these materials. Femtosecond laser interactions in fused silica could also result in moderately strong index contrast that has led to demonstration of phase gratings of low efficiencies of 25% for 4 µm period gratings [25]. Multilayered volume Fresnel plates have also been demonstrated with moderately good efficiency of 60%, but requiring wide refractive index zones of ~5 µm linewidth [26].

For the present objective of fabricating high resolution phase gratings, tighter focusing
conditions failed to generate strongly diffracting gratings when formed in a single layer array. The optimization of the laser exposure conditions for NA = 0.55 and 1.25 focusing, such as applied laser power, scan speed, polarization, sample scan direction, and grating period, maximized the measured diffraction efficiencies, but still fell short of requirements for practical applications.

Morphological and RNF evaluation of individual laser modification tracks for both focusing conditions (NA = 0.55 and 1.25) revealed the presence of both sufficient refractive index contrast (i.e. $\Delta n \sim +0.01$) and thickness ($d \sim 10 \mu m$) to exceed the $\pi$-phase shift requirement for efficient diffraction in simple scalar theory. The presence of both positive and negative index zones in the NA = 0.55 laser tracks (Section 4.3.1) would normally be expected to cancel and reduce the overall phase shift available from such gratings. However, optical modeling revealed an important new insight to enhance the diffraction efficiency when adjacent positive and negative index zones were positioned on half-Talbot planes of $c/2$.

The Talbot self-imaging distance that was first considered a severe restriction on the available diffraction efficiency from weak gratings (Section 4.1) sparked the concept of stacking grating layers that was theoretically found to enhance or diminish the 1st order diffraction efficiency with separation between grating layers aligned or misaligned according to the periodic Talbot planes (Section 5). While the unique resonant enhancement of the diffraction efficiency based on layer-to-layer separation was noted in theoretical models by Hargrove et al. [47], Malysh et al. [48] and Nordin et al. [49], this phenomena was never explained, or demonstrated, nor connected with Talbot planes. In Section 5, this coherent enhancement was verified both theoretically and experimentally to coincide with the Talbot planes of separation.

Moreover, this Talbot layering enhancement could be optimized with selection of the appropriate number of grating layers. Femtosecond laser fabrication of multi-level phase gratings, with high NA focusing of 1.25, was applied inside bulk glass and found
to demonstrate an 8-fold enhancement of the diffraction efficiency with the appropriate assembly of 8 grating layers. Further improvements in the laser fabrication technique will therefore permit multilayering of weakly diffracting volume gratings to generate a dramatically high potential diffraction efficiency of up to 95% theoretically that was otherwise impossible to generate from weakly contrasting volume gratings.

The advanced laser beam control methods employed here, such as in Section 6.3, further demonstrated new directions for the facile assembly of highly functional DOEs that can exploit coherent light diffraction. The novel concept of multilayered phase elements aligned on Talbot planes introduce a new, exciting regime of exploration that promise to extend current state-of-art light control. Fabrication methods that induce only small refractive index changes can now be harnessed for practical applications, a heretofore unexplored technique that could be exploited for limitless flexibility in design.

The culmination of the concepts herein introduced and verified provide new avenues in the pursuit of exploiting light diffraction for opportunities in improving the performance of holographic optical devices and extend further to the powerful combination of phase and amplitude modulation control. An example of this new direction was presented for generating 3D photonic crystal templates in Section 6.2.

### 7.2 Summary

This thesis addressed the main limitations of Talbot self-imaging in the diffraction efficiency available in weak index contrast gratings, a particular concern with direct laser writing of high-resolution volume DOEs. The FDTD optical modeling was used to identify and verify the diffraction efficiency enhancement with alignment on Talbot self-imaging planes. The morphology of the femtosecond laser tracks formed in fused silica glass were examined with various microscopy tools including optical, phase contrast and refractive near-field. This examination revealed finely structured zones of positive and
negative index change that were found to enhance or diminish diffraction efficiency based on coincidental alignment with Talbot self-imaging interference patterns.

The optimization of the femtosecond laser fabrication of arrayed volume gratings was examined, with respect to applied laser power, sample scan speed, incident laser polarization, sample scan direction, and periodicity, by assessing the generated diffraction efficiency. The morphology of the laser modification tracks revealed an expected strong dependence on applied laser power and sample scan speed. The assessment of diffraction efficiency from volume gratings confirmed birefringece effects resulting from femtosecond index modification. Further, the ‘quill’ effect, the directionally dependant writing strength of grating lines, was also confirmed by the differences in diffraction efficiency observed for volume gratings written in the different scan directions, even with otherwise identical laser exposure. Finally, the optimization of the grating period provided vital information for the inference of the laser modification track width as well as the suitability of each focusing condition, NA = 0.55 and 1.25, for the fabrication of high resolution volume gratings. For NA = 0.55 focusing, a grating resolution of $\Lambda = 1 \mu m$ was obtainable, while with NA = 1.25 focusing, gratings of down to $\Lambda = 0.6 \mu m$ yielded measurable diffraction orders.

Two levels of identical gratings were found to be enhanced when aligned on Talbot planes and diminished when aligned on half-Talbot planes. Further, eight layers of volume gratings spaced on Talbot planes were found to coherently enhance diffraction efficiency by 32-fold to 95% in optical modelling and 8-fold to 35% experimentally. This dramatic enhancement opens new opportunities to exploit low index contrast volume gratings for exciting new regimes of operation and potential for device integration. Finally, the advanced beam control methods demonstrated here underpin new directions for exploring volume DOE fabrication that, together with the theoretical insight herein, could open new approaches for the efficient manipulation of light.
7.3 Future Work

In the course of this thesis, several technical directions remained unexplored and are outlined below as future work.

(1) **Morphology with respect to grating period**

In Sections 4.3 and 4.4, the laser induced refractive index morphology was noted to change with the applied laser power as well as the scan speed. While these parameters were optimized for maximum diffraction efficiency, a deeper investigation can be made into the optimization of grating period for the various types and sizes of laser track morphology observed. It is possible that the changing horizontal widths and variations in the positive/negative index zones could be key to further optimization of the diffraction efficiency at each grating period, in light of the optical modeling analysis of the index variations in Section 4.3.1. While harnessing such femtosecond laser written tracks for waveguiding relies on generating a strong average index contrast over sufficient cross-sectional area, the finely pitched positive and negative refractive index change zones promise to generate much stronger diffracting devices in the future if better control were obtained over the fine scaled $\Delta n$ modification in relation to the small scale size of the Talbot plane separation, $c$.

(2) **High resolution microscopy**

One of the major roadblocks in the analysis of the laser induced modification tracks was the optical resolution of the microscopy tools available in this project. Since the submicron refractive index profiles were very similar to the resolution of $\sim0.5 \mu m$ in RNF, sufficiently accurate profiles of the fabricated laser tracks could not be determined. Further, the ability to directly analyse the morphology of the assembled gratings might reveal deeper insight into the diffracting behaviour of these arrayed gratings that otherwise revealed a poor $\Delta n$ contrast due to the limited optical resolution.

(3) **High efficiency low index contrast gratings**

The limitations of the laser direct writing, such as the positive and negative in-
dex change zones, limited the potential here to accurately assemble multilayered phase gratings in bulk fused silica and exploit the maximum available diffraction efficiency. In theory, thin layers of low index contrast gratings could be aligned on Talbot planes to fabricate high diffraction efficiencies of up to 95% or higher, with appropriate anti-reflection coatings. Improving the finesse of the laser fabrication process could potentially tap into this highly efficient regime of operation. Alternatively, different fabrication techniques could be exploited to demonstrate the unique enhancement of diffraction efficiency on Talbot planes.

(4) Multilayered 2D DOEs and 3D photonic crystals

The methods introduced in Section 6.3 that used AOM triggering to fabricate 2D DOEs could be potentially used to fabricate multilayered DOEs with high efficiency. Further, the flexibility of the laser direct writing could be exploited to introduce defects selectively to alter the generated periodic interference pattern. One potential application could be to introduce lines of high or low contrast in standing 3D intensity patterns. The exposure of these patterns in SU-8 could potentially result in selective fabrication of guiding walls or microfluidic troughs inside 3D structures and open new high speed 3D laser fabrication methods for industrial applications. Further, an improvement in the diffraction efficiencies of high resolution gratings would enable the fabrication of 3D photonic crystals. This approach would provide a quick and versatile method to fabricate and optimize 3D photonic crystal devices, with the potential for tuning the crystals and inserting beneficial optical defects.

The principles in this thesis introduced a deeper understanding to the fundamentals of diffraction theory, in addition to providing a comprehension exploration of femtosecond laser direct writing of diffracting devices. This insight may open many new directions in the design and fabrication of DOEs towards the completely controlled manipulation of light in novel and exciting optical device designs.
Appendix A

List of Acronyms and Symbols

List of Acronyms

2D Two-Dimensional
3D Three-Dimensional
AOM Acoustic-Optic Modulator
BCT Body-Centric Tetragonal
CGH Computer Generated Holograms
DOE Diffractive Optical Element
FDTD Finite Difference Time Domain
FWHM Full-Width Half-Maximum
MMI Multimode Interferometer Waveguides
NA Numerical Aperture
PC Photonic Crystal
PSO Position-Synchronized Output
RNF Refractive Near-Field
TTR Tetragonal
Appendix A. List of Acronyms and Symbols

List of Symbols

- $c$: Talbot self-imaging plane separation
- $\delta_m$: Relative phase
- $d$: Grating thickness
- $f$: Focal length
- $\eta$: Diffraction efficiency
- $\Delta n$: Refractive index contrast
- $I$: Intensity
- $l$: Layer-to-layer separation
- $\Lambda$: Grating period
- $\lambda$: Light wavelength
- $M^2$: Gaussian beam propagation factor or beam quality
- $N$: Number of grating layers
- $n_2$: Second order optical material non-linearity
- $n_r$: Refractive index
- $P$: Laser power
- $\phi$: Phase shift modulation
- $\theta_p$: Diffraction angle of order $p$
- $w_0$: Diffraction-limited waist radius in a dielectric
- $v$: Sample scan speed
Appendix B

Examples of GCode for Aerotech motion stages

(1) Array of x-axis laser tracks Originally authored by W.J. Chen

```c
// Straight waveguides
// 2 ablation lines at beginning and end with separation that’s
// 50% of DELTA_MINOR_AXIS
// 2 ablation lines between different depth with separation that’s
// 25% of DELTA_MINOR_AXIS
// 4 ablation lines between different power with separation that’s
// 25% of DELTA_MINOR_AXIS

// CHANGE THIS TO NUMBER OF DIFFERENT SCAN SPEEDS.
#define SPEED_COUNT 10
// CHANGE THIS TO NUMBER OF DIFFERENT WAVEGUIDE DEPTH.
#define DEPTH_COUNT 3
// CHANGE THIS TO NUMBER OF DIFFERENT POWER
#define POWER_COUNT 5
// CHANGE THIS TO SAMPLE WIDTH + A SMALL MARGIN IN mm.
#define SAMPLE_WIDTH 30
// CHANGE THIS TO THE DISTANCE BETWEEN 2 WAVEGUIDES IN mm.
#define DELTA_MINOR_AXIS 0.1
// CHANGE THIS TO THE SCAN SPEED OF ABLATION LINES IN mm/s.
#define ABLATION_SPEED 2
// CHANGE THIS TO THE ANGLE FOR MAXIMUM POWER IN degree.
#define ABLATION_POWER 19.472
```
DVAR $speed_count $depth_count $power_count $delta_minor_axis
DVAR $delta_major_axis $wg_speed[$speed_count] $depth[$depth_count]
DVAR $power[$power_count]

// CHANGE THIS TO APPROPRIATE WAVEGUIDE SPEED IN mm/s.
$wg_speed[0] = 1
$wg_speed[1] = 1
$wg_speed[2] = 2
$wg_speed[3] = 2
$wg_speed[5] = 5
$wg_speed[6] = 10
$wg_speed[7] = 10
$wg_speed[8] = 25
$wg_speed[9] = 25

// CHANGE THESE TO APPROPRIATE WAVEGUIDE DEPTH IN um.
$depth[0] = 125
$depth[1] = 150
$depth[2] = 200

// CHANGE THESE TO APPROPRIATE POWER ANGLES IN degree.
$power[0] = 18.962
$power[1] = 8.405
$power[2] = -0.227
$power[3] = -4.014
$power[4] = -7.8

ABSOLUTE
LINEAR UU(ABLATION_POWER) E(5)
INCREMENTAL
METRIC  // Distance unit = mm.
SECOND  // Time unit = s.
G92 X0 Y0 Z0  // Zero X and Y coordinate
$delta_major_axis = SAMPLE_WIDTH
$delta_minor_axis = DELTA_MINOR_AXIS

// 2 Starting ablation lines spaced 50% of DELTA_MINOR_AXIS
LINEAR X($delta_major_axis) F(ABLATION_SPEED)
$delta_major_axis = $delta_major_axis * -1
LINEAR Y(0.5*$delta_minor_axis) F1
LINEAR X($delta_major_axis) F(ABLATION_SPEED)
$delta_major_axis = $delta_major_axis * -1
LINEAR Y($delta_minor_axis) F1

FOR $power_count = 0 to $power_count-1
ABSOLUTE
LINEAR UU($power[$power_count]) E(5)
INCREMENTAL
FOR $depth_count = 0 TO DEPTH_COUNT-1
    ABSOLUTE
    LINEAR UU($power[$power_count]) E(5)
    LINEAR Z(-0.001*$depth[$depth_count]) F(1)
    INCREMENTAL
    FOR $speed_count = 0 TO SPEED_COUNT-1
        LINEAR X($delta_major_axis) F($wg_speed[$speed_count])
        $delta_major_axis = $delta_major_axis * -1
        LINEAR Y($delta_minor_axis) F1
    NEXT $speed_count
    IF $depth_count LT DEPTH_COUNT-1
        ABSOLUTE
        LINEAR UU(ABLATION_POWER) E(5)
        LINEAR Z(0) F(1)
        INCREMENTAL
        LINEAR X($delta_major_axis) F(ABLATION_SPEED)
        $delta_major_axis = $delta_major_axis * -1
        LINEAR Y(0.25*$delta_minor_axis) F1
        LINEAR X($delta_major_axis) F(ABLATION_SPEED)
        $delta_major_axis = $delta_major_axis * -1
        LINEAR Y($delta_minor_axis) F1
    ENDIF
NEXT $depth_count
IF $power_count LT POWER_COUNT-1
    ABSOLUTE
    LINEAR UU(ABLATION_POWER) E(5)
    LINEAR Z(0) F(1)
    INCREMENTAL
    LINEAR X($delta_major_axis) F(ABLATION_SPEED)
    $delta_major_axis = $delta_major_axis * -1
    LINEAR Y(0.25*$delta_minor_axis) F1
    LINEAR X($delta_major_axis) F(ABLATION_SPEED)
    $delta_major_axis = $delta_major_axis * -1
    LINEAR Y($delta_minor_axis) F1
    ENDIF
NEXT $power_count

ABSOLUTE
LINEAR UU(ABLATION_POWER) E(5)
LINEAR Z(0) F(1)
INCREMENTAL
LINEAR X($delta_major_axis) F(ABLATION_SPEED)
LINEAR Y(0.5*$delta_minor_axis) F1
$delta_major_axis = $delta_major_axis * -1
LINEAR X($delta_major_axis) F(ABLATION_SPEED)
LINEAR Y($delta_minor_axis) F1
ABSOLUTE
M02

(2) Array of y-axis laser tracks Originally authored by W.J. Chen

// Straight waveguides
// 2 ablation lines at beginning and end with separation that’s
// 50% of DELTA_MINOR_AXIS
// 2 ablation lines between different depth with separation that’s
// 25% of DELTA_MINOR_AXIS
// 4 ablation lines between different power with separation that’s
// 25% of DELTA_MINOR_AXIS

// CHANGE THIS TO NUMBER OF DIFFERENT SCAN SPEEDS.
#DEFINE SPEED_COUNT 7
// CHANGE THIS TO NUMBER OF DIFFERENT WAVEGUIDE DEPTH.
#DEFINE DEPTH_COUNT 3
// CHANGE THIS TO NUMBER OF DIFFERENT POWER
#DEFINE POWER_COUNT 6
// CHANGE THIS TO SAMPLE WIDTH + A SMALL MARGIN IN mm.
#DEFINE SAMPLE_WIDTH 55
// CHANGE THIS TO THE DISTANCE BETWEEN 2 WAVEGUIDES IN mm.
#DEFINE DELTA_MINOR_AXIS 0.1
// CHANGE THIS TO THE SCAN SPEED OF ABLATION LINES IN mm/s.
#DEFINE ABLATION_SPEED 5
// CHANGE THIS TO THE ANGLE FOR MAXIMUM POWER IN degree.
#DEFINE ABLATION_POWER -14.631

DVAR $speed_count $depth_count $power_count $delta_minor_axis
DVAR $delta_major_axis $wg_speed[SPEED_COUNT] $depth[DEPTH_COUNT]
DVAR $power[POWER_COUNT]

// CHANGE THIS TO APPROPRIATE WAVEGUIDE SPEED IN mm/s.
$wg_speed[0] = 1
$wg_speed[1] = 5
$wg_speed[2] = 10
$wg_speed[3] = 20
$wg_speed[4] = 40
Appendix B. Examples of GCode for Aerotech motion stages

$wg_speed[5] = 60
$wg_speed[6] = 80

// CHANGE THESE TO APPROPRIATE WAVEGUIDE DEPTH IN um.
$depth[0] = 50
$depth[1] = 100
$depth[2] = 150

// CHANGE THESE TO APPROPRIATE POWER ANGLES IN degree.
$power[0] = -7.352
$power[1] = -10.950
$power[3] = -20.018
$power[4] = -22.903

ABSOLUTE
LINEAR UU(ABLATION_POWER) E(5)
INCREMENTAL
METRIC // Distance unit = mm.
SECOND // Time unit = s.
G92 X0 Y0 Z0 // Zero X and Y coordinate
$delta_major_axis = SAMPLE_WIDTH
$delta_minor_axis = DELTA_MINOR_AXIS

// 2 Starting ablation lines spaced 50% of DELTA_MINOR_AXIS
LINEAR Y($delta_major_axis) F(ABLATION_SPEED)
$delta_major_axis = $delta_major_axis * -1
LINEAR X(0.5*$delta_minor_axis) F1
LINEAR Y($delta_major_axis) F(ABLATION_SPEED)
$delta_major_axis = $delta_major_axis * -1
LINEAR X($delta_minor_axis) F1

FOR $power_count = 0 to POWER_COUNT-1
    ABSOLUTE
    LINEAR UU($power[$power_count]) E(5)
    INCREMENTAL
    FOR $depth_count = 0 TO DEPTH_COUNT-1
        ABSOLUTE
        LINEAR UU($power[$power_count]) E(5)
        LINEAR Z(-0.001*$depth[$depth_count]) F(1)
        INCREMENTAL
        FOR $speed_count = 0 TO SPEED_COUNT-1
            LINEAR Y($delta_major_axis) F($wg_speed[$speed_count])
            $delta_major_axis = $delta_major_axis * -1
            LINEAR X($delta_minor_axis) F1
        NEXT $speed_count
    NEXT $depth_count
NEXT $power_count
IF $depth_count LT DEPTH_COUNT-1
  ABSOLUTE
  LINEAR UU(ABLATION_POWER) E(5)
  LINEAR Z(0) F(1)
  INCREMENTAL
  LINEAR Y($delta_major_axis) F(ABLATION_SPEED)
  $delta_major_axis = $delta_major_axis * -1
  LINEAR X(0.25*$delta_minor_axis) F1
  LINEAR Y($delta_major_axis) F(ABLATION_SPEED)
  $delta_major_axis = $delta_major_axis * -1
  LINEAR X($delta_minor_axis) F1
ENDIF
NEXT $depth_count
IF $power_count LT POWER_COUNT-1
  ABSOLUTE
  LINEAR UU(ABLATION_POWER) E(5)
  LINEAR Z(0) F(1)
  INCREMENTAL
  LINEAR Y($delta_major_axis) F(ABLATION_SPEED)
  $delta_major_axis = $delta_major_axis * -1
  LINEAR X(0.25*$delta_minor_axis) F1
  LINEAR Y($delta_major_axis) F(ABLATION_SPEED)
  $delta_major_axis = $delta_major_axis * -1
  LINEAR X(0.25*$delta_minor_axis) F1
  LINEAR Y($delta_major_axis) F(ABLATION_SPEED)
  $delta_major_axis = $delta_major_axis * -1
  LINEAR X($delta_minor_axis) F1
ENDIF
NEXT $power_count
ABSOLUTE
LINEAR UU(ABLATION_POWER) E(5)
LINEAR Z(0) F(1)
INCREMENTAL
LINEAR Y($delta_major_axis) F(ABLATION_SPEED)
LINEAR X(0.5*$delta_minor_axis) F1
$delta_major_axis = $delta_major_axis * -1
LINEAR Y($delta_major_axis) F(ABLATION_SPEED)
LINEAR X($delta_minor_axis) F1
ABSOLUTE
M02

(3) Gratings x-axis - Multiple powers, multiple scan speeds
//Author: M.L. Ng (ngmili@gmail.com)

#DEFINE DELTA_X1 0.001 //set grating period
#DEFINE DELTA_X2 0.002
#DEFINE DELTA_X3 0.004
#DEFINE DELTA_Y 15 //set grating length
#DEFINE LINE_CNT1 1000 //set number of lines of gratings
#DEFINE SCAN_SPEED 1 //set speed of writing laser tracks
#DEFINE POWER_1 -20.38 //set laser power according to rotation stage
#DEFINE POWER_2 -30.81
#DEFINE POWER_3 -37.58
#DEFINE POWER_4 -43.82

DVAR $delta_x1 $delta_x2 $delta_x3 $delta_y $scan_speed $cnt $cnt2
DVAR $power_1 $power_2 $power_3 $power_4

$delta_x1 = DELTA_X1
$delta_x2 = DELTA_X2
$delta_x3 = DELTA_X3
$delta_y = DELTA_Y
$scan_speed = SCAN_SPEED
$power_1 = POWER_1
$power_2 = POWER_2
$power_3 = POWER_3
$power_4 = POWER_4

//POWER 1
//SET 1
//1 micron separation
ABSOLUTE
LINEAR Z-0.075 F10
LINEAR UU($power_1) E3

INCREMENTAL

FOR $cnt = 1 TO 1
    LINEAR X($delta_y) F($scan_speed)
    LINEAR Y($delta_x1) F0.1
    LINEAR UU-66 E10
    $delta_y = -$delta_y
    LINEAR X($delta_y) F($scan_speed)
    LINEAR UU($power_1) E10
    $delta_y = -$delta_y
NEXT

LINEAR Z5 F5
LINEAR Y0.500 F2
ABSOLUTE
LINEAR Z-0.075 F5
INCREMENTAL

FOR $cnt = 1 TO 2
    FOR $cnt2 = 1 TO 2
        LINEAR X($delta_y) F($scan_speed)
        LINEAR Y($delta_x1) F0.1
        LINEAR UU-66 E10
        $delta_y = -$delta_y
        LINEAR X($delta_y) F($scan_speed)
        LINEAR UU($power_1) E10
        $delta_y = -$delta_y
    NEXT
    $delta_x1 = -$delta_x1
    LINEAR Z0.015 Y($delta_x1) F0.01
NEXT

LINEAR Z5 F5
LINEAR Y0.500 F2
ABSOLUTE
LINEAR Z-0.075 F5
INCREMENTAL

FOR $cnt = 1 TO 4
    FOR $cnt2 = 1 TO 4
        LINEAR X($delta_y) F($scan_speed)
        LINEAR Y($delta_x1) F0.1
        LINEAR UU-66 E10
        $delta_y = -$delta_y
        LINEAR X($delta_y) F($scan_speed)
        LINEAR UU($power_1) E10
        $delta_y = -$delta_y
    NEXT
    $delta_x1 = -$delta_x1
    LINEAR Z0.015 Y($delta_x1) F0.01
NEXT

LINEAR Z5 F5
LINEAR Y0.500 F2
ABSOLUTE
LINEAR Z-0.125 F5
INCREMENTAL

//SET 2
//Twomicron separation
ABSOLUTE
Appendix B. Examples of GCode for Aerotech motion stages

LINEAR Z-0.075 F10
INCREMENTAL

FOR $cnt = 1 TO 1
  LINEAR X($delta_y) F($scan_speed)
  LINEAR Y($delta_x2) F0.1
  LINEAR UU-66 E10
  $delta_y = -$delta_y
  LINEAR X($delta_y) F($scan_speed)
  LINEAR UU($power_1) E10
  $delta_y = -$delta_y
NEXT

LINEAR Z5 F5
LINEAR Y0.500 F2
ABSOLUTE
LINEAR Z-0.075 F5
INCREMENTAL

FOR $cnt = 1 TO 2
  FOR $cnt2 = 1 TO 2
    LINEAR X($delta_y) F($scan_speed)
    LINEAR Y($delta_x2) F0.1
    LINEAR UU-66 E10
    $delta_y = -$delta_y
    LINEAR X($delta_y) F($scan_speed)
    LINEAR UU($power_1) E10
    $delta_y = -$delta_y
  NEXT
  $delta_x2 = -$delta_x2
  LINEAR Z0.015 Y($delta_x2) F0.01
NEXT

LINEAR Z5 F5
LINEAR Y0.500 F2
ABSOLUTE
LINEAR Z-0.075 F5
INCREMENTAL

FOR $cnt = 1 TO 4
  FOR $cnt2 = 1 TO 4
    LINEAR X($delta_y) F($scan_speed)
    LINEAR Y($delta_x2) F0.1
    LINEAR UU-66 E10
    $delta_y = -$delta_y
    LINEAR X($delta_y) F($scan_speed)
LINEAR UU($power_1) E10
$delta_y = -$delta_y
NEXT
$delta_x2 = -$delta_x2
LINEAR Z0.015 Y($delta_x2) F0.01
NEXT

LINEAR Z5 F5
LINEAR Y0.500 F2
ABSOLUTE
LINEAR Z-0.125 F5
INCREMENTAL

//SET 3
//4 micron separation
ABSOLUTE
LINEAR Z-0.075 F10
INCREMENTAL

FOR $cnt = 1 TO 1
    LINEAR X($delta_y) F($scan_speed)
    LINEAR Y($delta_x3) F0.1
    LINEAR UU-66 E10
    $delta_y = -$delta_y
    LINEAR X($delta_y) F($scan_speed)
    LINEAR UU($power_1) E10
    $delta_y = -$delta_y
NEXT

LINEAR Z5 F5
LINEAR Y0.500 F2
ABSOLUTE
LINEAR Z-0.075 F5
INCREMENTAL

FOR $cnt = 1 TO 2
    FOR $cnt2 = 1 TO 2
        LINEAR X($delta_y) F($scan_speed)
        LINEAR Y($delta_x3) F0.1
        LINEAR UU-66 E10
        $delta_y = -$delta_y
        LINEAR X($delta_y) F($scan_speed)
        LINEAR UU($power_1) E10
        $delta_y = -$delta_y
    NEXT
    $delta_x3 = -$delta_x3
NEXT
LINEAR Z0.015 Y($delta_x3) F0.01
NEXT

LINEAR Z5 F5
LINEAR Y0.500 F2
ABSOLUTE
LINEAR Z-0.075 F5
INCREMENTAL

FOR $cnt = 1 TO 4
    FOR $cnt2 = 1 TO 4
        LINEAR X($delta_y) F($scan_speed)
        LINEAR Y($delta_x3) F0.1
        LINEAR UU-66 E10
        $delta_y = -$delta_y
        LINEAR X($delta_y) F($scan_speed)
        LINEAR UU($power_1) E10
        $delta_y = -$delta_y
    NEXT
    $delta_x3 = -$delta_x3
    LINEAR Z0.015 Y($delta_x3) F0.01
NEXT

LINEAR Z5 F5
LINEAR Y0.750 F2
ABSOLUTE
LINEAR Z-0.125 F5
INCREMENTAL

//POWER 2
//SET 1
//1 micron separation
ABSOLUTE
LINEAR Z-0.075 F10
LINEAR UU($power_2) E3
INCREMENTAL

FOR $cnt = 1 TO 1
    LINEAR X($delta_y) F($scan_speed)
    LINEAR Y($delta_x1) F0.1
    LINEAR UU-66 E10
    $delta_y = -$delta_y
    LINEAR X($delta_y) F($scan_speed)
    LINEAR UU($power_2) E10
    $delta_y = -$delta_y
NEXT
Appendix B. Examples of GCode for Aerotech motion stages

LINEAR Z5 F5
LINEAR Y0.500 F2
ABSOLUTE
LINEAR Z-0.075 F5
INCREMENTAL

FOR $cnt = 1 TO 2
    FOR $cnt2 = 1 TO 2
        LINEAR X($delta_y) F($scan_speed)
        LINEAR Y($delta_x1) F0.1
        LINEAR UU-66 E10
        $delta_y = -$delta_y
        LINEAR X($delta_y) F($scan_speed)
        LINEAR UU($power_2) E10
        $delta_y = -$delta_y
    NEXT
    $delta_x1 = -$delta_x1
    LINEAR Z0.015 Y($delta_x1) F0.01
NEXT

LINEAR Z5 F5
LINEAR Y0.500 F2
ABSOLUTE
LINEAR Z-0.075 F5
INCREMENTAL

FOR $cnt = 1 TO 4
    FOR $cnt2 = 1 TO 4
        LINEAR X($delta_y) F($scan_speed)
        LINEAR Y($delta_x1) F0.1
        LINEAR UU-66 E10
        $delta_y = -$delta_y
        LINEAR X($delta_y) F($scan_speed)
        LINEAR UU($power_2) E10
        $delta_y = -$delta_y
    NEXT
    $delta_x1 = -$delta_x1
    LINEAR Z0.015 Y($delta_x1) F0.01
NEXT

LINEAR Z5 F5
LINEAR Y0.500 F2
ABSOLUTE
LINEAR Z-0.125 F5
INCREMENTAL
//SET 2
//Twomicron separation
ABSOLUTE
LINEAR Z-0.075 F10

INCREMENTAL

FOR $cnt = 1 TO 1
  LINEAR X($delta_y) F($scan_speed)
  LINEAR Y($delta_x2) F0.1
  LINEAR UU-66 E10
  $delta_y = -$delta_y
  LINEAR X($delta_y) F($scan_speed)
  LINEAR UU($power_2) E10
  $delta_y = -$delta_y
NEXT

LINEAR Z5 F5
LINEAR Y0.500 F2
ABSOLUTE
LINEAR Z-0.075 F5
INCREMENTAL

FOR $cnt = 1 TO 2
  FOR $cnt2 = 1 TO 2
    LINEAR X($delta_y) F($scan_speed)
    LINEAR Y($delta_x2) F0.1
    LINEAR UU-66 E10
    $delta_y = -$delta_y
    LINEAR X($delta_y) F($scan_speed)
    LINEAR UU($power_2) E10
    $delta_y = -$delta_y
  NEXT
  $delta_x2 = -$delta_x2
  LINEAR Z0.015 Y($delta_x2) F0.01
NEXT

LINEAR Z5 F5
LINEAR Y0.500 F2
ABSOLUTE
LINEAR Z-0.075 F5
INCREMENTAL

FOR $cnt = 1 TO 4
  FOR $cnt2 = 1 TO 4
    LINEAR X($delta_y) F($scan_speed)
    LINEAR Y($delta_x2) F0.1
  NEXT
LINEAR UU-66 E10
$\delta_y = -\delta_y$
LINEAR X($\delta_y$) F($\text{scan\_speed}$)
LINEAR UU($\text{power\_2}$) E10
$\delta_y = -\delta_y$
NEXT
$\delta_x2 = -\delta_x2$
LINEAR Z0.015 Y($\delta_x2$) F0.01
NEXT

LINEAR Z5 F5
LINEAR Y0.500 F2
ABSOLUTE
LINEAR Z-0.125 F5
INCREMENTAL

//SET 3
//4 micron separation
ABSOLUTE
LINEAR Z-0.075 F10
INCREMENTAL

FOR $\text{cnt} = 1$ TO 1
    LINEAR X($\delta_y$) F($\text{scan\_speed}$)
    LINEAR Y($\delta_x3$) F0.1
    LINEAR UU-66 E10
    $\delta_y = -\delta_y$
    LINEAR X($\delta_y$) F($\text{scan\_speed}$)
    LINEAR UU($\text{power\_2}$) E10
    $\delta_y = -\delta_y$
NEXT

LINEAR Z5 F5
LINEAR Y0.500 F2
ABSOLUTE
LINEAR Z-0.075 F5
INCREMENTAL

FOR $\text{cnt} = 1$ TO 2
    FOR $\text{cnt2} = 1$ TO 2
        LINEAR X($\delta_y$) F($\text{scan\_speed}$)
        LINEAR Y($\delta_x3$) F0.1
        LINEAR UU-66 E10
        $\delta_y = -\delta_y$
        LINEAR X($\delta_y$) F($\text{scan\_speed}$)
        LINEAR UU($\text{power\_2}$) E10
    NEXT
NEXT
$\delta_y = -\delta_y$

NEXT

$\delta_x3 = -\delta_x3$

LINEAR Z0.015 Y($\delta_x3$) F0.01

NEXT

LINEAR Z5 F5
LINEAR Y0.500 F2
ABSOLUTE
LINEAR Z-0.075 F5
INCREMENTAL

FOR $\text{cnt} = 1$ TO 4
  FOR $\text{cnt2} = 1$ TO 4
    LINEAR X($\delta_y$) F($\text{scan}\_\text{speed}$)
    LINEAR Y($\delta_x3$) F0.1
    LINEAR UU-66 E10
    $\delta_y = -\delta_y$
    LINEAR X($\delta_y$) F($\text{scan}\_\text{speed}$)
    LINEAR UU($\text{power}\_2$) E10
    $\delta_y = -\delta_y$
  NEXT
  $\delta_x3 = -\delta_x3$
  LINEAR Z0.015 Y($\delta_x3$) F0.01
NEXT

//POWER 4
//SET 1
//1 micron separation
ABSOLUTE
LINEAR Z-0.075 F10
LINEAR UU($\text{power}\_3$) E3
INCREMENTAL

FOR $\text{cnt} = 1$ TO 1
  LINEAR X($\delta_y$) F($\text{scan}\_\text{speed}$)
  LINEAR Y($\delta_x1$) F0.1
  LINEAR UU-66 E10
  $\delta_y = -\delta_y$
  LINEAR X($\delta_y$) F($\text{scan}\_\text{speed}$)
  LINEAR UU($\text{power}\_3$) E10
  $\delta_y = -\delta_y$
NEXT

LINEAR Z5 F5
LINEAR Y0.500 F2
Appendix B. Examples of GCode for Aerotech motion stages

ABSOLUTE
LINEAR Z-0.075 F5
INCREMENTAL

FOR $cnt = 1 TO 2
  FOR $cnt2 = 1 TO 2
    LINEAR X($delta_y) F($scan_speed)
    LINEAR Y($delta_x1) F0.1
    LINEAR UU-66 E10
    $delta_y = -$delta_y
    LINEAR X($delta_y) F($scan_speed)
    LINEAR UU($power_3) E10
    $delta_y = -$delta_y
  NEXT
  $delta_x1 = -$delta_x1
  LINEAR Z0.015 Y($delta_x1) F0.01
NEXT

LINEAR Z5 F5
LINEAR Y0.500 F2
ABSOLUTE
LINEAR Z-0.075 F5
INCREMENTAL

FOR $cnt = 1 TO 4
  FOR $cnt2 = 1 TO 4
    LINEAR X($delta_y) F($scan_speed)
    LINEAR Y($delta_x1) F0.1
    LINEAR UU-66 E10
    $delta_y = -$delta_y
    LINEAR X($delta_y) F($scan_speed)
    LINEAR UU($power_3) E10
    $delta_y = -$delta_y
  NEXT
  $delta_x1 = -$delta_x1
  LINEAR Z0.015 Y($delta_x1) F0.01
NEXT

LINEAR Z5 F5
LINEAR Y0.500 F2
ABSOLUTE
LINEAR Z-0.125 F5
INCREMENTAL

//SET 2
//Twomicron separation
ABSOLUTE
LINEAR Z-0.075 F10

INCREMENTAL

FOR $cnt = 1 TO 1
    LINEAR X($delta_y) F($scan_speed)
    LINEAR Y($delta_x2) F0.1
    LINEAR UU-66 E10
    $delta_y = -$delta_y
    LINEAR X($delta_y) F($scan_speed)
    LINEAR UU($power_3) E10
    $delta_y = -$delta_y
NEXT

LINEAR Z5 F5
LINEAR Y0.500 F2
ABSOLUTE
LINEAR Z-0.075 F5
INCREMENTAL

FOR $cnt = 1 TO 2
    FOR $cnt2 = 1 TO 2
        LINEAR X($delta_y) F($scan_speed)
        LINEAR Y($delta_x2) F0.1
        LINEAR UU-66 E10
        $delta_y = -$delta_y
        LINEAR X($delta_y) F($scan_speed)
        LINEAR UU($power_3) E10
        $delta_y = -$delta_y
    NEXT
    $delta_x2 = -$delta_x2
    LINEAR Z0.015 Y($delta_x2) F0.01
NEXT

LINEAR Z5 F5
LINEAR Y0.500 F2
ABSOLUTE
LINEAR Z-0.075 F5
INCREMENTAL

FOR $cnt = 1 TO 4
    FOR $cnt2 = 1 TO 4
        LINEAR X($delta_y) F($scan_speed)
        LINEAR Y($delta_x2) F0.1
        LINEAR UU-66 E10
        $delta_y = -$delta_y
        LINEAR X($delta_y) F($scan_speed)
Appendix B. Examples of GCode for Aerotech motion stages

```plaintext
LINEAR UU($power_3) E10
$delta_y = -$delta_y
NEXT
$delta_x2 = -$delta_x2
LINEAR Z0.015 Y($delta_x2) F0.01
NEXT
LINEAR Z5 F5
LINEAR Y0.500 F2
ABSOLUTE
LINEAR Z-0.125 F5
INCREMENTAL

//SET 3
//4 micron separation
ABSOLUTE
LINEAR Z-0.075 F10
INCREMENTAL

FOR $cnt = 1 TO 1
    LINEAR X($delta_y) F($scan_speed)
    LINEAR Y($delta_x3) F0.1
    LINEAR UU-66 E10
    $delta_y = -$delta_y
    LINEAR X($delta_y) F($scan_speed)
    LINEAR UU($power_3) E10
    $delta_y = -$delta_y
NEXT
LINEAR Z5 F5
LINEAR Y0.500 F2
ABSOLUTE
LINEAR Z-0.075 F5
INCREMENTAL

FOR $cnt = 1 TO 2
    FOR $cnt2 = 1 TO 2
        LINEAR X($delta_y) F($scan_speed)
        LINEAR Y($delta_x3) F0.1
        LINEAR UU-66 E10
        $delta_y = -$delta_y
        LINEAR X($delta_y) F($scan_speed)
        LINEAR UU($power_3) E10
        $delta_y = -$delta_y
    NEXT
$delta_x3 = -$delta_x3
```
LINEAR Z0.015 Y($delta_x3) F0.01
NEXT

LINEAR Z5 F5
LINEAR Y0.500 F2
ABSOLUTE
LINEAR Z-0.075 F5
INCREMENTAL

FOR $cnt = 1 TO 4
    FOR $cnt2 = 1 TO 4
        LINEAR X($delta_y) F($scan_speed)
        LINEAR Y($delta_x3) F0.1
        LINEAR UU-66 E10
        $delta_y = -$delta_y
        LINEAR X($delta_y) F($scan_speed)
        LINEAR UU($power_3) E10
        $delta_y = -$delta_y
    NEXT
    $delta_x3 = -$delta_x3
    LINEAR Z0.015 Y($delta_x3) F0.01
NEXT

LINEAR Z5 F5
LINEAR Y0.750 F2
ABSOLUTE
LINEAR Z-0.125 F5
INCREMENTAL

//POWER 3
//SET 1
//1 micron separation
ABSOLUTE
LINEAR Z-0.075 F10
LINEAR UU($power_4) E3
INCREMENTAL

FOR $cnt = 1 TO 1
    LINEAR X($delta_y) F($scan_speed)
    LINEAR Y($delta_x1) F0.1
    LINEAR UU-66 E10
    $delta_y = -$delta_y
    LINEAR X($delta_y) F($scan_speed)
    LINEAR UU($power_4) E10
    $delta_y = -$delta_y
NEXT
LINEAR Z5 F5
LINEAR Y0.500 F2
ABSOLUTE
LINEAR Z-0.075 F5
INCREMENTAL

FOR $cnt = 1 TO 2
  FOR $cnt2 = 1 TO 2
    LINEAR X($delta_y) F($scan_speed)
    LINEAR Y($delta_x1) F0.1
    LINEAR UU-66 E10
    $delta_y = -$delta_y
    LINEAR X($delta_y) F($scan_speed)
    LINEAR UU($power_4) E10
    $delta_y = -$delta_y
  NEXT
$delta_x1 = -$delta_x1
LINEAR Z0.015 Y($delta_x1) F0.01
NEXT

LINEAR Z5 F5
LINEAR Y0.500 F2
ABSOLUTE
LINEAR Z-0.075 F5
INCREMENTAL

FOR $cnt = 1 TO 4
  FOR $cnt2 = 1 TO 4
    LINEAR X($delta_y) F($scan_speed)
    LINEAR Y($delta_x1) F0.1
    LINEAR UU-66 E10
    $delta_y = -$delta_y
    LINEAR X($delta_y) F($scan_speed)
    LINEAR UU($power_4) E10
    $delta_y = -$delta_y
  NEXT
$delta_x1 = -$delta_x1
LINEAR Z0.015 Y($delta_x1) F0.01
NEXT

LINEAR Z5 F5
LINEAR Y0.500 F2
ABSOLUTE
LINEAR Z-0.125 F5
INCREMENTAL
Appendix B. Examples of GCode for Aerotech motion stages

//SET 2
//Twomicron separation
ABSOLUTE
LINEAR Z-0.075 F10

INCREMENTAL

FOR $cnt = 1 TO 1
    LINEAR X($delta_y) F($scan_speed)
    LINEAR Y($delta_x2) F0.1
    LINEAR UU-66 E10
    $delta_y = -$delta_y
    LINEAR X($delta_y) F($scan_speed)
    LINEAR UU($power_4) E10
    $delta_y = -$delta_y
NEXT

LINEAR Z5 F5
LINEAR Y0.500 F2
ABSOLUTE
LINEAR Z-0.075 F5
INCREMENTAL

FOR $cnt = 1 TO 2
    FOR $cnt2 = 1 TO 2
        LINEAR X($delta_y) F($scan_speed)
        LINEAR Y($delta_x2) F0.1
        LINEAR UU-66 E10
        $delta_y = -$delta_y
        LINEAR X($delta_y) F($scan_speed)
        LINEAR UU($power_4) E10
        $delta_y = -$delta_y
    NEXT
    $delta_x2 = -$delta_x2
    LINEAR Z0.015 Y($delta_x2) F0.01
NEXT

LINEAR Z5 F5
LINEAR Y0.500 F2
ABSOLUTE
LINEAR Z-0.075 F5
INCREMENTAL

FOR $cnt = 1 TO 4
    FOR $cnt2 = 1 TO 4
        LINEAR X($delta_y) F($scan_speed)
        LINEAR Y($delta_x2) F0.1
    NEXT
NEXT
LINEAR UU-66 E10
$delta_y = -$delta_y
LINEAR X($delta_y) F($scan_speed)
LINEAR UU($power_4) E10
$delta_y = -$delta_y

NEXT
$delta_x2 = -$delta_x2
LINEAR Z0.015 Y($delta_x2) F0.01

NEXT

LINEAR Z5 F5
LINEAR Y0.500 F2
ABSOLUTE
LINEAR Z-0.125 F5
INCREMENTAL

//SET 3
//4 micron separation
ABSOLUTE
LINEAR Z-0.075 F10
INCREMENTAL

FOR $cnt = 1 TO 1
    LINEAR X($delta_y) F($scan_speed)
    LINEAR Y($delta_x3) F0.1
    LINEAR UU-66 E10
    $delta_y = -$delta_y
    LINEAR X($delta_y) F($scan_speed)
    LINEAR UU($power_4) E10
    $delta_y = -$delta_y

NEXT

LINEAR Z5 F5
LINEAR Y0.500 F2
ABSOLUTE
LINEAR Z-0.075 F5
INCREMENTAL

FOR $cnt = 1 TO 2
    FOR $cnt2 = 1 TO 2
        LINEAR X($delta_y) F($scan_speed)
        LINEAR Y($delta_x3) F0.1
        LINEAR UU-66 E10
        $delta_y = -$delta_y
        LINEAR X($delta_y) F($scan_speed)
        LINEAR UU($power_4) E10

NEXT

LINEAR Z5 F5
LINEAR Y0.500 F2
ABSOLUTE
LINEAR Z-0.075 F5
INCREMENTAL

FOR $cnt = 1 TO 2
    FOR $cnt2 = 1 TO 2
        LINEAR X($delta_y) F($scan_speed)
        LINEAR Y($delta_x3) F0.1
        LINEAR UU-66 E10
        $delta_y = -$delta_y
        LINEAR X($delta_y) F($scan_speed)
        LINEAR UU($power_4) E10
\texttt{
\begin{verbatim}
$\delta_y = -$\delta_y
NEXT
$\delta_x3 = -$\delta_x3
LINEAR Z0.015 Y(\delta_x3) F0.01
\end{verbatim}

LINEAR Z5 F5
LINEAR Y0.500 F2
ABSOLUTE
LINEAR Z-0.075 F5
INCREMENTAL

FOR $\texttt{cnt} = 1 \texttt{TO} 4
  FOR $\texttt{cnt2} = 1 \texttt{TO} 4
    LINEAR X(\delta_y) F(\texttt{scan\_speed})
    LINEAR Y(\delta_x3) F0.1
    LINEAR UU-66 E10
    $\delta_y = -$\delta_y
    LINEAR X(\delta_y) F(\texttt{scan\_speed})
    LINEAR UU(\texttt{power\_4}) E10
    $\delta_y = -$\delta_y
  \end{verbatim}

NEXT
$\delta_x3 = -$\delta_x3
LINEAR Z0.015 Y(\delta_x3) F0.01
\end{verbatim}

LINEAR Z5 F5
LINEAR Y0.750 F2
ABSOLUTE
LINEAR Z-0.125 F5
INCREMENTAL
ABSOLUTE
LINEAR Z5 F1

M2

(4) x- and y-axis gratings
\end{verbatim}
}
Appendix C

Lumerical

Lumerical .lsf code used to project interference intensity profiles generated by FDTD solutions to the farfield for the determination of diffraction efficiency

```
#%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Author: Debashis Chanda, debashis.chanda@gmail.com
Date : July 10, 2010
#%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
# sets variable Ndt, which denotes the number of points to
# simulate for Grating Groove Depth
Ndt = 1;

# sets variable Nd, which denotes the number of points to simulate for
# two Grating separation distance
Nd = 1;

#Number of Refractive Index Contrast
Nn = 1;

#Max Number of Layers Scan
N = 20;

# creates vector "dt" groove depth and
# "d"for separation between two grating
dt = 7.0e-6;
d = 3.82e-6; #Edge to Edge separation between Two Layers
n_high = 1.485;
n_low = 1.46;
```
Period = 1e-6;

logfile = "DE_Summary_Number_of_Layers"+.txt;
rm(logfile);

for (pp = 1:N) { #Layer Scan
    for (mm = 1:Nd) { #Layer Separation Scan
        for (nn = 1:Nn) { #Index Scan

            #filename of relevant .fsp modeling file
            filename = "dt_"+num2str(dt*1e6)+"um_d_"+num2str(d(mm)*1e6)+
                        "um_delta-n_"+num2str(n_high(nn)-n_low)+
                        ".NLayers_"+num2str(pp)+"_Pol_TM.fsp";
            load(filename);

            ?"Working on Number of Layers (N)= "+num2str(pp)+" of "+num2str(N);
            ?outstring= "--------Number of Layers (N)= "+num2str(pp)+"--------";
            write(logfile,outstring);

            # calculates and plots the strengths of each order for a
            # monitors;
            # get the grating angles
            Diff_angle = gratingangle("T");
            ?Diff_angle;
            m = gratingn("T");

            # get the strength of each grating
            order_strength = grating("T");
            # calculate the total transmission through the monitor "T",
            # normalized to the source input power
            T_power = transmission("T");
            ?outstring="Summary of grating order strengths";
            write(logfile,outstring);
            ?outstring="m, angle(degrees), relative strength, strength
            normalized to source";
            write(logfile,outstring);

            for(i=1:length(Diff_angle)) {
                if(order_strength(i) > 0) {
                    ?outstring = num2str(m(i)) + ", " +
                                num2str(Diff_angle(i)) + ", " +
                                num2str(order_strength(i)) + ", " +
                                num2str(order_strength(i)*T_power);
                    write(logfile,outstring);
                }
            }
        }
    }
}
} }
Figure C.1: Screenshot of Lumerical UI for 5 layers of gratings.
Figure C.2: Example of Mesh settings in Lumerical.
Figure C.3: Example of Boundary settings in Lumerical.
Figure C.4: Example of Advanced settings in Lumerical.
Bibliography


